

Lecture 01

0:11

And welcome to lecture #1 So in this lecture we will be looking at the applications of fluid mechanics.

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So this corresponds with reader chapter 3 properly, but I would note that chapters one and two respectively on thermodynamic equilibrium and basic fluid mechanics, these are provided simply as a revisionary activity.

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If you didn't feel completely confident in either of those classes and you wanted a little bit of a refresher to make sure we can start talking about fluids for unit operations.

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So by the end of this first lecture in a week, it would be good to have a quick flip through chapters one and two of the reader just to make sure you're comfortable.

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But really the intention is to spend time on chapter 3, which is our basics or flow characteristics.

1:05

Now, I would point out something that we're going to be looking at a bit in the coming lectures.

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And I'll, I'll touch back to this, but there are some points of chapter 2 where we're looking at fluid mechanics in a slightly different way.

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And so I'll be referring to some of the tables and equations in chapter two of the reader as we go through both this lecture and the next for that background.

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Now, if you find chapter three of the reader on flow characteristics to be a bit challenging and you want some additional support in reading, we would go to chapters two and three of the required unit textbooks.

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So McCabe 7th edition.

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And these go a bit more, these chapters go a bit more in depth as to the role of fluid mechanics that we're going to be looking at here, right?

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So when we first begin one of the the core concepts and I'm going to try to lay out the two or three core concepts of fluid mechanics that we really are going to be deploying for unit operations.

2:01

And the first of these is making sure we're comfortable with the concept of fluid head.

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So what fluid head means is if I can imagine if I'm on top of an ocean surface and then if

I go 10 meters down into the ocean surface, the effective weight, the weight of that water column on top of me as a diver is going to apply additional pressure, right?

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So the way that we characterize that would be the density of whatever fluid is on top of me.

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It could be the water.

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If I'm in the ocean, it could be air, right?

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As I stand on the Earth, sit on the beach, I have a, an air column that goes from the top of my head to the top of the atmosphere.

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And so the density of that area is much, much less, but its height is much greater.

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So the the characteristics that we look at then are the density of whatever fluid is going to be above me or above the position that I'm looking at the gravitational field in which that fluid sits.

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So in this case, G would be relative to the the planet Earth 9.81 meters per second squared and R sub M here, which we would also call H or ΔZ in a different parlance, all mean the same thing.

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And that's the height how what's the linear distance of the fluid above my head?

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So exploiting this principle of fluid head $\rho G H$ or $\rho G \Delta Z$ allows us to use a device called a manometer.

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And what this does, as shown here on the left hand side is a very this most simple schematic of a manometer where I'm looking at two points in pressure.

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So I have the pressure at point A and the pressure at point B.

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And this is what the monometer is connected to, to measure.

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So these could be exposed to the atmosphere.

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If I'm going to take pressure measurements of say, on the outside of an airplane in flight, these are the devices that are used, or they could be connected to a flow channel and that could be something like the unit operation I'm concerned with.

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And I want to know what the pressure is between these two points.

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And the working concept of a manometer is that I'm going to consider the difference between 2 fluid heads.

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One of those fluids is my working fluid, which is shown here with the cross hatched marks.

4:11

This would have a density ρ sub A.

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And the second fluid is that connected to my operating system.

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So that could be air, atmospheric air.

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In the case of my airplane, it could be a different fluid if I'm working in my unit operation.

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So there's a, a connection here where this fluid B with the density ρ sub B is connected into my system of measurement.

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And so the measurement principle of the manometer is that at which between these two different points in pressure, what I'm measuring is R sub M, the difference in height of my working fluid where it is exposed in one side to pressure piece of A and on the other side to pressure piece of B.

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And the reason that we like manometers is that we can, if we know the density and we tend to pick fluids for these manometers of known and hopefully constant density over the the period of assessment.

5:04

So if I know the density of the fluid, I only need to take one measurement of this R sub M, so the height difference between the left and the right hand side to then determine the difference in pressure between these two points.

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So when I go back to the principles of metrology, that is the science of measurement.

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The reason we like the manometer is that to directly measure something like pressure is a much more elaborate and involved measurement.

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I might need a diaphragm or a strain gauge that can tell me how much pressure is being applied to it, and as an aside, the measurement of differential pressure.

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So I can buy something like a differential pressure transducer so that it can use a double diaphragm that is even more elaborate and much, much, much more expensive.

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For reference, I think to get A, at least in the past five years, a differential pressure measurement within say a kilopascal uncertainty and a typical medium pressure application would cost us something on the order of about 10,000 Australian dollars.

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So very expensive measurements.

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If I'm using strain gauges or diaphragms to measure differential pressure, but height, you know, linear distance, I could use a ruler, a common household ruler to take the measurement of differential pressure here because I'm only measuring $R \text{ sub } M$.

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So that's why we like manometers.

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They're a very inexpensive, very reliable method to obtain differential pressure measurements.

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Now on the right hand side, we can look at an example of a manometer applied to an internal flow system.

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And you might remember from some of our basic operations in thermodynamics the concept of a choke.

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So here I have some inlet fluid coming into my pipe system and I've applied a choke.

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And we would remember from thermodynamics, these are isenthalpic processes.

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So the enthalpy of my fluid at point A is equal to the enthalpy of my fluid at point B.

7:00

And I can see here the dark that the diagram is showing me.

7:03

The choke is closing in.

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The teeth of the choke in 360° are closing in on that fluid flow profile.

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So we've connected the manometer here to a point upstream and a point downstream and we have our working fluid in this same cross hash method.

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So what we can then do is measure this height difference here, that is $R \text{ sub } M$, and if we know what the densities are, it tells us the amount of pressure decrease or the differential pressure caused by my choke.

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And so this is a very elegant solution if I need something like a real time measurement or a feedback or feed forward control where I can take a measurement of the

effectiveness of that choke, meaning the amount of pressure that it's reduced, and relate that back to whether the choke is too open, too closed or just right now.

7:56

I can, you know, if I have a very, very small pressure difference between 2 points, one of the techniques I can use on the right hand side is to take an inclined manometer, right?

8:08

So if I'm looking at a very small differential pressure that I know I need to measure, I effectively take the manometer and I stretch it out over a much larger point in space.

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And I'm going to put it on an incline, right?

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So that the $R \sin \theta$ that I'm measuring here is a trigonometric function of θ and R .

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So the distance in that the height of the fluid.

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So this is a slightly different take off on how I could apply a manometer.

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But what you'll find is in the rear there are some worked examples of you know, if I know what the densities are and I know $R \sin \theta$ I can get the differential pressure.

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Conversely, if I know the differential pressure and the densities, I can calculate $R \sin \theta$.

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Now this concept of fluid head also comes into play in a different application.

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And that's where we want to start looking at things like separation of fluids and or solids.

9:04

And so because I'm working in a constant accelerational field from the Earth's gravity, if I put a series of fluids or solids in a tank and I simply allow them to sit there, the difference in the fluid density and the effective head difference as I go from the very top of the fluid profile down into the bottom of the tank, the pressure is going to increase as a function of the height and the density.

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And these are cumulative, right?

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So the pressure experienced by the solids here is $\rho_1 h$ of the heavy liquid, meaning the high density liquid plus $\rho_2 h$ of the low density liquid.

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Now exploiting this same concept, you might say to yourself, well, if I have a very small density difference between MY2, in this case immiscible liquids, meaning they don't dissolve in each other and perhaps MY solids are not that different in density, it's a very small density differences here.

10:07

This type of gravimetric separation can take a very long time or we'd also call these gravity decanters as a unit operation.

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So this can take a very, very long time to, to give you an example, if I had a gravity separator the size of a typical automobile, I say filled up with an oil, filled up with some water and maybe a few solids, it could take on the order of weeks to achieve a perfect separation depending on both the density.

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And then as we go further into our curriculum, we're going to be looking at the chemical characteristics.

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So if I have a very chemically heterogeneous system, maybe I have some soaps in one of these phases, or both, it can take a very long time for that to work.

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So we can use our knowledge of force to design A slightly different system.

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That's pictured on the right hand side, and this is a centrifugal canter.

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So in this system what we're doing is spinning the entire system.

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It's rotating around this feed axis, as I can see.

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So the feed is through the centre line here and the system itself is a cylinder in rotation as shown by the pointer.

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Now what that's going to do is push, right, all of my most dense material, whether that's a liquid or a solid.

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Now in this case, as we've drawn it, it's a solid.

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It's going to push all of that most dense material to the very outside of the centrifugal decanter.

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Now you'd note that the way we've drawn this here, the solids are shown on on the outside and also the bottom.

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Because remembering that the the degree to which I spin this, it is still experiencing Earth's gravity.

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So there's a natural inclination to pull everything heavy downward.

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And the speed, the rotational speed with which I spin this is going to balance against that natural Earth's gravity.

12:01

All right.

12:01

So if I spin it very in the way we've drawn this here, I would be spinning this maybe at something like 100 RPM.

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And that's why I'm getting a majority of my solids on the bottom.

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If I were to increase the spinning rate to say 5000 RPM or some of our our more modern systems might go 10 or 12,000 RPM rotations per minute, then I would see all of those solids on the only the outside wall and nothing on the bottom.

12:28

And in the same way, the force, the centrifugal force that's applied in this will push my heavier more dense liquid to the outside of the decanter and my lighter or less lower density liquid to the inside of the decanter.

12:44

So if I needed to to perform a large scale separation very quickly, a centrifugal decanter allows me to effectively add more force to the system beyond just that of Earth's acceleration and significantly increase the speed of that separation process.

13:01

So this concept of fluid head ρGH , $\rho G \Delta Z$ is something that I can exploit both for really clever measurements in unit operations, but also for unit operations themselves, right?

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And separation is one of the simplest operations we can perform.

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Now when we're, we're starting to talk about fluid motion.

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Now it's important that we are comfortable with from fluid mechanics, the concepts of shear rate, shear stress and viscosity, right?

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And how they're linked together.

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So in this middle equation here, we're looking at the shear stress that is effectively meaning the stress that the force that that fluid is going to apply, right?

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And I can see that the very definition of shear stress, we'll use the Greek letter Tau for this is the force that's being applied on the area of application, right?

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So the shear stress tells me if I'm in a flowing system effectively on normalized per area, how much force is this fluid applying to its container because of its motion.

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And I can fundamentally define shear stress as the product of viscosity, and this is dynamic viscosity.

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We use the Greek letter μ and the shear rate.

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Now the shear rate we can, I would typically write with the Greek letter γ and often $\dot{\gamma}$ to indicate it is a rate.

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But fundamentally the definition of shear rate is how the velocity of the fluid changes as it approaches its wall.

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And we'll look at an example of this in the coming slide.

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So the product of the shear rate and the dynamic viscosity gives me this shear stress.

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Now you can see in this equation here, right?

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If the purpose of the engineer is to manipulate and or exploit the shear rate.

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DUDY, in this diagram on the left, it's also labeled in an older nomenclature the velocity gradient.

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Then this model or this equation assumes that the dynamic viscosity is going to be constant, right?

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It's a constant proportionality, how much shear rates of basically how much momentum energy, fluid energy is in the system.

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It's a proportionality that dictates how much of that fluid motion is represented in the shear stress.

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And we would call that condition a Newtonian fluid.

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So this is shown on the left, oops on the left hand side here where I have a shear stress and I'm plotting the shear stress τ as a function of a velocity gradient or the the shear rate.

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DUDY if there is a linear behavior between the two, then that is consistent with a Newtonian fluid.

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Now this may not always be the case.

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And I think even though in in our unit operations labs we're not going to be working with non Newtonian fluids very much.

15:56

Some of the fluids we look at are will have some non Newtonian behavior.

16:00

But we tend to try to work in the Newtonian space in undergraduate curriculum When when you get out into industry, this is always a good assumption to check, right?

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You will typically work on systems that have been designed with the assumption of Newtonian fluids, meaning that for every amount of shear rate I increase I get a constant proportional increase in shear stress.

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But that might not always be the case and it's it's often times an assumption that's made and can be forgotten about as an engineering design or a unit operation design will matriculate through it's different stages.

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Now I can have a few different variants on this.

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I can have a dilatant that's shown in in curve D here where effectively that as I increase the amount of shear or as I increase the shear rate in the system, I get a decrease, well I get a lesser proportional increase in the shear stress.

17:00

So a good example of this would be quicksand, right?

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The faster I try to push, the less effective it is at creating a force on that fluid.

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The inversion of that would be latex, my pseudoplastic right where I'm I'm still having a constant condition of at 0 shear stress, there is 0 shear rate.

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But as I start to increase that shear rate, meaning I'm starting to move the fluid faster, I get a disproportionately high increase in shear stress.

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And so I can see this is sitting above that Newtonian line.

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And the the other type of fluid departure I can have is what we would typically or historically refer to as a Bingham plastic.

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And this what I can see here is I first start to see any shear stress from the fluid.

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So for the fluid itself to apply shear stress, I have to 1st surpass the amount of sorry, invert that to see the fluid move.

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I first have to put some amount of shear on the system that we would typically call the yield stress.

18:06

So τ not this is the yielding stress after I increase the force on that fluid, right?

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F sub S in this parlance beyond a certain point, or F not τ not in this point or in this case.

18:19

I then start to see the fluid move, right?

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So this yield stress behavior, this is a really interesting thing to keep an eye on, particularly as an engineer, right?

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What makes the Bingham plastic a Bingham plastic is that it has a yield stress.

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Now, the way this diagram has been drawn, this also looks quite Newtonian beyond that point of yield stress, right?

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Once I get beyond the yielding behavior, for every amount of stress I put in, I see a proportional and constant proportional response in the shear rate.

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However, that is not always the case.

18:52

Once I surpass the old stress, I can have either a disproportionately high or disproportionately low track and how that fluid is then going to respond to additional stress applied to it.

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So all of this to say when we get into real world engineering problems it is not uncommon to see the assumption of a Newtonian fluid in play.

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And yet some of our most complex problems are working with fluids that have either a yield stress condition to them.

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So this τ not behaviour and or a non Newtonian response as I then further increase the shear stress on my system.

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And a very good example of this would be any one of type of hydrocarbon, right?

19:42

So this could be a hydrocarbon chain that's derived organically, one that comes from nature like a sunflower oil or one that's taken out of the ground like crude oil.

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These kinds of fluids that have very complex integrated chemistries tend to result in yield stress type behavior.

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So once my fluid starts to move right, I've either applied my initial stress or I've exceeded the yield stress.

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So now I'm in a point of fluid motion.

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We then have to think about, well, how is that that fluid motion going to establish a full flow profile?

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And this is what the undergraduate discipline of fluid mechanics would have spent quite a bit of time talking about.

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So I'm not going to rehash the entire argument here, but I want to make sure we're comfortable with a few core concepts.

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The first of these is that no matter what fluid I have, I must must must have the condition satisfied that there is no fluid motion at the point that the fluid meets the wall.

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So as my fluid, as the the final row of molecules of fluid are in contact with the wall, that final row of molecules does not have any motion to it.

20:58

And as I go from that interface between the fluid and wall out into the centre line of the fluid, I go from a point of no flow to a point of full flow.

21:08

Now the transition between these two is what we look at is the the establishment of a boundary layer, the growth of that boundary layer and ultimately the establishment of a full flow profile.

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So if I'm plotting this out, I can see if the Y axis here is the distance from the wall.

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So at the point of 0 I'm at the wall and the right is a represent or on the X axis is a representation of the local fluid velocity.

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So at the point of the wall at this must bisect 00.

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And as I go away from the wall, I can see my fluid velocity is going to increase and increase and these are representing different planes of the fluid.

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And I can start to see that this increase right is eventually going to reach some point of a maximum.

21:56

And then as I hit the and it will be maximum at that centre line of the pipe if I'm in laminar flow.

22:01

And then as I take one step beyond the centre line, I'm now approaching the other side of the wall if I'm in a say, a classic cylindrical flow channel.

22:11

Now the point of representing it like this is that you can remember our shear rate was $\frac{du}{dy}$ the velocity gradient.

22:19

So I can take the the numerical or analytical differential.

22:23

If I have a laminar flow system, I can differentiate this u with respect to y each step along this curve, and I can then represent u as a function of distance from the wall.

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So there's a few points to make here.

22:39

The nature of having a no slip condition at my wall.

22:44

And this is a classic assumption of fluid mechanics that we apply to absolutely every system on which we work.

22:51

The nature of that is what gives rise to a maximal shear rate at the wall, right?

22:59

And this is the the molecules in the first two rows above the wall.

23:03

That is where the gradient of velocity is the highest.

23:08

OK, And I can see this emerge numerically.

23:11

So if I had a a Newtonian fluid for simplicity, right, constant viscosity, then what's dictating my shear stress?

23:18

τ , if I have a constant viscosity, is going to be the highest shear stress is the point in the system where I have the highest shear rate.

23:28

And this is an interesting point, right?

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Because we often think conceptually, well, if I, I use the example of my kitchen faucet, right, if I imagine the water that's flowing through that pipe and out through the kitchen faucet, I would normally think intuitively that the highest point of stress in the system should be the centre of that fluid, right?

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So the most force that's being applied would be the centre of fluid.

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But in fact, that's not correct.

23:56

The highest point of stress, where the most force of the highest amount of force from that fluid is applied, is actually at the wall, meaning the cylindrical container wall, the circle that is containing the water in the tap that when it's in motion, that's where the greatest stress is being applied.

24:17

As an aside, This is why we get phenomena like corrosion and erosion, corrosion happening at that wall because the fluids are constantly applying stress to it and this at that wall as opposed to the centre line of the fluid.

24:33

Now, the way we've drawn this here, right where we have a, a constant and smooth and I would say monotonic, meaning it's always changing in the same direction, but a constant and, and smooth monotonic curve in terms of the decrease in shear rate as I go from the wall to the centre line.

24:49

And then I can imagine this inverts and flips as I go from the center line to the other wall.

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This would be consistent with a laminar flow profile that we would have seen in fluid mechanics.

24:59

If I was in a highly turbulent system, for instance, I would expect, let me see if I can grab my pen here.

25:06

I would expect something a little more like this where I have a very sharp increase.

25:11

And if that's highly turbulent, then I would achieve a constant condition through the center line of the pipe.

25:19

All right, So this is turbulent and this would be for a laminar flow system.

25:25

All right.

25:28

So now we can imagine in fluid mechanics and what we've just looked at those two flow profiles, those are consistent with our representations of laminar and turbulent flow at when it's fully established, right, when it's at steady state one of departing from undergraduate fluid mechanics and now looking at unit operations, one of the key concepts that we're aiming to drive home is that we now need to think about what happens when that flow is not fully established.

26:05

So my discipline of fluid mechanics is going to inform for me what is the end condition of the system when it is fully established flow.

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But we don't know what happens leading up to that, and that's what we need to explore.

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Now, we would have talked about in fluid mechanics the idea of a boundary layer.

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What I'm particularly interested in here is not the existence of that boundary layer, but in fact how it evolves in space and time.

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So what we're looking at in this plot, on the left hand side, the Y axis is the thickness of my boundary layer.

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And if we're talking only about fluid mechanics right now, we would call this the hydrodynamic or the fluid boundary layer.

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And on the X axis, we're looking at the distance from the leading edge.

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So let's take a minute to think about what that means.

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In this system, the distance from the leading edge means that I have fluid contacting a new wall for the first time.

27:06

A good visual metaphor for that might be if I were to go out into the garden and I have a garden hose and a garden tap.

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Well, I could unscrew the garden hose and hold it really close to the garden tap.

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But so that I know I can see the fluid going from the tap into the hose, meaning it's not a constant flow, but rather the the water exits the tap is in air for a few microseconds and then goes into the hose.

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So it's entering a new environment for the very first time at the entry point of that hose.

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That's what we mean is the leading edge.

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No, I can write the same metaphor for a flat plate versus a cylindrical hose, but I tend to prefer to think about cylindrical pipes because we see them so often in our daily lives.

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So that's that distance from the leading edge.

27:52

And what I can see is when I my fluid first contacts the system when it first enters or it contacts with a new wall.

28:00

In fact, I have no boundary layer.

28:04

It's only after some amount of time and in this case time and space, because my fluids are flowing at velocity.

28:12

But I see the establishment growth and eventually the steady state profile or the the equilibrium or fully developed flow profile for my boundary layer.

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So initially when fluids first contact a new wall, I see the onset of a boundary layer in which the flow inside of it is laminar.

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Now as that boundary layer is growing in this initial.

28:38

It grows with a function of X , so distance from the leading edge to the power of .5 as it grows.

28:46

So at some point thick enough that I'm going to get the onset of turbulence, so I get these little turbulent eddies that we would have seen in fluid mechanics inside of that boundary layer onsetting.

28:58

When that happens, my boundary layer functionally is going to split into three different regions.

29:05

And we have a really cool visualization of this at the end of the lecture.

29:10

So what I'm going to see my area of laminar flow.

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Let me grab my pen to mark this.

29:17

So here we have laminar flow and here we have laminar flow and down the same as down here is laminar flow.

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So I'm going to see this laminar flow in what we would call a viscous sublayer.

29:32

But this laminar flow layer continue right to evolve, but it will shrink back down.

29:38

And so I even in a highly turbulent system, I maintain a very, very thin annulus if I'm in a cylindrical environment, a very thin annulus of a laminar viscous sublayer for the fluid directly in contact with the wall.

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And as we'll see in the visualization, the the height of this sub layer is very, very, very small.

30:02

Now if I go out into the bulk of the boundary layer, as it continues to grow, it will evolve initially with the distance to the power of 1.5 and then as it starts to tail off towards its fully developed profile with thick distance to the .8.

30:18

So combination of these two powers is, is what I'm ultimately looking at for prediction.

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So I have these turbulent eddies that are going to persist out in this turbulent flow within the boundary layer.

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And then we have a, a buffer layer that effectively is the connecting region, right?

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So in, in classical fluid mechanics, you would have learned that you have either laminar or turbulent flow.

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And what we would call transition flow is sitting in the middle of the two and we get properties of both that show up within that.

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But we probably wouldn't have looked at a system where we simultaneously have laminar flow and turbulent flow and a transition region in the middle, which in an older parlance we would call a buffer region or a buffer layer.

30:59

So I get characteristics of both the laminar and the turbulent flow that are are showing up and again, this very thin buffer region.

31:08

So if I were to to predict the thickness right of the boundary layer as a function of distance, so the thickness of the boundary layer, little delta, Greek letter small delta, and I'm here, I'm just normalizing this as a function of X right distance from the leading edge.

31:25

So I could multiply X across the right hand side and I could directly calculate delta, little delta as a function of the distance from the leading edge and the Reynolds number as that evolves through the leading edge, right?

31:39

So my same Reynolds number calculation, I'm just applying the length scale here instead of the cross or the diameter of the pipe or the characteristic length of the flow channel.

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In this case, Reynolds number is calculated with XI can also calculate the OR apply a similar approximation instead of a formal analytical solution.

32:01

For Blasius, I can approximate what happens in the turbulent thickness by replacing five with .385.

32:09

So this is clearly an empirical solution and a Reynolds number instead of to the .5 power to the .2 power.

32:16

And here I can see this is now taking a balance, an empirical balance between these growth profiles .51 point 5 and .8.

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So there are again in the reader some example calculations that you can use to estimate what is the thickness of this boundary layer as we go.

32:34

And I'd really encourage, particularly as we come into the laboratories, to take some time and make sure you're comfortable with that.

32:42

Now the reason why this matters when we're looking here at this very top diagram, what we would have learned in fluid mechanics is what happens or how to predict the profile in fully developed flow.

32:56

Now we would recognize immediately this here what I'm plotting is laminar flow because I have a perfect parabola in the fully developed profile.

33:06

What we're interested in.

33:08

If I go to the very left and I go back to that metaphor of the garden hose, when water exits the tap, goes through a few microseconds of air and boom, enters the garden hose.

33:18

So it's a new wall for the first time again, I have no boundary layer and I have a constant cross section of velocity and stress in the fluid.

33:28

Now as the fluid continues to flow through the garden hose and this would I'll grab my laser pen here.

33:36

So as we go to the right, this would be distance from the leading edge as well that we looked at on the previous slide.

33:43

Here I can see the growth of these dashed lines indicate the growth of the boundary layer in time.

33:49

Now, because I don't have a lot of turbulence in the system, in fact, this is a laminar system, I will continue to grow to that power of one.

33:56

One over the Reynolds number, square or square root of the Reynolds number, one over the square root of the Reynolds number, right?

34:03

So as this boundary layer grows from both sides and laminar flow, it eventually connects in the center line of the pipe.

34:12

And in fact, this is what leads to that beautiful parabola that we get in a laminar flow profile.

34:20

If I'm reflecting on the previous slide, if I'm in a turbulent system, then I can see that the laminar portion of the boundary layer is going to peel off at some point, right?

34:30

It's going to peel off maybe halfway through it's point of establishment.

34:33

And that growth of the turbulence is what leads me to that kind of almost a bullhead shape where I have a region of a very thin region of laminar flow, but all of these turbulent eddies in the centre line of the pipe.

34:47

So if I were to draw an overlay again for the turbulent flow, the profile I would expect in this what we classically would call a bullhead shape will look something, and I'm exaggerating this, but something a bit more like this, right?

35:01

I might have let me switch colours, I might have a bit of curvature to this right, But by and large the point of of turbulent flow is that I'm isolating a majority of of that flow channel for a constant velocity and a a constant stress environment.

35:22

Now what this is going to do, if I think about how much stress is applied to my container wall, well, it's this gradient, right?

35:29

It's the velocity gradient or the shear rate, DUDY.

35:33

That gradient is what dictates my stress and and for this we're assuming the Newtonian and constant dynamic viscosity for both systems just for comparative purposes.

35:44

So I can see in laminar flow, this gradient as I come toward the wall is much, much lower, much smaller than that for turbulent flow where I can see a very, very sharp gradient here.

35:55

So this means as I go toward and into the turbulent flow region, the other effect I need to think about is that the amount of sheer stress, meaning the force that's applied to that container wall, increases directly with the degree to which I'm turbulent.

36:12

And This is why, for example, if I'm worried about having entrained air or solids in a liquid flow channel, I need to really think carefully about whether I'm flowing too fast and can cause erosion in the system, right?

36:26

Meaning that the, the force that's applied to that wall is enough to to effectively eat right or, or to chip away at that solid wall and in very small chunks as we continue flowing.

36:39

If I'm also working in it as an aside, in an aqueous system where I have the where access to weak acids or CO₂ and I can then start getting corrosion in the system.

36:51

I have to be even doubly careful about the the potential for that high shear stress turbulent flow to eat away at the wall in a potentially corroding environment.

37:01

Because I can then through an erosion process accelerate the rate of corrosion.

37:07

And what we call this is a coupled erosion corrosion phenomenon.

37:11

Now the the point I really wanted to make on on this slide is we would have study this right hand side either my perfect parabola for laminar flow or my bullhead profile for turbulent flow.

37:24

We would study that in fluid mechanics and learn how to predict this and how it's sensitive to different properties.

37:32

But in unit operations, what we're particularly concerned with is what happens as I go from the left hand side to the fluids first entering that garden hose to the right hand side where I have fully established flow, right?

37:46

And the thing that I don't know in this is how much time did that take?

37:51

So I have some amount of time to go from that left to the right.

37:57

Now here's the rub.

37:59

In all of my fluid mechanics, my heat transfer, my mass transfer, all of my chemical engineering correlations, we are assuming fully developed flow.

38:11

So the rate of heat transfer assumes we have a fully developed flow profile.

38:16

The rate of mass transfer assumes fully developed flow.

38:21

That is not the case here.

38:24

We have a region in our system when fluids first enter a new pipe in which I don't have fully developed flow.

38:31

So the question we want to raise is what happens if I'm in a heat transfer system, Maybe

I have a hot pipe or fluid in a pipe that's warm and I'm exposing it the pipe to air to cool it down.

38:44

Well, if my heat transfer correlations are built for this fully developed flow condition, if maybe half of my pipe length is fully developed but the other half isn't, what happens to my heat transfer rate?

38:56

Is it higher or lower?

38:59

These are the questions that we're going to start exploring when we get into the labs and we start thinking about both heat transfer and mass transfer.

39:07

What I effectively can see, we have an inhibition of our heat and mass transfer in this developing flow region.

39:17

So we need to be really, really careful.

39:19

This is one of the key mistakes a young engineer can make out in the field is designing a system to say, OK, maybe for this ambient heat transfer problem or a simple mass transfer problem.

39:32

My calculation suggests we need 10 meters of pipe, 10 meters long of pipe.

39:38

That will be sufficient to, you know, just sufficient because we don't want to waste materials, we don't want to spend extra money.

39:44

We need just 10 meters of pipe to do the job.

39:48

Not correct.

39:49

We're going to end up underestimating the amount of pipe that we need if we don't account for the region in which this flow is developing, meaning it's going from its initial condition to a fully developed condition.

40:04

So then we might ask ourselves, what does the engineer use, right.

40:08

We, we've gone through in, in heat transfer heaps of these nussle correlations and we're going to see more nussle number correlations come up.

40:15

We're also going to be using the corollary Sherwood number correlations for mass transfer.

40:21

We've spent a lot of time and we're about to spend a lot more time working on these correlations to predict just the basic rate of heat or mass transfer in fully developed flow.

40:32

So what on earth is the engineer to do to account for this, this developing flow region?

40:38

And this is where we turn to the use of heuristics.

40:41

And a heuristic can be translated as a rule of thumb.

40:45

Now like any rule of thumb, it doesn't work all the time.

40:48

It works most of the time sufficiently so that we use it as a first approximation.

40:55

So if I am in a turbulent flow, then the length of the developing flow region, we use the heuristic of approximately 50 pipe diameters.

41:07

So if my pipe diameter is 1 centimeter, I need 50 centimeters of pipe length before I have fully developed turbulent flow approximately.

41:18

All right.

41:18

These are heuristic, so they're approximate.

41:21

If I'm in laminar flow, again I have a 1 centimetre pipe, I need 100 centimetres of pipe length to see this fully developed laminar flow profile.

41:35

So these are really good numbers.

41:38

Now we tend not to work in laminar flow as engineers, it's a very, unless we have a very good reason to do so, maybe something like pharmaceutical management.

41:46

If, if we're in a pharmaceutical manufacturing facility, perhaps there we want laminar flow to protect the chemicals from destruction or the the crystals formation from destruction.

41:59

So we tend to work in turbulent flow, which means 50 pipe diameters is a really good heuristic to have on the top of your head as you go out into the field as an engineer.

42:10

The the reason we use this as a heuristic is that it tends not to depend heavily on Reynolds number.

42:16

Once we get into the region of turbulence, whether I'm in a region of moderate turbulence or really high turbulence, it's still about 50 pipe diameters.

42:25

So there are a couple things I need to think about around this.

42:28

If I have these 50 and 100, these are for typical pipe roughnesses.

42:33

And we're going to be looking over the coming chapters and weeks as to what pipe roughness is going to mean in this context.

42:39

But effectively, when I say typical pipe roughnesses, I mean the types of pipes that we would see for water transport in a city.

42:48

Typical water pipes, if I am in a highly rough system, meaning maybe I have a pipe that's 100mm in diameter and I might have little, we call them asperities, meaning little micro variations in the surface of the pipe roughness.

43:08

And what we characterize roughness by is the average size or average height of those asperities.

43:14

So if I'm in 100 millimetre pipe and I have an average asperity size of say one millimetre, that would be considered an extraordinarily rough pipe.

43:24

So 1% of my pipe diameter is occupied by roughness.

43:30

That's a very, very, very rough system.

43:33

If I have a rough pipe, then I have much, much longer transition regions and developing flow regions.

43:40

And the reason why we can imagine as fluid is entering this, if I have the pipe itself jaggedly going up and down, it's going to effectively bounce this boundary layer up and down and prevent it in early regions from establishing a full flow profile.

43:59

Now as a, a practicing engineer, if you were to have to go out and design a system right, that needs to account for this flow profile and the developing region for it.

44:10

I've, I've designed a number of systems where this has come up.

44:14

My personal approach, I will always start with 50 pipe diameters and unless I have a very, very good reason, I'm going to double it.

44:22

So I work in turbulent systems 99.9% of the time.

44:28

I will tend to use 50 as an absolute minimum or we're not going to do the system in the project, but I would, I will be comfortable with 100.

44:36

So whatever the heuristic is, double it.

44:39

Now, in this case, the reason I'm doing that is because in the systems I'm looking at, I'm also designing measurements, right?

44:46

So I need to put temperature, pressure, flow, compositional measurements on the system.

44:52

So I need to know how long of a pipe run do I need to give it before I can take a reliable measurement.

45:00

So in that case, if we're going to spend \$100 on piping and as we were just talking about for things like differential pressure measurements, which the system I'm thinking about was used for, we're going to spend \$20,000 on differential pressure measurements.

45:15

Well, in that case, absolutely, you give it a much longer run of pipe because it's much, much cheaper than putting it to \$10,000 pressure differential pressure transducers on the system and taking an incorrect measurement because one of your points is connected here to the developing region.

45:33

So the reason we care about these developing flow regions, two things.

45:38

The 1st that I need to ensure I am beyond the length of developing flow before I ever take a measurement, pressure, temperature, composition.

45:52

I cannot measure these things reliably if I'm in a developing flow region.

45:57

The second reason is that if I'm trying to diagnose a system, why is this system not performing at spec or why is it not being predicted correctly by theory?

46:09

In that case, I have to account for the fact that this developing flow region is going to inhibit the effectiveness of my heat transfer and or mass transfer.

46:20

So this is a really important concept to take from fluid mechanics as we start to think about how we apply our knowledge into a real unit operation.

46:33

OK.

46:34

And finally, we'll end with this visualization.

46:37

Now this is coming from the University of Melbourne and it's an experimental study of boundary layer investigation.

46:44

Now this is for a flat plate.

46:46

So what we're looking at here is we're going to be looking at different plate velocities, meaning I have a flat plate moving and the flow around is what I'm going to look at. Now, when in the visualization, regions that are white indicate very low velocity, right?

47:04

So the brightest white in this or this video we're going to watch corresponds to the most laminar point in the system, OK?

47:14

So we can see we can initiate the boundary layer here.

47:18

And the reason it's showing up white is that they're using a fluorescent dye system.

47:22

And look at that as we're increasing the Reynolds number here, we're showing the Reynolds number at the point of maximum shear stress.

47:29

I can see this laminar boundary layer, but I get the evolution of these gorgeous eddies in that turbulent region as flow is being established in the system.

47:39

OK, so this is for a plate velocity .22 meters per second.

47:43

Now we're going to try to .9 here.

47:46

I can see I still have that that maximal laminar boundary layer at the very interface, but I have a much thinner region of the turbulent portion of the boundary layer.

48:01

And I can just see these beautiful eddies that are showing up as an illustration, right?

48:06

And then I can compare the two.

48:09

So on the top, we can almost see emerging.

48:13

This is what gives me that gorgeous parabola when it finally reaches the point of fully established flow.

48:19

Whereas on the bottom, I'm in a turbulent region.

48:22

And so I get that much more sharp shear, shear rate and shear stress near the wall as it comes into the more bullhead type flow in the central line of the pipe.

48:33

OK, So I'll leave these play in slow motion as we wrap up this lecture.

48:38

The point to make is that here we're looking at variations for parallel flow.

48:43

So I might have some object in the flow that the fluid is moving around, and that's what we're looking at in these videos.

48:49

But the other thing that's going to come up in the the next lecture and over the coming few weeks is what happens if I have objects in the middle of my flow?

48:57

So to prepare as we're getting into the next lecture, let's think for a minute about the types of these gorgeous turbulent eddies that we're observing here.

49:04

But instead of having a a parallel flat plate, what would happen if I inverted that 90°?

49:10

The flow is going to hit it head on.

49:13

Well in that case I don't get eddies forming really.

49:16

I have a few but not really forming at the interface.

49:19

Here I have massive Eddy formation in what we would call a wake zone after the the plate.

49:25

So objects immersed in this flow, I get the same types of Eddy formation, but it's all in the back end of the object as opposed to along its interface.

49:35

OK, so as a reminder, this this lecture would correspond to to chapter 3 in the reader and chapters two and three in McCabe.

49:46

Chapters one and two in the reader, respectively go through thermodynamic equilibrium and very basic fluid mechanics.

49:51

Just as a bit of a revision.

49:54

And I'll be referring back to Chapter 2 again a little bit in our next lecture because we're going to be doing a bit more with things like friction loss.

50:02

OK, Have a wonderful rest of your day everyone, and we'll talk to you again soon.

50:06

Bye.

Lecture 02

0:10

All right, and welcome to lecture #2 So this is our second of two lectures looking at the applications of fluid mechanics inside of our unit operations.

0:21

This lecture corresponds with Chapter 4 in the reader Flow with Solids, and you'll see in the next slide.

0:28

There's also a bit here that touches into Chapter 2, basic fluid mechanics when we talk about the renewal equation.

0:34

So I would recommend just to have a quick flip through chapter two of the reader to make sure you're comfortable with some of the concepts we're going to be talking about in more applications of the Bernoulli equation.

0:47

But it's really Chapter 4 is where the meat of this lecture is going to come from.

0:52

As always, if you find that the combination of the lecture and the reader still is leaving a bit of uncertainty and you want some more reading and some more insight around this.

1:03

This lecture would correspond to chapters 4-5 and seven of our required class textbook, and that's the 7th edition of McCabe's Unit Operations.

1:12

Okay, so the first point we want to start with is looking at the Bernoulli equation.

1:19

So on the top here, what we're seeing, this is the Bernoulli equation written for a difference between 2 points in space, point A and point B as we flow.

1:29

And here the equation is corresponding to this diagram from McCabe's textbook that's also present in the reader.

1:36

So everything with a subscript A is corresponding to what happens before we enter this complex flow system, and B corresponds to the exit point of the complex flow system.

1:47

So we're looking at the difference between points A and point B.

1:50

Now in classic fluid mechanics, what we would have seen as we would have applied this probably to a constant cylindrical flow channel or or a ducted flow channel.

2:01

So we don't have all of this elaborate stuff happening in the middle here in class of fluid mechanics.

2:06

And what we're looking to do with the Bernoulli equation is relate the pressure, velocity and potential energy.

2:12

So if we recall back to thermodynamics that the fluid velocity is coming from Lord's Kelvin, Lord Kelvin's definition of kinetic energy, my ΔP is the momentum driving force and GZ is the potential energy at that upstream condition.

2:29

And conversely, on the downstream side, we have the the second definition of velocity related to its pressure and potential energy.

2:37

Now what makes this a bit of a step forward?

2:39

And again, this this slide corresponds to what's going on in chapter two of the reader is that we've also introduced, of course, pump work from the Bernoulli equation.

2:47

So the number of joules per second that my pump is putting in times its efficiency with the Greek letter η .

2:54

But we've also now added this $H_{sub F}$ term.

2:58

Now classically $H_{sub F}$ accounts for the wall friction.

3:00

So I can imagine that if I'm looking at a, a constant flow channel, well, I have pump work that's coming in as a positive.

3:07

So that's upstream and I have some loss term frictional loss because the fluid is contacting with the wall.

3:14

And I have the my energy cascade so that the transmission of kinetic energy from my large eddies to the intermediate eddies to the smaller eddies.

3:24

This energy cascade takes place largely without energy loss until I get down to the Kolmogorov length scale.

3:31

That's the smallest length scale of eddies in my system.

3:33

After this point, we dissipate that kinetic energy as friction.

3:37

So this is where the definition of the term frictional loss comes from that flow transmission from by larger to smaller, smaller eddies and finally flipping from Eddy transmission to frictional dissipation.

3:49

So classically, we would have treated this, this wall friction factor and and maybe used a Moody diagram or or a Fanning friction factor calculation to look up what $H_{sub F}$ would be.

3:59

But in unit operations, we're not dealing with perfect cylindrical constant flow in in pipes right here.

4:08

We need to start thinking about, well, what's going to happen if for instance, I have a change in diameter.

4:13

So I go from a large diameter to a smaller diameter over some distance.

4:18

Maybe I have a fitting or, or some kind of valve that's going to be sitting in the middle here and then I'm going to expand that flow back outward.

4:25

Now this is the simplest type of, of combination we would expect to see.

4:29

I have a effectively what's going to introduce a choke point and an expansion point.

4:34

So we call this upstream contraction sub C and expansion sub E, or it might have some number of valves in the middle.

4:41

I can also have twists and turns and bends in the pipe, right?

4:46

And all of that's going to increase the amount of friction beyond that, what I would get off Moody diagram.

4:52

So in unit operations, we're going to take this $H_{sub F}$ term, and instead of keeping only the classical definition of wall friction, we're going to add to this some number of other terms.

5:03

Right now, this particular definition, one contraction, one expansion, and one fitting, is exactly what's shown in this exemplar diagram.

5:12

1 contraction, one expansion, and one fitting in the middle.

5:17

However, I can have any number of these things.

5:20

I can have multiple contractions, multiple expansions, I can certainly have multiple fittings, and I simply keep adding in another K term every time.

5:31

And so in this way, the way that I write frictional loss in the context of unit operations is to actually trace the flow profile through my unit operation network.

5:42

And one by one, I add up each of these terms, right?

5:47

You'll see this come up in different engineering parlances called something like loss factors.

5:56

So what we're here to then look at, and this is what corresponds to Chapter 2 is in particular, I want to focus on this case of F for a minute.

6:05

And if you look at Table 2.1 in the reader, what you're going to see, and this is the the same as reflected in Chapters 4-5 and seven of McCabe is an example of how this case of F term is going to change for different types of either fittings or pipe bends or or pipe angles.

6:24

So one example, if I have something like a gate valve, right?

6:29

And so here what we're showing, this is a type of valve that I can use.

6:32

If I have an angle valve or a gate valve, I can look up in Table 2.1 and say, well, for 1/2 open gate valve, my case of F, my fitting factor or friction factor is 4.5.

6:47

If I have an angle valve, it's 2.0 when it's wide open.

6:50

And if I have a globe valve, it's 6.0.

6:53

So these terms I can directly drop into this equation.

6:57

And as a result, get out, well, what's the actual momentum energy loss as a function of of course, what we would naturally look at some change in potential energy, but also as a function of the cumulative resistances across the system.

7:11

So if I had three different valves, one gate 1 angle and one globe valve, I would have three case of S that are added together in sequence.

7:19

And you might say to yourself, well, shouldn't we be applying the velocity term at each of these valve points?

7:27

And you would be absolutely right to do so.

7:29

And if you were to solve this type of equation or type of approach for a as realistic a system as possible, you would probably do some computational fluid dynamics CFD to be able to estimate those velocities at each point in the valve.

7:44

The way we're writing it here is with \overline{AV} , meaning the average velocity across the system.

7:49

And that's what we're using because we only have two measurement points in pressure.

7:53

So that's why we're using \overline{AV} in this instance.

7:56

Now the other point of Table 2.1 that it's critical to tease out is what happens when I start looking at elbows and Tees.

8:04

So if I have a welded bend, see I can look at Table 2.1 and see a 90° bend.

8:10

I have K factor case of F that's going to range between 0.19 and 0.21.

8:19

So putting a bend into my pipe and and those ranges are for different radii of bends so that the longer the radius of the bend, the smoother the profile mean the less impact I have on friction.

8:31

But in each case, the nature of having put a bend into the system means that I'm taking additional frictional loss, right?

8:39

So this L term would be for a perfectly straight pipe.

8:44

But as soon as I start introducing bends, I start adding more case of FS Here you will also see this come up in talking about what's called the effective length.

8:57

So I can imagine if I had a pipe network, so instead of having a perfectly linear water pipe, I might have a pipe network where I have a, you know, 1090° bends as this water pipe winds all the way through the house to make to my kitchen floss.

9:15

Now I can account for each of those bends by putting in another case of F .

9:20

So if I have 10 different bends in the system, I have 10 different case of FS as I add everything up.

9:25

And what I'm getting out of this is an average velocity related to the ΔP .

9:30

The other way I can represent that is to talk about what once I do that calculation, what is the L , the effective length that I would need to have of the pipe to be the same momentum or pressure differential momentum energy drop.

9:48

So if my pipe is 10 meters and I have 10 bends in the system, I can do $L = 10$ and I add in 10 another 10 case of FS or let's say a length of 10 meters and eight bends to make it so clear.

10:05

So my length would be 10 meters and I put in eight different K sub F terms.

10:09

Alternatively, once I do that calculation, I can say, well what is the L , the effective length that would be equal to the same summation term here that's encapsulated in purple.

10:23

And what I would find is if I had eight bends and a 10m pipe, my effective length is going to be something like 14 or 15 meters.

10:33

So the effective length represents how long of a pipe would equally produce the same pressure drop.

10:41

Now this is really, really an important concept because when we start looking at process plants and industrial operations, we tend to talk about effective pipe length as opposed to accounting for each of these bends individually.

10:56

So that tends to be a more common nomenclature with industry.

11:00

But the point I want to make here is you can you can characterize the system equally through either approach.

11:08

So this is a quick summation of what we want to make sure we're comfortable with from Chapter 2 in the reader.

11:14

There is a very, very good set of calculations and examples in the reader, and in fact, what you can also look at is how we treat pipe roughness and some of the correlations for different roughness in Table 2.2 and how they come into this.

11:29

So I definitely suggest spending a few minutes there to make sure you're comfortable with the approach.

11:36

OK, so now for the rest of the lecture, we're going to be looking at a summary of the core content in Chapter 4.

11:44

Now so far what we've been talking about is what happens when fluids flow through a channel that is a solid wall.

11:53

So water flowing through a water pipe or or hydrocarbons flowing through a ducted system.

12:01

And this it's the nature of that, that manipulable fluid contacting a wall that has occupied much of our time in fluid mechanics and so far in unit operations.

12:12

The next question we want to ask ourselves is what happens if if I go back to the end of last lecture and I looked at that example of taking an object and putting it into the flow.

12:23

Now I need to think about what if I have immersed solids in a flow that are not moving?

12:29

Then the type of turbulence that's generated.

12:32

I still get those gorgeous eddies that we were looking at at the end of the lecture, but those now exist around my immersed object as opposed to happening just at the wall.

12:43

So if I were to imagine, let's say a really big coffee cup, right, filled up with little marbles.

12:49

That's the the metaphor we're going to use here.

12:52

Well, if I have flow, if I'm constantly, if I drill a hole in the bottom of the coffee cup and I'm constantly pouring coffee in and I have all these marbles in there and I'm draining coffee out the bottom.

13:03

I have to think to myself, where, where are the eddies coming from?

13:06

Where is the turbulence in the system?

13:08

Well, I have turbulence emerging both because of the fluid contact with the wall and because of the fluid contact with the individual objects in flow, each of the marbles.

13:21

And so I generate these turbulent eddies around each marble and at the wall of the coffee cup.

13:29

So to make the to take the metaphor from pipe flow or channel flow and bring it into thinking about objects, we're going to go back to what we first talked about as the definition of shear stress.

13:43

And if we recall from last lecture that shear stress emerges by thinking about the gradient of velocity.

13:50

All right, So how the shear rate, so the gradient of velocity that approaches a solid object and the viscosity, dynamic viscosity of the fluid that's approaching the object.

14:02

Well, when I have the immersed solid, I have the same kind of force that fluid is still applying force to my solid object.

14:09

And in fact, I still retain my no slip condition at the interface, the molecular interface of the fluid in the object the both things poured over.

14:20

But instead of calling it a a flowing shear stress, which we typically use to denote contact between the fluid in the wall.

14:27

Now I'm going to introduce a new term called the drag coefficient that relates that force when it's applied to an immersed object, right?

14:38

So it's the metaphor of shear stress.

14:40

But when the object is immersed and not the container, we call it drag.

14:45

So this drag coefficient is defined here on the left.

14:48

It is proportional in kind to the flowing shear stress.

14:53

So I can see that same stress or that same force per area term showing up.

14:58

But now what we're looking at is the dependence on velocity, the fluid velocity coming in.

15:03

And in fact, we can rewrite this fundamental definition of the drag coefficient by looking by considering what we now call a particle Reynolds number.

15:14

So I have some proportionality Φ that we're going to get into a little bit later.

15:18

But next to Φ I'm multiplying this by the Reynolds number of flow as it contacts the object.

15:26

So what's the definition of Reynolds number when I have a single marble and I'm flowing coffee around that?

15:33

So I have my same fluid density.

15:35

So the fluid that's flowing same density matters the same dynamic viscosity μ the

upstream or we similarly in olden nomenclature call this an approach velocity U not so basically the the viscosity, density and velocity of the flow coming at the object a a reasonable distance away.

15:54

So it's not interrupted by the object yet.

15:57

But you might ask yourself in a typical Reynolds number, we care about, say the diameter of the the pipe flow or the effective length of the ducted flow.

16:05

So what characteristic length are we going to use here to define the Reynolds number?

16:11

And what we're using is the characteristic length of the object itself.

16:16

So one of the ways that we get this as engineers is if we take a three-dimensional object.

16:20

So I can imagine this is a marble and I have flowing coffee around it.

16:24

Well, the two-dimensional projection of that marble conveniently is a perfect circle.

16:30

And it is the diameter of that circle in the case of a spherical object that we consider the characteristic length D sub P .

16:38

So when I have the particle Reynolds number, it's effectively the fluid Reynolds number, but the length I care about is the diameter of that immersed object if it were a sphere.

16:48

Now, as I start putting in objects that deviate away from a perfect sphere, I'm going to have different characteristic lengths.

16:55

So it's not always as simple as looking at A2 dimensional projection.

16:59

And in fact, the characteristic length of an object is when we start thinking about putting objects in my unit operation, solid objects, that characteristic length is one of the parameters that when I call a company to buy said objects, that's one of the parameters that will be listed for me to choose from.

17:18

So I as the engineer need to make the choice what is the characteristic length I care about.

17:23

Now we start talking about a sphere because it's the very simplest of our potential immersed objects, right?

17:32

But often times the purpose of us putting immersed objects in a flow system.

17:38

So again, coffee cup or marbles in my coffee cup is that I want the objects to do something or enable something in my fluid itself.

17:48

I could be enabling heat, more heat transfer or more mass transfer, or I could be enabling more momentum transfer or momentum loss in this case.

17:58

So the choice of this this object characteristic length is not insignificant.

18:04

It's in fact the number one reason that I choose to immerse objects in my flow channel.

18:11

So let's take a look at how this is going to play out.

18:14

Now, if I have again the metaphor of of marbles in my very large coffee cup, I can imagine maybe I have 100 or 200 marbles in this this gigantic coffee cup.

18:28

What we would call that is a packed bed, right?

18:32

And this is a very, very old engineering term.

18:35

But a packed bed basically means I have a bed of solid objects.

18:41

And then when engineers use the term bed, what they mean is that solid objects that are not yet in motion.

18:48

So if a bed is forming, I have a region of highly number dense.

18:54

I have a region of high concentrations of these solid objects.

18:58

Now if if the bed is perfectly stale, still there is no motion in my solid objects and none of the marbles in my coffee cup are in motion as I pour coffee around them, then I would call that a stationary bed.

19:12

But if I'm again drill the hole in the bottom of my coffee cup so as I pour fluid fast enough, or if I were pumping coffee up through the cup and it's exiting and overflowing over the top, then I can imagine I could start to get some motion in those solid objects.

19:27

And we would call that a moving bed.

19:30

So the term packed bed is more general and it it refers to and encapsulates both stationary and moving beds.

19:38

So when we talk about a packed bed, all it means is a whole bunch of solid objects, usually the the same object chosen intentionally, but a whole bunch of solid objects are in a container and stuff is flowing around it.

19:51

That's all a packed bed means.

19:54

So the goal that we want to look at then is how can we take what we just talked about in terms of the Bernoulli equation where we're relating this momentum force.

20:04

Now again, we tend not to have really significant contribution of potential energy.

20:08

So we'll, we'll put that potential term to a side for a minute.

20:11

But this loss term and those $K_{sub FS}$ that we were looking at for channel flow.

20:16

Well, how do I start accounting for the kinetic energy loss and the the turbulence dissipation of flow around these solid objects?

20:26

Well, that's where we get the Ergen equation.

20:30

So you're also going to see this in 3018.

20:33

And so the point of these units is that they work together.

20:37

But the Ergen equation is what allows me, it's an an adoption of Bernoulli that allows me to talk about the frictional loss.

20:43

So how much momentum am I burning as a consequence of flowing around all of these objects in my packed bed?

20:52

And chapter 4 in the Reader goes into quite some detail as to how the Ergen equation emerges.

20:58

And it's a really good thing to know.

21:01

There are two contributing factors to this.

21:04

We have one in terms of kinetic loss on the right, shown in red.

21:08

So this kinetic loss term is effectively what I would be.

21:11

It's the allegory of dissipating a lot of friction energy because of those turbulent eddies hitting the wall.

21:19

But I also have because I have so many walls, effective walls in that pack that every time a solid object meets the fluid, I have another wall.

21:29

So I end up, if I remember back to the the video at the end of lecture one that that bright white thin line that was always at the interface between my fluid and my flat plate.

21:42

Well, I have a lot of energy built up in that viscous loss contribution as well to the very end of my energy cascade.

21:50

And it turns out that I can use if I know my fluid is very moving very, very fast.

21:57

It turns out that the kinetic loss term the which we would normally call the Burke Plummer equation, and we would represent only the red contribution on its own for a highly turbulent system tends to be dominating.

22:11

Whereas if my flow is very, very docile through my packed bed, I would use the Cozini Carmen equation.

22:17

Oh, that's the blue contribution.

22:20

And the Ergun equation just says, well, look, if I'm flowing really, really slow, then the contribution of the red bit is less than 1%.

22:29

And if I'm flowing really, really fast, the contribution of the blue bit is also less than 1%.

22:34

So at the end of the day, I can add the two together and that yields for me the Ergun equation.

22:39

So when we talk about packed beds, what we're going to be looking at is the Ergun equation.

22:45

So let's look at the terms that are inside of this.

22:48

I have my same from the metaphor on the previous slide.

22:51

I'm still using the same velocity.

22:53

This is the average upstream where the approach velocity of fluids coming in V naughty.

22:59

Here on the the Burke Plummer contribution it's squared and the Cosini Carmen contribution it's just on its own the same dynamic viscosity of the fluid that only shows up in Cosini Carmen.

23:10

The same characteristic length of my immersed objects here is squared, here is not.

23:17

And I have two new terms that are going to emerge.

23:20

The first is capital Φ sub S , right?

23:24

This is a measurement we call sphericity.

23:27

It is basically a quantitative measurement of how close to a sphere is the object of my choice.

23:35

So my marbles have a sphericity of one.

23:38

Anything not spherical has a sphericity less than one.

23:43

And in fact, the degree to which it is non spherical, I get a lower sphericity.

23:49

So Ottawa sand, this is Ottawa as in Ottawa, Canada, Ottawa sand is a very common, in fact one of the most common early packed bed materials.

24:00

So this is the early part of the 20th century because it has a sphericity naturally occurring very close to one, right?

24:08

And we as engineers love to use materials that are a naturally occurring because we know they're likely going to be inner, especially something like sand that's in constant contact with ecosystems.

24:20

And sand has the benefit of being very, very cheap.

24:24

So instead of going out to a manufacturing facility and paying to have a perfectly spherical particles made in the early 20th century, we would take Ottawa sand because it's its nature's very close approximation.

24:37

But if I go all the way down to something like mica flakes.

24:41

So mica is a type of rock where when I fracture it, I get these large plates that fracture off as opposed to cracks directly through the rock yielding ever smaller spherical particles.

24:53

So mica flakes kind of feel when I start to break mica down like I'm taking a ream of paper and throwing it up in the air and I get all these these plate type flakes that will will come off of mica.

25:05

So I can see in that example, you know, reams of paper when I break the paper up into little sheets, these are not spherical objects.

25:12

And so I get a sphericity closer to 0 than it is to one.

25:17

But of course, as we we move away from the early 20th century and into the the latter part of the 20th century, we then start thinking, well, what can we manufacture intentionally to control or optimize things like sphericity and characteristic length for whatever operation I'm choosing from?

25:38

And so two of the most common types of materials are called ratchet rings and barrel saddles.

25:44

So a ratchet ring is shown here is basically an annular cylinder, a cylinder with an annular profile, cross-sectional profile.

25:55

In our first, sorry, our second lab on AB ABS orption, we will be using a system with plastic ratchet rings.

26:04

And I can see here these give me an intermediate depending on the size of the diameter that I'm choosing.

26:09

So D1 and D2 would be two different diameters.

26:12

I get different types of sphericity showing up right?

26:15

Obviously, I can imagine the closer the length of the ring is to its diameter as those two things equal each other.

26:22

I have the most spherical ring I can imagine, whereas a barrel saddle comes from a horse name coming from a horse saddle here I can see the the shape of it.

26:33

This is very clearly a non spherical object has a tremendous surface area relative to the volume that it occupies.

26:42

And so the point of this is that whether I'm going from an AD absorption to an AD absorption, AB to AD in both of these two unit operations.

26:52

So labs number two and four, we're going to be using packed beds and the first packed bed we use with absorption will be deploying ceramic plastic ratchet rings.

27:05

But the second lab we're doing adsorption and that will be using a natural material where I'm going to be absorbing some, some component chemical component of interest onto my solid.

27:19

So we, we care about what is the nature of the sphericity capital Φ sub X and the characteristic diameter of what I've packed my bed with.

27:29

And then the, the final term that we're introducing in both Kozeny Carmen and Burke Plummer equations is the void fraction, right?

27:37

So that's epsilon shown here.

27:40

So the void fraction is, as the name would imply, what percent of my volume is not solid.

27:50

So if I have my whole coffee cup and I've filled everything up with marbles, what is the volume of air left in the coffee cup before I start pouring liquid in?

27:59

That's the void fraction.

28:02

And so this epsilon term you can see features, predominant features in both the Kozeny Carmen and Burke Plummer equations as it naturally should because this is the volume available effectively the percent of volume available for fluid to flow around my packed objects.

28:18

So to execute this both components of this Ergun equation, what I need to know is what type of fluid I have, what's its average velocity?

28:30

And I need 3 characteristics of my solids, what's the void fraction, sphericity and the characteristic length.

28:37

And in fact, when I go through the reader Chapter 4, and this is also reflected in chapters 4-5 and seven of McCabe's 7th edition, I can see examples of how to calculate this.

28:49

And I would really encourage everyone to spend some time practicing with those calculations.

28:54

The point of doing this is to be able to calculate what is the pressure drop in my system per length.

29:01

So effectively, how many pascals do I lose for every meter of length in my system?

29:08

The reason I need to know that is to get flow in this system I have to pressurize things up the fluid up before it enters.

29:16

So I'm hitting this with some fluid under pressure.

29:19

I need to know how much.

29:21

And often times if we're exhausting to the atmosphere afterward, then I know I'm bounded by the downstream pressure being bad of the atmosphere to what atmosphere.

29:31

So I need to choose how high of an upstream pressure do I need for the choices that I've made, either of my solid materials or the fluid that I'm working with, viscosity, density and velocity.

29:47

And the reason this matters is that as engineers, 9 times out of 10, the most expensive thing we're going to decide upon in any given unit operation or industrial process plant is the generation of pressure and how that pressure is made.

30:06

The creation of pressure is an incredibly expensive thing to do.

30:10

And so we need to be sure if we're going to go out and say we want to buy a fluid pump or a gas compressor, right?

30:17

The same operation pump surfer liquid or predominantly liquid compressors are for gas.

30:23

However, whatever fluid I'm working with, the choice of what my pump or compressor can deliver is the most expensive choice I can make.

30:32

So I need to make sure that I have correctly sized this.

30:37

I don't want to spend a quarter \$1,000,000 on an inexpensive pump that will get me halfway there if for \$300,000 I can get the correct pump and execute the operation right.

30:50

And and we point this out because pumps and compressors cannot operate over an infinite range.

30:56

I buy a pump or compressor and it has a defined range of pressure that it can deliver and it should not operate outside of those stated ranges.

31:05

So we want to point this out up front because it's our connection of fluid mechanics into two of our core unit operations, both absorption and absorption.

31:18

Now when we think about our packed bed, and here's a, you know, really simple diagram, I'm going to be maybe using air flowing across a packed bed.

31:27

So the air is going to flow from the bottom upward.

31:31

I would be using a gas compressor to create pressure in that air system.

31:35

And here is a plate maybe that's represents the bottom of my packed bed and I have some length of packing materials within this.

31:43

And the question we want to ask is, OK, the Ergen equation allows us to calculate the pressure drop over a wide range of gas velocities.

31:54

But what happens to the bit, the nature of the bed?

31:57

What happens to that void fraction term as we go to higher and higher velocities, right.

32:03

If we have a stationary bed, we can imagine that the void fraction should always be the same.

32:09

But as soon as we go to a non stationary bed, if we get motion in that bed, then the void fraction is going to be changing, right?

32:17

This marbles in my coffee cup are going to be lifting.

32:20

And so I get a a different void fraction after some critical velocity.

32:27

And that's what we're representing in this middle panel here.

32:31

So I'm plotting here both the pressure drop and the pressure drop as shown as this top curve and the bed height or sorry and and the pressure drop.

32:40

So sorry, the bed height is shown on top is L and the pressure drop across the bed is shown on the bottom curve is ΔP .

32:48

So what we're plotting here is both of these terms as a function of, say, the superficial gas velocity.

32:55

So that would be the gas velocity if the flow channel was only occupied by the gas.

33:01

It's just a way that lets us compare a different system.

33:03

So it's a very useful term in in applied fluid mechanics.

33:07

And what we're going to do intellectually is start at the position of 0 gas velocity.

33:13

So I've packed my bed with some material of interest, might be a barrel saddle, might be a ratchet ring, might be Ottawa's hand right, if we're doing an early 20th century experiment.

33:23

So I've packed this bed, but I initially have no flow of air.

33:27

What happens is I start to increase that air velocity.

33:31

Well, I immediately, here's my upward arrow.

33:35

So I get a linear and immediate response in the pressure drop.

33:38

The more that the soup or the gas velocities increase, the higher the pressure drop.

33:44

But the bed height isn't really changing over this.

33:47

In fact it's constant.

33:49

And we would call this, this represents our packed bed condition.

33:52

And another engineering parlance would be called a stationary bed condition.

33:57

Now at some point I start to get a little wiggle in.

34:00

The distribution of those solid objects ever so slightly begin to change as I transition from this stationary or packed bed to what we're going to call the initial point of fluidization.

34:13

And I'll come back to that term fluidization again in the next couple of slides.

34:19

What it means is the marbles in my coffee cup have jostled ever so slightly as I go from point A to point B by increasing the gas velocity.

34:29

Now, something really interesting happens here.

34:34

As soon as I fluidize the bed, meaning I now have a sustained gas velocity from the bottom hitting that bed.

34:42

So those marbles, as soon as they jostle ever so slightly, if I keep increasing the gas velocity beyond that point, the marbles stay jostling and they're going to jostle randomly and in different directions, but they stay jostling.

34:57

The nature of that means now their, their mass and, and their weight is no longer transmitted through the contact of marble to marble, right?

35:08

Because they're no longer perfectly packed together.

35:11

Now between individual marbles, there's a little air gap, little air gap.

35:16

If I'm using air as the working fluid, could be a liquid gap, but no longer is the weight of each marble transmitted through a connection to the next marble.

35:26

Now they're all suspended, and in the context of a bed, we call that a fluidized bed.

35:32

Now once my superficial velocity achieves that point of minimum fluidization, very interesting phenomena emerges.

35:41

If I increase the gas velocity beyond that point, I do not see a significant change in the pressure drop.

35:50

This here is why we need the contributions of both the Cosini Carmen and the Burke Plummer equations because I'm representing both sides of this diagram on either side of this dashed line from the fixed bed to the fluidized bed.

36:05

So if I go to higher and higher velocities, my pressure drop, it's not perfectly linear, but it stays more or less constant.

36:13

Within a few percent, I'm not going to see a very large change, but the bed height changes drastically.

36:21

So if I increase the gas velocity, the height of this material, this L, the effect of L increases.

36:29

And I see that represented here.

36:30

As I go from a packed bed to that point of minimum fluidization to more fluidization, I have an increase in the height.

36:38

And in fact, if I were to then go all the way to this Point C, so the terminal gas velocity and turn back around and start decreasing the velocity of the gas in the bed, I get a contraction of the bed height.

36:52

And so this allows the engineer, if I need different void fractions, I can choose the velocity that I need or I can put that in as a variable.

37:00

If I need to cool the bed off a little bit, you know, perhaps I have some reaction in between the fluid and the solids in my bed that's creating heat, very normal.

37:11

If I need to cool the bed off a little bit, I can bump up the gas velocity for a little while.

37:17

It increases the effect of length and gives more air, more fluid flow around each of these objects, effectively for the objects to breathe a little bit.

37:26

And then once I'm done with that, that short or temporal operation, I can pull the gas velocity back down and the bed beautifully contracts back along the same line.

37:38

But something finally interesting happens if I then drop that gas velocity back down beyond its fluidization point.

37:47

And this is if I can imagine when I first start the bed here, I have a, well, I have a random packing of materials, right?

37:57

So all of the materials in my bed, they've been dumped randomly in there.

38:02

But once they've been able to jostle around a little bit for some amount of time now as they come back down into that fixed bed, they're, they're going to be even more randomly distributed.

38:15

And what I end up with is a slightly higher bed height than what I began with.

38:21

So I don't have that perfect deficiency of packing.

38:24

And what I see on the outcome here is then a steeper or sorry, a shallower gradient in the pressure drop as I decrease back down.

38:34

So what we're going to be working on in our unit operations labs are beds that are operating at a constant velocity.

38:41

We're not going to be doing temporal or time based operations with these beds right now.

38:46

But the point is that as you get into the industrial processes, this is an option available to the engineer that is very important to be aware of.

38:55

Now I think one of the connection points that you're going to make with 3018, we'll also be looking at, well, what happens as I start increasing gas velocity beyond this Point C, which if I grab my pen real quick, this would correspond to smooth, smooth fluidization would correspond to Point C here, right?

39:13

But I can increase the gas velocity beyond that.

39:16

And what's going to happen in these latter regions is I effectively am going to get first pockets of in this case we're using gas, but I'm getting pockets of gas that are now going to effectively bubble through the bed without really contacting much solid.

39:33

So the gas is going to aggregate together as a phase because it makes it faster for that phase to get through the bed.

39:40

This is the the system when I have multiple phases in contact, this is the system trying to find its most efficient path through, right?

39:49

So as opposed to every new volume of gas contacting every surface of the material, it's instead I'm going to continue contacting the same number of surfaces from smooth fluidization, but I'm going to get these gas pockets that are rushing through.

40:04

If I kept increasing the gas velocity, I get more of those gas pockets.

40:08

But at some point the gas pockets themselves have enough momentum energy to push the first marble out of the bed.

40:16

And when that happens, we start going from a.

40:20

Fluidization point to a conveying point where I'm now pushing my marbles through the copper out of the coffee cup.

40:28

I'm pushing my materials up through the bed and out the top.

40:32

And as you can imagine, the purpose of doing that is an entirely different unit operation, right?

40:37

If I'm using this bed as a vehicle to do a reaction or some kind of chemical modification, maybe I'm pulling material out of my fluid of interest and I need to constantly refresh that bed with new material, putting it into a conveying state where I'm pushing spent material out the top and I can reintroduce new solids through the bottom while I'm regenerating that spent material is 1 mechanism that I could use to do this.

41:02

But if we don't intend to that operation, we typically would not operate the spent past the point of bubbling fluidization.

41:12

OK.

41:12

And then on the previous slide, the thing we needed to really calculate well, at what point am I going to get this transition from a, a packed bed to a fluidized bed?

41:24

How do I know where I'm at?

41:26

I need to dial in a velocity to intentionally choose to stay on one side of that, that barrier.

41:33

And in fact, I can take the Ergen equation and I can see, well, this has the term fluid velocity and it's average fluid, superficial fluid velocity in it.

41:42

Well, that's convenient because what I can do is solve that equation directly for and in fact, I can imagine because I have AV^2 and I don't get a very elegant solution.

41:54

So I'm going to solve it in two domains.

41:56

One is if I have really low velocity.

41:58

So this is coming from the Burke Plummer, sorry, the Cozzini Carmen contribution.

42:02

If I have small particles or low velocity, Either way, the point is that I have, let's see, a particle Reynolds number below 1.

42:11

All right, as we calculated or showed at the beginning of lecture, if I have a particle Reynolds number below 1, then I can use this Cozzini carbon contribution and directly solve for this V or that superficial velocity at which point I get fluidization.

42:28

And this M is meaning that the minimum fluidization velocity.

42:32

So this M here is where I get the M there from.

42:38

And conversely, if I have very large particles or a very turbulent system that I'm going to be looking at the Burke Plummer side of that equation.

42:47

And if I flip that around and solve it for the minimum fluidization velocity, I get the solution on the bottom.

42:53

This is bounded by the requirement that the particle Reynolds number is greater than 10 to the third right.

42:59

And like most things in fluid mechanics, if my bed is operating at conditions of a particle Reynolds number somewhere between 1:00 and 10:00 to the third, I'm going to have some combination of two and I will be bounded by these two end member conditions.

43:13

If I'm in a transit, a transitory region in bed fluidization.

43:18

So I can use these solutions, either the forward solution of the Ergen equation or the backward solution for minimum fluidization velocity.

43:27

And I can plot here something like the contribution.

43:31

This is the contribution of the void fraction component or the calculation of the bed height L .

43:37

And I can see here is my point of minimum fluidization right on either side of where this flat point starts transiting upward.

43:44

And what I'm, I'm plotting here is to look at, well, how does it, in this particular example from McCabe's textbook, how does this theory from the, the combined or the composite Ergen equation compare to a basic experiment?

43:57

And these are the comparison points here.

43:59

So what we want to highlight is that this is not a perfect solution, right?

44:04

Very much an approximate.

44:05

In fact, in some places I can have deviations that are on the order of say 10 to 15%, which is not insignificant for the engineer.

44:13

And this is, you know, a very early lesson when we talk about unit operations.

44:17

This is one of those reasons why we introduce things like engineering factors, safety factors, and redundancy factors throughout the design of our systems because we know that the theory we're applying is not perfect, right?

44:31

There are some things it misses.

44:33

And in this case, I can see as I'm in an intermediate velocity region, I can get some deviations from that theory where I don't have a packed bed and I'm not at a very isotropic and homogeneous fluidization condition that I might otherwise expect at higher velocities.

44:49

So this intermediate region, you know, this would be a really good rationale for why I might get deviations between theory and reality in a packed bed because I'm not really perfectly described by either the Cozzini-Carmen or the Burke-Flemmer contributions to the Ergun equation, but I'm in some combination of the two, and it's not always linear.

45:11

So I would very much encourage everyone to take a look at Chapter 4 in the Reader.

45:18

And again, this corresponds to chapters 4-5 and seven of McCabe's textbook.

45:23

If you'd like some further reading and some more clarification around it, Chapter four of The Reader does go through some worked examples.

45:30

And so this should be an opportunity to make sure our applications of fluid mechanics are comfortable, right?

45:38

We're basically taking off from the Bernoulli equation, but applying it to a different type of system than we would have seen in the past.

45:46

And we need to make sure we're comfortable with that because as we come into labs two and four, these calculations now become extremely relevant to our ability to compare our theory of heat or mass transfer to that of the reality.

46:02

Have a wonderful rest of your day, everyone, and we'll see you in Lecture 3.

46:06

Take care.

Lecture 03

0:10

OK, and welcome to lecture #3.

0:13

So we're now beginning our second module of the unit, and this is on heat exchangers.

0:19

Now I, I do appreciate there are a few nuances around heat exchangers that we're going to be talking through.

0:28

This does build on the foundational knowledge of heat and mass transfer, obviously the, the heat transfer side of this.

0:34

And So what I've done, because heat transfer's not an easy discipline, what I've done is to put Chapter 5 into the reader.

0:42

And this is A, a basic revision of heat transfer.

0:46

The purpose is to make sure that you're comfortable with a, where do these terms come from and what do they relate to?

0:53

And B, how do I use them to calculate something like an overall heat transfer coefficient?

0:58

So I would encourage everyone, if you, even if you're perfectly comfortable with heat transfer, have a a quick flip through Chapter 5 in the reader and make sure that these concepts are comfortable in their application.

1:13

And there are some worked examples in there that you can follow along through as additional revision activities.

1:20

Now, the core of this lecture is also going to be delivered in chapter six of the reader.

1:27

So Chapter 5 again is provided for revision, but Chapter 6 is where the core content that we're going to be talking about today comes from.

1:37

Let's see if you find that the combination of this lecture and the readers still leaves a little bit that you want to revise, you can go to the unit textbook.

1:47

So this is McCabe's 7th edition, and here we're looking at a combination of chapters 10/11/12 and 13.

1:56

Now these are not all big chapters, which is why we've done them all together here, but they do provide some additional context.

2:03

So if by the end of the lecture you say look between the reader and the lecturer, I'm still a bit uncomfortable with how we're going to do some basic heat exchange design.

2:12

Definitely, definitely go to the unit textbook on this particular topic.

2:17

It is very, very good for heat exchangers and one of the reasons why we've selected it.

2:24

OK.

2:26

So of course in unit operations, the the thing that we care about is that we're usually moving a working fluid of some sort through a system of our own design.

2:37

And this is where we begin with our revision and applications of fluid mechanics because we firstly need to understand or be able to approximate how those fluids are going to migrate through the system.

2:49

But then we have to think about what operations do we care about.

2:53

Well, the term unit operations comes from the fact that we're either doing something with mass or doing something with heat, right?

3:01

Beyond knowing the nature of the fluid flow, we have to be able to determine how does this fluid flow affect our heat transfer or our mass transfer.

3:12

And like with most units, we start here with heat transfer in our heat transfer unit operation because to be direct heat transfer is although it's complex, it is easier than mass transfer.

3:24

So in virtually every curriculum worldwide, This is why heat transfer always comes first.

3:29

And we then build analogues when we talk about mass transfer because heat transfer is something we can visualize much better.

3:37

Excuse me.

3:39

So in heat transfer, one of the first things we need to think about is, well, how does the nature of heat?

3:45

If I have a say, a warm fluid, and a good example would be if I have a warm working fluid and I want to use ambient air, so outside air flow to cool that fluid down.

3:57

Well, I'm probably not going to expose a working fluid to the environment, but if I put it through a pipe and run that pipe outside, I can effectively cool my fluid down.

4:06

So when I then start thinking about fluid flow through a pipe, we've just spent a couple weeks thinking around boundary layers and the nature of turbulence.

4:16

And I insinuated that these boundary layers would absolutely affect our ability to do things like heat or mass transfer, which is why we need to consider them.

4:26

Well, in the domain of heat transfer, it turns out we can actually say something a bit more specific and a bit more quantitative.

4:34

And the way we're going to do that is through the introduction.

4:37

So early on, Let me grab my marker here.

4:40

Early on, in the first couple of weeks, we were talking about hydrodynamic boundary layers.

4:46

So that is the actual boundary layer of fluid turbulence.

4:50

But now we can add to this a new contribution and that is the thermal boundary layer.

4:57

So the fluid at the wall must be equal to the temperature at the wall.

5:02

So I have right, I have a thermal continuity through the system in the same way I have velocity continuity.

5:10

There is a no slip condition at the wall.

5:12

So these two terms are allegories of one another.

5:17

And I also know that if I have a warm fluid, grab my laser pointer, if I have a warm fluid at some point in this bulk, well, my fluid temperature, if I'm changing is going to have to have some bounding condition where it meets the the core temperature of the fluid in the middle and the wall temperature on the side.

5:38

As a consequence of that, I have the same set up to boundary layers, but in terms of heat, and we call this the thermal boundary layer.

5:47

Now, if I've already calculated and done all of this work for the hydrodynamic boundary layer, wouldn't it be convenient, instead of having to start from scratch to figure out what the thermal boundary layer looks like?

5:59

Wouldn't it be convenient if I could use a clever term to relate the thermal and the hydrodynamic boundary layers so that at any point in my system, I've calculated what the hydrodynamic boundary layer looks like, whether I'm in laminar or turbulent flow.

6:15

And I can start to get that, that evolution that we looked at at the end of Lecture 1.

6:21

And I can then say, well, here's the relation between that and the thermal boundary layer.

6:26

And the way that we're going to do this is the introduction of a new dimensionless quantity that we obviously not new for many of us, we would have seen as a heat transfer, but that is the Prandtl number.

6:36

So the Prandtl number.

6:38

And we represent this in chemical engineering as Pr is defined as the kinematic viscosity on the thermal diffusivity.

6:46

I'm sorry, the momentum, apologies, the momentum diffusivity, which itself is the kinematic viscosity on the thermal diffusivity.

6:54

So I can, if I write these two terms, I can expand them outward with my definition of thermal diffusivity and my definition of kinematic viscosity.

7:03

And I can see, well, the densities here are going to be aligned.

7:06

And so I can simplify this down.

7:08

And what I walk away with is the dependency on the heat capacity of my fluid.

7:15

All right.

7:15

And so this is heat capacity as we did in introductory thermodynamics.

7:19

It's that heat capacity, my dynamic viscosity, which is the Greek letter μ .

7:25

This is what we measure in centipoise usually, and the thermal conductivity, so that is of the fluid itself.

7:32

How easily is thermal energy conducted through my fluid k ?

7:39

That's the term K . So the higher the K value of a fluid, the the greater ease with which that fluid can transmit thermal energy.

7:47

Conversely, the lower the K value, the harder it is for the fluid to transmit energy and I get a less efficient heat transfer.

7:56

And the critical point here is that when my Prandtl number equals one, the hydrodynamic and thermal boundary layers are identical.

8:07

They are mirrors of one another.

8:10

This is why we talk about momentum on thermal diffusivity because it's that equilibrium point.

8:15

So when Prandtl number equals one, I have equivalent boundary layer thicknesses.

8:20

I do my calculations for the hydrodynamic boundary layer and the thermal boundary layer looks identical if the Prandtl number is greater than one.

8:29

What this means is I have more, right?

8:32

If I go back to the definition of it, I have more momentum diffusivity than I have thermal diffusivity.

8:38

What does that mean?

8:40

The ease with which I can diffuse or or distribute momentum into my system is greater than the ease with which I can distribute thermal energy.

8:50

So when the Prandtl number is greater than one, it means I have a harder time distributing that thermal energy and as a consequence, my thermal boundary layer is thinner.

9:00

So this this diagram down here again, this is that distance from the leading edge we've looked at in this diagram.

9:06

This is a Prandtl number less than one or sorry, Prandtl number greater than one because my thermal boundary layer is smaller.

9:16

So a few kind of benchmarks we would typically expect.

9:19

So for for water, as we warm water up say to 70° , the the Prandtl number will be greater than one, approximately 2.5.

9:29

So I can get a range on this Prandtl number that can go up into the hundreds for extreme conditions.

9:36

But, but typically we would expect Prandtl numbers on the order of an integer, right?

9:41

So on the order of say one to 10.

9:44

And in rare cases we have to have some pretty exotic fluids to get it significantly below one.

9:50

But I tend to find that in many applications, this thermal boundary layer tends to be on the smaller side of the hydrodynamic boundary layer.

9:58

But as long as I know it's thermodynamic, we're Thermo physical properties, heat capacity, viscosity and thermal conductivity, I can directly calculate it.

10:08

So when we're thinking then about fluid flow, one of the core concepts of heat transfer that we would have gone through is the combination of convection and conduction, right?

10:20

So the easiest thing we can think about there is conduction is when I put a hot, say, a hot pan from the stove onto a granite countertop or onto a hot pad, I'm conducting thermal energy into, say, granite.

10:37

For simplicity, I'm taking that hot pan off the stove.

10:40

I can put it on granite.

10:41

It's one of the few materials that can directly take a hot surface like that.

10:44

I can put that pot right on a granite stick or on a granite countertop, and I'm conducting thermal energy into the countertop.

10:53

So if no other heat transfer is taking place, the time required for that pot of warm food or liquid to cool down would be dictated by the rate at which it's conducting into the granite, right?

11:07

So no, I'm not accounting for fluid motion there.

11:10

If I were to say put the lid on the pot, but put a fan outside the pot so it's sitting on the granite countertop, but I put a fan there to blow room air around it.

11:21

Now I have both conduction into the granite countertop and convection so that the ambient air from the kitchen will be blowing past the side of that pot and picking up thermal energy as it goes.

11:35

The consequence of the two is that I can cool the pot down faster, right?

11:40

And there are many metaphors we can use.

11:41

I tend to use cooking metaphors because they come up the most common in everyday life.

11:46

So the core concept from heat transfer that we are picking up with, so I'm not doing a lot of revision on this, we're picking up with and we're now going to run with into new domains is the ability to calculate what we call this overall heat transfer coefficient.

12:02

And we give this the letter capital U.

12:05

Now, when we think about a system in which we have convection and conduction, so let's say if we go back to that metaphor, I have my warm pot of material of food, right?

12:15

And I put that from the stove.

12:17

I put it directly on my granite.

12:18

I put my little fan around it outside.

12:21

And maybe to help the process, I'm going to take the the spoon from the stove and stir, stir the material in the pot as it's cooling down.

12:29

So let's think about that situation.

12:31

It means I have convection inside of the system, meaning inside the pot of food.

12:38

I also have conduction through the wall of the pot to the outside air and conduction into the granite.

12:44

And I also have been a final layer of convection of the room air blowing around the pot.

12:50

So I have these three contributions.

12:53

So let's zoom in and think about the metal wall of that pot where here I'm on the outside.

12:58

So this is my room air that my fan is blowing across it.

13:02

This is the conduction of thermal energy through the wall, the metallic wall of that pot.

13:07

And here's the convection inside where this would be where my spoon is stirring it to help equilibrate or homogenize, thermally homogenize the material inside the pot.

13:19

So there are a few characteristics that we want to highlight.

13:21

First, I have thermal continuity at each point.

13:25

So as I go from the average temperature of the stuff in the pot $T_{\text{sub A}}$, I'm going to have a continuous temperature profile, right?

13:35

It's going to be cooling down because the outside air, say is 20° or maybe a bit cooler in the winter.

13:41

I know I'm going to be decreasing in temperature.

13:43

So I go from my maximal temperature inside the pot as I'm stirring it, I will have a decrease as I approach the wall.

13:51

And then when I hit the thermal boundary layer, I'm going to have a very sharp decrease.

13:56

And this is a convecting system, very sharp decrease.

14:01

The degree of that decrease I can think about the Prandtl number would give me some insight to the degree of turbulence inside.

14:08

So in the same way that we said a high a , a rapidly or a high turbulence system is going to have a very high shear stress because it has a very high shear rate or velocity gradient as the fluid approaches the wall.

14:24

I get the mirror of that in thermal space.

14:27

So I have a if I'm mixing this vigorously by hand, and you'll notice the engineers and chemists and when they don't know what else to say about high turbulence, they'll say mixed vigorously.

14:38

You'll see this show up in literature quite often.

14:40

I find it funny.

14:42

So I'm mixing vigorously, meaning I have a highly turbulent environment.

14:45

Well, I get a very high hydrodynamic shear stress against the wall, but I also get a corollary, a mirror of that thermal boundary layer.

14:54

So I have a very sharp temperature decrease against the wall when I'm mixing it vigorously.

15:00

Now I have a conduction across the wall, and this means I have a slightly cooler temperature outside than I do inside.

15:07

But the point we want to make here is that when I'm conducting, I always have a linear temperature profile.

15:14

The nature of conduction is that of a linear change in temperature in space, whereas in convection, right, I have either an exponential or a parabolic temperature profile as I approach the wall.

15:28

And then when I get to the outside of the metallic pot and I have the fan blowing the kitchen air around it, I have the mirror of what's happening on the inside to the outside.

15:38

So I have that same boundary layer here.

15:41

The way we've drawn it, we have a thicker thermal boundary layer, meaning we have a less steep gradient, so less shear stress.

15:47

And that makes sense, right?

15:48

If I have, say, a manual spoon and I'm mixing vigorously versus a fan that's casually blowing air outside of the pot, I probably have a lot more turbulence inside than outside.

16:00

And so as a consequence thereof, I would expect to see a larger thermal boundary layer on the outside and a slower gradient as that temperature comes down South in this temperature network.

16:12

And the purpose of heat transfer is being able to calculate what these curves look like and put them on AY axis.

16:19

That's quantitative.

16:20

Say here is the temperature profile estimated through each point in the system.

16:24

I characterize my convection through a convective heat transfer coefficient $H_{\text{sub I}}$.

16:31

So I have one for the inside, and this is corresponding to my manual vigorous mixing with the kitchen spoon.

16:38

And I have a convective heat transfer coefficient H_{not} for the outside.

16:42

That's corresponding to the effect of my fan blowing air around it.

16:47

Now, there are two types of convection that we're going to talk about.

16:51

If I took the fan away, right?

16:53

So I just, I'm manually mixing the inside, I'm manually agitating the system I have, we call that forced convection.

17:02

If I had the fan blowing on the outside, that's another type of forced convection, doesn't require a human hand.

17:07

All it means is that some, some operation is in place to force the convection around that interface.

17:15

But if I took the fan away so I don't have anything forcing air movement toward the fan, you might ask yourself, is it still convection?

17:24

So I have this warm pot that's sitting on my granite and I'm I'm mixing it inside to keep everything thermally homogenized.

17:31

So I cool it down as fast as possible, but I don't have access to a fan.

17:36

Is it still convecting heat into the kitchen air?

17:39

And the answer is absolutely, because as that kitchen air contacts the so the molecule, the row of molecules that first contacts the side of the pot, will they heat up?

17:50

They heat up very quickly, don't they?

17:52

And what do we know about war molecules?

17:54

If we go all the way back to thermodynamics, what do we know about war molecules?

17:58

As they take on energy, they have access to more and more degrees of freedom and they are able to load energy predominantly into their translational degrees of freedom, meaning they move faster.

18:13

And as a consequence of moving faster, they move away from the pot.

18:19

So they move away from the pot.

18:20

Well, I'm not creating a vacuum, so other molecules must move in.

18:25

And this process we call natural convection.

18:29

So if I take the fan away from the kitchen, I still have a convecting environment, but instead of a forced convection from my fan or my manual agitation, I would have natural convection.

18:40

And one of the things we're going to be going into in, in Chapters 5, but predominantly six of the reader, is looking at how we can calculate these forced or natural convective heat transfer coefficients.

18:54

So H sub IH sub O .

18:57

Now, when I get to conduction in the middle, conduction is always something I need to be concerned about, but it's much easier to treat because it depends on only two things.

19:08

One is the thickness of this wall.

19:10

So how thick is my pot from the stove, the wall thickness and what is its thermal conductivity K sub W ?

19:21

So I need to know the material property of my metal, the thermal conductivity, and I need to measure it or know the thickness of the wall and then I can use that to directly calculate its contribution to the heat transfer profile.

19:37

OK, So this should all be relatively comfortable revision coming from heat transfer.

19:43

I just wanted to make sure we're all on the same page before we get kicked into the unit operations side of this.

19:48

Our purpose here, right, is when we start calculating the internal, well, not internal.

19:55

These can be in any configuration.

19:57

When I'm calculating my convective heat transfer coefficients, these are things I need to reach toward the heat transfer literature and.

20:06

Frankly, empirical, semi empirical solutions to be able to calculate.

20:11

So that's what we're going to spend our time on, the thermal conductivity of materials.

20:16

This is a, what we would call a thermodynamic or a thermal physical property.

20:20

So this is a property of the material itself that I can go to any reputable source.

20:24

And again, we'll see this come up a few times, but engineering toolbox is not a reputable source, but something like Perry's Chemical Engineering Handbook is our unit textbook is or the peer reviewed literature would be.

20:37

So I need to find a reputable source for that thermal conductivity, but I can usually pull that from literature.

20:44

So the, the real stress for the engineer is how do I get access or be able to estimate these convective heat transfer coefficients, whether they are natural or forced.

20:56

And the way we combine these would be the in, well, we're adding them in series.

21:03

So my overall heat transfer coefficient and and we typically would write this as one over U sub I = 1 over H sub I + 1 over H sub O plus kW over K sorry X the the thickness on the thermal conductivity.

21:20

But if we wanted to solve directly for U sub I then I would just take one over the whole right hand side.

21:26

So this should have been where most of the heat transfer curriculum that you've been through ended.

21:31

Again, if that, if that's a bit uncomfortable, I would very much recommend spending some time with chapter five of the reader and going through the calculations.

21:39

And if, if then it's still a bit uncomfortable.

21:41

Chapters 10/11/12 and 13 of the textbook walks us through this journey.

21:47

So when we're solving for this overall heat transfer coefficient, the thing we care about is getting an accurate estimate for our convective heat transfer coefficients 99.9% of the time.

22:00

Why do I say it that way?

22:01

So if you did pure heat and mass transfer, you would not have been given a bias toward do we jump to calculate convection or do we jump to calculate conduction first?

22:12

And that's fair, right?

22:13

Because it's teaching it from a theoretical foundation standpoint.

22:17

When we think about practically unit operations, what we're going to find, because again, engineers tend not to work in laminar flow.

22:25

We don't like laminar flow.

22:26

It's inefficient.

22:27

The only time we want to use laminar flow is to protect something precious like a pharmaceutical.

22:33

Then we'll start to think about, is laminar the right choice?

22:36

We tend to operate in turbulent environments.

22:39

What does that mean when we're operating with any degree of turbulence?

22:44

Can the rule of thumb, the heuristic you can walk away with is that conduction tends to represent less than 1% of the overall heat transfer, right.

22:56

So we jump to calculate the convective heat transfer coefficients because in most 99% of the cases they represent 99% of the heat transfer.

23:09

That's where the heat is transferring us through convection for our practical engineering systems.

23:15

So the two exceptions where that heuristic falls over are when we have a very thick wall.

23:22

And when I say very thick, I mean the wall thickness is some number of integers greater than the flow channel, right.

23:30

So I can imagine say a 2cm cylindrical pipe with a 10 centimeter wall, that is a thick walled problem, right?

23:41

Not even on the same order of magnitude.

23:44

We need to have a much larger wall than we do flow channel for a large wall problem to take hold.

23:49

And in that limit, we will then care much more about conduction.

23:54

The other exception I've already listed and that's laminar flow.

23:58

When we get into laminar flow, conduction can be absolutely a limiting factor.

24:03

So the purpose that we have here is that we're trying to figure out for the different systems that we want to interrogate what is our convective heat transfer coefficients look like.

24:12

And I will ultimately sum these by saying one on U right is apologies for my bad writing.

24:19

Is the Riemann sum of overall potential convective contribution of one on the H sub is right.

24:29

So this is let me see if I can write a better U than that.

24:33

So this this is my formal definition of how I can bring together multiple convective heat transfer systems and produce those into an overall heat transfer coefficient U that I care about.

24:47

And if I did have multiple conductions, then I would also have another sum term over the number of conducting layers.

24:53

So maybe I have a pipe that's built of three different materials laminated together.

24:59

Well, I have a different thermal conductivity through each, so I have to account for each one in sequence.

25:04

And so in the same way I would have the thickness of that each material J and the thermal conductivity of that material J for all JS .

25:16

So if I grab my highlighter, this is the contribution that we care most about, and this is the one we're going to spend most of our time working on.

25:27

These H values can vary right from as low as 1 Watt per meter squared Kelvin up to 100,000.

25:35

So one would be akin to natural convection of air in a very, very calm environment.

25:43

100,000 would be the forced convection of super heated steam blasting something head on.

25:50

That's a very, very high heat transfer coefficient.

25:53

So we can see that these convective coefficients run over a huge space and they're also very dependent on geometry.

26:01

And so This is why we're spending so much time because we need to unpack what is the solution technique we're going to take for each of these coefficients across different geometries and in critically across forced and natural convection.

26:15

OK.

26:16

Now when we start thinking about our unit operations and the first one up that we're working on in our second module is refrigeration and really heat transfer within the refrigeration system writ large.

26:29

Now one of the key questions is going to be why does my theory deviate from reality?

26:37

And I can imagine that if I start to have, let's go back to the allegory or the example of my kitchen pot being put on Grant, if I start to have, let's say, pieces of food that are, are as they're cooling down, maybe I'm making a soup of some sort, right?

26:55

Or a sauce as it's cooling down, I might have part of that sauce that solidifies onto the pipe wall inside, right?

27:03

A good example is anyone that's ever made a homemade Alfredo sauce, right?

27:07

If you cook it at too high a temperature for too long, you'll get kind of a crust of of milk, of solid milk material that will be solidified to the inside of that pot.

27:20

This is a perfect example of what we will call fouling, and fouling in this means I have some portion of my working fluid now.

27:28

It can be a contaminant, it can be a naturally curing portion of my working fluid, but some portion of that has solidified out.

27:37

It's no longer in the liquid or fluid phase and it is now a solid sitting on the inside or outside of my, of my, my solid wall.

27:49

So I have a second solid that I need to think about.

27:52

So in just the same way that if I had a kitchen pot that was a combination of stainless steel and copper, right?

27:58

And we find that more expensive kitchen pots tend to use copper because they have really good thermal conductivity where copper does well.

28:06

If I start to have fouling, and this can be any organic biomaterial, inorganic material that would solidify on the inside or outside, I now have another solid to consider, another solid through which heat must be transferred.

28:22

So this is also why if you scald something when you're cooking or you burn milk, if you're making an Alfredo, the nature of having burned or having scalded that food changes the heat transfer profile.

28:35

So you have to, you know, if you don't want to throw it all out and start over, which I hate to do, then you have to adjust your cooking strategy to account for the fact you have fouling material.

28:45

You've fouled the system.

28:47

And so it changes, it makes it harder for heat to enter into the system, right?

28:52

It slows the rate at which heat is going to come across.

28:57

OK, So the purpose here we want to go after calculating or how we can calculate our convective heat transfer coefficients.

29:06

So let's first start with our simplest system that we can think of and that's laminar flow.

29:13

Now in laminar flow, I have energy being conducted between the fluid layers.

29:21

Remember I said that the two conditions under which my heuristic of the 99% of heat transfer, 99% of it is convection, the one of two conditions that violates that is laminar flow.

29:34

And This is why when I have laminar flow and I have that beautiful parabolic profile in its cylinder pipe, as we would have seen in fluid mechanics and in the first lecture, what we're actually doing is conducting energy between layers of fluid that are stacked together.

29:53

And the analogue here is if you took a deck of playing cards, like a standard deck of, of playing cards and you took them and put them on the table and then used your hand to smear them out.

30:06

So almost like a Vegas or a Crown casino card dealers, they smear them out on the table, the shorter one, and then pull them back.

30:12

That analogue of these, these layers of cards flowing one on top of another.

30:17

That's what my laminar fluid looks like from a heat transfer perspective, and I'm conducting so physically conducting energy from like the same analogue as my pot to my granite countertop.

30:29

I'm conducting energy through each card in the deck as we go.

30:34

So in laminar flow, I need to use a correlation for conduction.

30:41

Now the way we're going to handle this is the introduction of another dimensionless quantity, and this is the Nusselt number that we define as nu .

30:52

So the Nusselt number, and this is a really good thing to know, represents the ratio of convective to conductive heat transfer resistance.

31:02

So a high Nusselt number means my resistance is primarily convective.

31:09

A very low Nusselt number means my resistance is primarily conductive.

31:15

And this is what we can use to then estimate what my overall heat transfer looks like when I have a combinatorial convective and conductive system.

31:25

Now the solution strategy, so we're going to look at one solution and then we're going to

apply it and we're going to look at how this changes across different types of geometries and different types of convection, beginning with laminar flow across a flat plate.

31:38

So if I draw that analogy of a flat plate where I have my hydrodynamic and thermal boundary layers, what I'm trying to figure out what is the effective heat transfer coefficient.

31:50

So the convective heat transfer coefficient from the fluid to the flat plate.

31:57

So the way we're going to handle this, and this is two things we're going to see simultaneously.

32:03

First thing, let me erase this and highlight it.

32:08

It is critical to write down, to memorize, to be comfortable.

32:12

That's not going to work.

32:15

It is critical.

32:16

This is the definition of the Nusselt number.

32:20

It is a foundational definition, right?

32:25

So every time we solve the problem, a heat transfer, we're going to be using a correlation.

32:32

We're going to be looking at a whole bunch of correlations today.

32:35

We're going to be using a correlation to calculate the Nusselt number.

32:40

But you say, well, the Nusselt number just tells me something about the proportionality.

32:43

I can't report that I need a heat transfer coefficient.

32:46

That's what I care about.

32:47

Ah, the trick.

32:49

And we're going to see the same analogue and mass transfer.

32:52

The trick is that I once I have that Nusselt number calculated from say this correlation, then I go back to the definition because the only thing I don't know is h . So I start here, I execute this correlation that produces for me the Nusselt number.

33:16

And from that I get that was a very bad three.

33:21

From that I get the convective heat transfer coefficient.

33:30

Delete this circle.

33:31

So it's a bit easier to see.

33:33

So it's a 123 step process.

33:37

OK, so let's look at a few examples here.

33:41

So in the first instance, how do I calculate convective heat transfer across a flat plate, right?

33:48

And this would be the analog of my pot that I've put on the granite stove.

33:53

So I have one very warm interface and I have one wall that I'm transferring heat through.

34:01

So what I care about are two different, well, three different contributions that we're going to see show up over and over in different permutations.

34:09

The 1st is an empirical pre factor.

34:12

So in this case it's 0.664 and that's for the flat plate.

34:18

And we're going to see different variants on this emerge for different geometries and different types of convection.

34:24

The 2nd contribution is the Prandtl number, right?

34:28

And this is the same Prandtl number that we just looked at.

34:30

So the same definition of that Prandtl number I can put in.

34:34

That's the ratio of the momentum diffusivity to the thermal diffusivity.

34:37

I can put that same relationship into this definition which we have here.

34:43

And I have to always be careful because this Prandtl number is going to be raised to different powers.

34:50

Sometimes we can write it conveniently as the square root or the third root or the 4th root.

34:55

Sometimes we're going to be raising it to an empirical power, like the Prandtl number to the .251 power, for example.

35:03

So I have my pre factor first, I have my Prandtl number that's raised to a power, and I have my Reynolds number raised again to a power.

35:14

So in this case for a flat plate, the three characteristic quantities are my pre factor is 0.664, my Prandtl number is the cubic root and my Reynolds number is the square root.

35:25

And I can expand through the definition of the Reynolds number and Prandtl numbers to get this larger equation on the right hand side.

35:31

So I can the heat capacity, dynamic viscosity, thermal conductivity, and then I expand out my Reynolds number, density, velocity, dynamic viscosity.

35:42

And here the characteristic length for a flat plate is X, right?

35:46

Is the distance from the leading edge of the flat plate.

35:50

OK, so when I look at this system, what I'm getting is to say, ah, if I look at the right hand side, what do I need to know?

36:00

Well, density, dynamic viscosity, thermal conductivity, and heat capacity.

36:05

So these four things are Thermo physical properties, right?

36:09

I can get them from Perry's Chemical Engineering Handbook.

36:12

I can get them from both my introductory and advanced thermodynamics textbooks.

36:17

I can go to peer reviewed literature to find them being physically measured for a system of interest.

36:24

Or I can go to another reputable database, something like the NIST Chemical Web book that we would have seen in thermodynamics.

36:30

These are why the nature of why these show up, where they show up is why thermodynamics comes first in the curriculum, right?

36:38

Because these quantities, to be able to use them, we have to appreciate what they are and where they come from.

36:44

So these are my Thermo physical quantities.

36:46

They're defined for the fluid.

36:49

They, they're dependent on my thermodynamic condition.

36:52

So they change as a function of temperature and pressure and composition, which means that if I'm operating over a range of those conditions, maybe I'm going from 20 to 40°C and a pressure between 1:00 and 10:00 mega Pascals.

37:08

OK, I need to calculate or look up the Thermo physical properties at those bounding conditions and I'm going to take an average of those.

37:19

All right.

37:20

So I'm, I'm incorporating the range of of solutions here.

37:23

And this is again a source of uncertainty in the application of our theory.

37:28

Now if you might ask yourself where, where am I taking that average over my?

37:34

My approach is that we take it over a volumetric space.

37:38

So if I have 1% of my system that's sitting at 20°C and one megapascal and 99% of my system volume, the experience of volume of my system sitting at 10 megapascal and 40°, see I'm going to take 1% times the first property plus 99% times the 2nd.

37:59

So I'm balancing it based on the volume distribution in my system.

38:04

OK, So my first four terms, these are all Thermo physical.

38:07

These are coming from the domain of thermodynamics and viscosity, a bit fluid, fluid mechanics and thermodynamics together.

38:13

This is the least understood of my Thermo physical properties at present.

38:19

I then have a geometric consideration in X , all right, what's the characteristic length of my flat plate or my system?

38:26

As we're going to see in latter slides, this could also be the characteristic diameter of my flow channel or the diameter of my cylindrical pipe.

38:35

And then I have what the engineer gets to choose and that's the velocity.

38:39

How fast are we moving through the system?

38:42

So I have one depth or U knot so that the characteristic velocity this is and this is we can see here representing the average, the mean velocity in the center of the flow channel.

38:55

So we're we're outside of the boundary layer contribution.

38:57

That's why it's U not.

39:00

I have one geometric consideration, I have one velocity consideration, and I have 4 Thermo physical properties from that I can calculate if I can satisfy these and every problem we have will I can directly calculate the Nusselt number, right?

39:17

And this will have some value.

39:19

Say we can see here on the bottom, we can see a Nusselt number of 2.5 would not be unreasonable for a liquid or a gas or sorry, Nusselt number of greater.

39:31

So let's say 25, right?

39:32

And Prandtl number is about 2.5.

39:35

So I'm calculating my Nusselt number.

39:37

Let's say for argument's sake that the calculation I output is a Nusselt number of 25.

39:42

So then I say, OK, I have this.

39:44

I've, I've done all this work.

39:46

I'm in the laminar system.

39:47

I'm thinking through all these considerations and I've calculated my Nusselt number in the equals 25.

39:53

What do I do then?

39:54

Because the Nusselt number is not the heat transfer coefficient.

39:57

Well, then I say, ah, I have already determined the thermal conductivity.

40:03

Ki had to use it over here, right?

40:05

So I've determined K and I've set the characteristic length of the system.

40:09

I had to use it for my Reynolds number, didn't I?

40:12

So D&K here.

40:13

I've already done these.

40:15

I know what those are.

40:15

So if I've calculated my Nusselt number, then from its foundational definition, the only thing I don't know is H So I can multiply that Nusselt number by K and divide it by D.

40:27

And what I'm left with is my convective heat transfer coefficient H in units of Watt per meter squared Kelvin.

40:36

And this is the convective heat transfer coefficient I can then bring in to all of my calculations for that system.

40:45

So we often times don't work with laminar flow and we definitely don't work with flat plates.

40:50

Very often they do come up, but most of the time what we're considering is channel flow or piped flow.

40:58

So let's look at a more complex or, or more practical set of calculations.

41:05

So these are, now we're going to go through what what we're calling the Nusselt number correlations, right?

41:11

And these are discussed and gone through at length in chapter 5 and chapter six of the reader and chapters 10/11/12 and 13.

41:19

That's why it's such a long set of chapters from the McCabe's textbook because they're going through each of these examples, right?

41:27

So I definitely, if you're a bit uncomfortable with how to apply these and the reader does have some examples that you can work alongside and go through.

41:35

There are many more examples in McCabe's textbook that I would highly recommend if if you're finding these a bit uncomfortable for the moment.

41:43

So let's look at 2 examples or two different systems for Nusselt number correlations under laminar flow.

41:50

So the first is the flat plate that we just looked at.

41:53

And the way I've tried to organise this is to showcase that the length here, the characteristic length of concern is the the length of that flat plate.

42:02

And often times, all right, what we're going to find is that, well, not often times, every time, either our Nusselt number or Sherwood number correlations are constrained to Sherwood being mass transfer.

42:15

We'll get to later.

42:16

But my correlations for these are constrained to a specific set of conditions.

42:22

They're constrained by the geometry.

42:24

And in the case of my heat transfer, they're constrained to Prandtl numbers and Nusselt numbers.

42:30

So I have to always make sure that when I use a Nusselt number correlation, I refer back to where did this correlation come from and what were the constraints placed across it.

42:41

Now, if you get into a scenario where you simply don't have a Nusselt number correlation for the situation you're trying to describe, it is not unreasonable to use the nearest neighbor that you can find.

42:53

But that then becomes the headline assumption that you have to put at the first line of your report or the first line of your tech memo, right?

43:02

I said, hey, this is a knowledge gap, and I've had to adapt a Nusselt number correlation for deployment here, which means the result is high in uncertainty.

43:13

And as best as possible, we would want to calculate that.

43:17

So here is the flat plate correlation that we just looked at.

43:20

The prefactor is .664.

43:22

The Prandtl number is taken to the cubic root and the Reynolds number is taken to the square root.

43:29

Now if I'm taking laminar flow in a pipe, so a cylindrical pipe, which in older parlance we would call a duct.

43:36

So that means, you know I can have a cross section of a square or a rectangle or a circle or anything in between.

43:44

So if I laminar flow through a pipe or a duct, now my Nusselt number definition, the prefactor is 1.85 instead of 0.664.

43:54

The Prandtl number is taken to the one third power and the Reynolds number is taken to the one third power.

44:01

So they're both taken to the cubic root and I have to correct this by adding in AD on L here.

44:08

So this is the characteristic length L of my system and the D the diameter of my pipe or duct.

44:15

So if I have a cylindrical pipe, $d = L$, right?

44:20

So that term drops out.

44:21

And this, you know, we tend to work in cylindrical pipes.

44:24

So most often you will see this correlation written as 1.85 times the cubic root of the Crandall times the cubic root of the Reynolds, because $D = L$.

44:34

But if I go into something like a square duct or a rectangular duct, then my characteristic length is different to the diameter of the system.

44:42

And in that case I use this D on L term to correct it.

44:47

And then we've also added in one final term here, little Φ .

44:51

This is the small Greek letter Φ sub V .

44:54

This accounts for variances in fluid viscosity, OK.

45:00

And the definition of it is here.

45:02

It is defined as the real dynamic viscosity of the fluid divided by the dynamic viscosity of water to the .14 power.

45:10

So clearly we're using a highly empirical approach saying, as we've said in thermodynamics, viscosity is the most complex of the Thermo physical properties to predict for fluids.

45:20

It's the least understood in chemical physics.

45:24

So we tend to use empirical or correlative approaches.

45:28

And the thing we really love to correlate viscosity to is water.

45:32

Why?

45:33

Because the viscosity of water is conveniently 1 centipoise, the definite where we got the centipoise from.

45:40

So the viscosity of water at room temperature and atmospheric pressure is always one centipoise, which allows me then and it's, it also tends to be highly invariant, right.

45:51

I do not get large ranges of viscosity in water.

45:54

So it's a very constant property that I can always benchmark to.

45:58

So in this case, if I'm working with say a light hydrocarbon fluid, the viscosity which is 10 centipoise, I would say, OK, well I have 10 centipoise divided by 1 centipoise.

46:09

So the value of 10 raised to the .14 power and that becomes my Φ sub V correction term.

46:18

Now conveniently what we're going to see in in the book or sorry the reader and the book both contain the same plot.

46:24

Here.

46:24

I reference from the book on this that this correlation for laminar flow in a pipe, a cylindrical pipe or or a non cylindrical duct has a limiting value of 3.66 in the Nusselt number.

46:39

So as I take it to the the maximal extent of laminar flow right before I, I transition in or I move into transition or turbulent flow.

46:49

So I'm at the Max the end member condition of laminar flow.

46:53

I have a Nusselt value of 3.66 in pipe flow.

46:57

And that's a really convenient thing for a quick back of the envelope calculation because then I can say conveniently, if I know my, you know, if I'm flowing laminar, I'm probably going to flow as as high velocity as possible, you know, because I'm still going to be able to protect whatever material like a pharmaceutical I've chosen.

47:18

But to be able to solve that problem, all I need to know is the characteristic length D and the thermal conductivity K.

47:25

And I, I, the Nusselt number I can assume is 3.66, multiply it by K, right?

47:31

Divide it by D and I can directly calculate H Now most of the time, 99% of the time we work in turbulent flow because it's much, much more efficient for mass and heat transfer operations of our concern.

47:45

So here if I'm thinking about turbulent flow, I can use two different correlations.

47:53

The 1st and this is for a Reynolds number above 6000.

47:56

So we're in pipe flow, but we need to be sufficiently, sufficiently turbulent.

48:02

So we're really away from that transition region where we have less insight as to what's going on in the fluid, the turbulent eddies.

48:09

So with ducted or pipe flow above a Reynolds number of 6000, we can use the Dittus-Boelter correlation.

48:15

This is the Nusselt number h sub D here just indicates it's an internal heat transfer coefficient because we're in ducted or pipe flow.

48:24

And again, look at the formalism of what we see.

48:27

The pre factor is now 0.023.

48:29

That's the first thing.

48:31

I have the Prandtl number raised to a power and I have the Reynolds number raised to a power.

48:35

And this is the same formalism we're going to see over and over and over for all of these different geometries, different flow conditions.

48:43

So the Reynolds number for a pipe I can certainly calculate from fluid mechanics.

48:47

And the Prandtl number is the same as we looked at.

48:50

So we can calculate that based on our knowledge of the material properties and the power that we raise it to in the Dittus-Boelter correlation.

48:58

If I'm warming the fluid up, meaning so the stuff coming through my pipe, if the operation is attempting to heat that working fluid, then the Prandtl number is raised to the 0.4 power.

49:09

If the operation is to cool that working fluid, then the Prandtl number is raised to the .3 power.

49:15

All right.

49:16

So this is arguably one of the most useful Nusselt number correlations that you can work

with because we tend to work in cylindrical pipe flow very, very often as chemical engineers.

49:31

So the second approach and I can alternatively use either of these, right?

49:35

So these are different correlations for slightly different nuances.

49:39

But if I'm thinking about a turbulent ducted system, I can do both calculations and see if they agree.

49:45

The Seider Tate correlation again this is the same internal convective heat transfer coefficient, clearly the same pre factor, obviously the the same power on the Reynolds number.

49:57

The only thing that changes between Didis Boltler and Cedar Tate is that my Prandtl number instead of being optionally raised to .3 or .4 is raised to the one third right, so somewhere in between .3 and .4.

50:10

But it is appreciated that the reason why I get a difference in behaviour right of momentum to to thermal diffusivity than is the Prandtl number when I'm heating or cooling.

50:23

It's largely driven by viscous effects.

50:26

So Cedar Tate suggested that the Prandtl number should be raised to a more theoretical power of $1/3$ or the cubic root identical to what we saw up here.

50:36

And I now incorporate this viscosity correction, all right, where we've just gone through an example above of how to deploy that value if I had a, for an example, hydrocarbonate 10 centipoise relating it to water at one centipoise raised to the .14 power.

50:53

So when I'm dealing with turbulent flow in pipe networks and that's going to be a majority of our focus, right, Turbulent flow is efficient as long as I'm not worried about them physically harming the the working fluid of the material of my interest, then turbulent flow is going to give me the most efficient system.

51:14

So that and I always would want to operate at the limit of turbulence before I start to either degrade the pipe wall through erosion or harm the material inside.

51:26

So these correlations either Adidas Boltler or if I know something about the viscosity, then I would absolutely deploy the seed or Tate correlation because it's a much finer tuned to the specific viscosity of the material of interest, right.

51:39

As as opposed to assuming that the viscosity is not changing and rather reflecting that in the variance of the Prandtl number's power.

51:48

OK, so we're almost done.

51:50

I know this, this lecture is running a bit longer than I had planned it to, but let's look at now some more or a variance in the geometry.

52:00

So we're going to stay with our, our discussion of turbulence, but now, right, instead of thinking about the convective heat transfer coefficient inside my pipe, my cylindrical pipe, I also, if I'm going to solve a whole system, I darn well better be able to calculate the convective heat transfer on the outside of the pipe, right?

52:20

Because I have to bring those two things together to get an overall heat transfer coefficient.

52:25

So I need this $H_{\text{sub } H}$ not or the H of the outside of the pipe.

52:30

So the first example we'll look at is if I have what we'll call external convection.

52:35

External meaning indicates convecting outside of my pipe and working fluid and forest meaning I have a fan or I'm manually agitating.

52:44

So I'm, I'm doing something to cause convection on the outside of the pipe to the analogy we started with.

52:52

This would be like putting the the kitchen fan out so that I can move air around that cooling pot faster.

53:00

Now when we think about external convection, we have to think about directionality, right?

53:07

If my kitchen fan, let's say were pointed, the blades are pointed directly at the cooling pot, right?

53:15

That is going to be normal.

53:17

So it's flowing normal to these cylinders.

53:21

That's going to be a very efficient setup for heat transfer.

53:26

What if I put the kitchen fan on the other side of the kitchen pointed toward the wall?

53:33

Am I going to improve the heat transfer?

53:35

Well, the answer is yes, I'm increasing the turbulence in the kitchen air.

53:39

So by its very nature, I'm going to improve the heat transfer, but not as much as if I point the fan normal to the these axis of the cylinder.

53:51

And so the first correlation we'll look at is that we position our our convecting air or our convecting fluid normal to that cylinder.

54:00

And I need to be at a Reynolds number between one and 1000 right now, bearing in mind the Reynolds number boundaries for external turbulent flow are different to those of our typical internal flow boundaries.

54:15

So both the reader and the textbook go into more detail and review those bounds, but we're not looking at our classical bounds from laminar to transition to turbulent when we're talking about flow outside of objects and around them.

54:30

So the correlation, the Nussle correlation here, and I've not written right.

54:35

I've not written the Nussle number equals right.

54:41

I very well could, but here I'm taking a shorthand and simply representing the definition of the Nusselt number.

54:47

So I know that what I calculate out of this correlation I'm just going to relate back to get h_0 .

54:52

So this correlation my it looks a bit different because my pre factor is now split in two.

54:58

I have both a static pre factor and a second pre factor term that's directly multiplying the Reynolds number.

55:05

So $.35 + .56$ times the external Reynolds number to the raised to the power of $.52$.

55:14

And now we're multiplying the entire thing by the Prandtl number, the external Prandtl number to the power of $.3$.

55:22

OK, now we might ask ourselves, so, so if we, well, if we know something about the characteristic length of my tube, right?

55:30

So if I'm we're in a cylindrical geometry and I'm blowing air across it, then the characteristic length of that tube is going to be the diameter right of the cylinder that I'm using to contain my working fluid.

55:42

So I need to know the characteristic length and then what else it's the heat capacity, thermal conductivity, dynamic viscosity and density of the external fluid of the working fluid of the air that's blowing across it.

55:57

Or if I conversely if I'm using something like a a sub or a sea based heat exchanger, it would be these properties of the ocean water flowing across it.

56:08

So it's the same type of calculation, but I'm now using the properties of the external fluid instead of that flowing inside the pipe.

56:18

Now this on the right hand side.

56:20

This is a really interesting diagram.

56:22

What I'm plotting is the Nusselt number as a function of the direction, the angular direction of flow.

56:29

So at 90° right is where we get normal flow or say you know, 90 to 110 is the region in which because the, the flow is going to be bending around the object.

56:40

So I have a, a wider sweet spot than calling it perfectly normal at 90° .

56:47

But the reason we talk about the importance of normal flow or, or flow normal to our, our cylinder.

56:53

And this is an example of, of normal flow.

56:55

So the cross section of my cylinder, I'm blowing directly across it and I can see the turbulent eddies picking up here to the right.

57:03

The reason that I care about that is that here is the region in which I get the best Nusselt number outcomes.

57:11

So I'm plotting the Nusselt number versus that angular coordinate for all different types of Reynolds numbers, right?

57:17

I'm all through 10 to the five powers, and these are measured, right?

57:21

So this is coming from McCabe's textbook as an exemplar measurement of this type of calculation.

57:27

It is in that region of normal flow to the tube that I get the best Nusselt number outcome.

57:33

And what the the point that this plot is making is that, you know, if, if U is the engineer, we're saying, OK, let's look at the top three data sets here.

57:41

Reynolds number going from a lower value, a lower bound of 1.7×10^5 to the five to an upper value of 2.19×10^5 .

57:50

Well, if I were to, to choose an incorrect geometry, So if I'm, let's say I'm going to be blowing down the length, blowing air down the length of the tube and not across it, not normal to it.

58:04

Well then I'm going to be here on the Y axis, right?

58:11

Whereas if I change it and I, I turn the set up by 90° , so I'm blowing air or water normal to the tubes I'm operating in this region.

58:21

Well, here I get a much, much better convective heat transfer coefficient, in fact, at my lower Reynolds number than I did at my higher Reynolds number, right, because I've chosen a cleverer position to do it with.

58:36

And the reason I point this out is we go back to the beginning part of the lecture where I talk about the most expensive or sorry, last lecture.

58:43

The most expensive operation an engineer will typically be responsible for choosing is the amount of pressure, right?

58:52

That the size of the compressor or the size of the pump.

58:55

Well, the purpose of those is to create velocity.

58:59

So if I need a higher velocity, I need a bigger compressor or a bigger pump.

59:04

And I'm in forced convection.

59:06

So that means I've done something to force this convection.

59:09

So instead of spending another 100,000 or at an industrial scale, \$50 million on a more expensive compressor or pump or fan to push more and more stuff across this, I can get

just that same value out of thinking about am I flowing normal too, or across the length of these tubes.

59:33

Because by positioning the right geometry, I'm going to minimize the amount of spend, minimize the amount of materials and subsequently energy emissions that are associated with the operation.

59:45

I'm making a clever choice to work in the most optimized direction.

59:51

OK, So this, this forced external convection, you know, I, I think a long time ago we tended away from external convection because it tends to be less effective than having say pipe and pipe heat exchangers or where we're using a secondary working fluid to cool things down, particularly with a focus on emissions reductions and in particular in the limit.

1:00:15

Of associating a cost to emissions reductions, which is not a threshold we've yet crossed globally, but we certainly well need to, once we can quantify the cost of doing this right, of making a cleverer choice, we're going to see I believe a significant increase in the number of external convection systems deployed in chemical engineering operations, right?

1:00:40

Because nature does a very good job of creating an external convective environments for us, whether it's the atmospheric air or the oceanic water, we have access to a massive thermal reserve that can allow us to deliver a, a critical operation for a, a much more emissions controlled or energy controlled process.

1:01:05

Now, if I don't want to necessarily use forced convection, maybe I don't want to install.

1:01:10

We definitely don't want to install subsea blades, right, to push seawater.

1:01:15

That would not be good for the ecosystem.

1:01:17

We could probably install some fans in the air, you know, if we put a cage around them to make sure that they're safe.

1:01:23

But it's easier to force convection with air than the considerations of doing that with seawater.

1:01:29

But what if we wanted to, to not use forced convection?

1:01:32

We instead wanted to use natural convection.

1:01:35

So in this way what we're going to look at or in the model for this is shown here on the right hand side where I might have, we're here suggesting water is the working fluid.

1:01:46

So water is going to in is come into each of these tube sets, flow through the tube set and back out the other side.

1:01:54

And I'm simply stacking layers of these tube sets so that I get air flow above and below.

1:01:59

Right now the first thing we would think about is if this air flow, and this is naturally current air flow is our cooling or heating medium.

1:02:08

Whatever operation we're we're taking here, typically it would be cooling.

1:02:12

But for this medium, you can see here, we would naturally position it to be the air flow to be normal to the cross section of most of those pipe cylinders, right?

1:02:25

So the portion of the pipe that's aligned with the direction of air flow is not going to be very good for heat transfer.

1:02:31

But that's why the majority of our tube bundle is laid out normal to the direction of air flow.

1:02:37

So for the engineer who's designing an external heat exchanger, right, Maybe they come in and say, hey, we now have a price on CO₂ globally or in the nation that we can use.

1:02:49

So the operation that you're conducting, that's using a large amount of energy.

1:02:53

I think as the engineer I can come in and if we build 1 steel object or one material based object, I think I can save this process plant say the equivalent of \$1,000,000 a year in emission cost by replacing your forced internal convection with a natural external convection.

1:03:14

The first thing we would need to think about is a study on what is the air flow, What does the wind flow look like in my location and how does that change over every season, right in the year?

1:03:25

And what are those averages from day to night, from season to season so that I can look at from the directionality and the strength of the wind flow, what is the best possible position so that I'm normal to the tube bundle a maximal fraction of the time.

1:03:42

So when I'm using natural convection, the challenge that I face is if you can imagine errors initially entering this tube bundle here, well, it's flowing through and across these tubes.

1:03:54

But the air, if I'm in a, let's say a using hot water and I'm cooling it down with air, the air is going to start heating up.

1:04:02

And so as the air starts heating up, it's going to want to rise like all air that heats up.

1:04:08

And so if that air wants to rise, I now have to deal with a new phenomenon because I'm not forcing the convection anymore.

1:04:16

I have to deal with the buoyancy of my external medium of my external fluid.

1:04:23

And so to account for this buoyancy, we're going to capture this in what we call the Grashof number.

1:04:29

So this has Gr is its definition or is it its name?

1:04:35

So this Grashof number, I can see the same Thermo physical property showing up.

1:04:41

The characteristic diameter of the outer tube bundle, the dynamic viscosity and the density of my, in this case, error or my external fluid across it.

1:04:50

The temperature difference between the wall of my tube bundle and the air that's coming across.

1:04:57

Obviously this ΔT is going to change from day to night, from season to season.

1:05:01

So this is a dynamic property to think about G , the gravitational acceleration, this is obviously going to come in because I have to deal with buoyancy effects.

1:05:09

So the Earth's gravitational field becomes relevant again and β , now β is going to represent the coefficient of volume expansion, right?

1:05:19

So this is if we, for those that said, oh, all the partial differentials in Thermo, are these really going to come up in real life calculations?

1:05:27

The answer is absolutely.

1:05:28

And here's where they start to show up.

1:05:30

So the coefficient of volumetric expansion, β , this is my property from thermodynamics.

1:05:37

This is why, in fact, that property was tabulated right well before the discipline of thermodynamics derived it, because when we're dealing with Boolean systems, we must understand volume expansivity, or in older parlance, coefficient of volume expansion.

1:05:57

OK, so this beta is still a Thermo physical property.

1:06:01

So I can see here I have 3 Thermo physical properties.

1:06:05

One characteristic diameter G is a constant at least on the planet Earth and ΔT is a system specific definition.

1:06:15

So from these I can capture the Grashoff number.

1:06:18

Now we can see in the solution approach here I still retain the same pre factor.

1:06:24

Now the pre factor is going to change a little bit from system to system, which is why I've just written it as little B for now.

1:06:30

I still have my Prandtl number, but instead of the Reynolds number, I'm replacing the Reynolds number with the Grashoff number.

1:06:37

So when I go from, when I'm forcing convection, I use Reynolds number.

1:06:41

If I'm using natural convection, I use the Grashoff number.

1:06:47

And I'm raising both of these to the power of N So on the bottom here, this is a table that I've modified clumsily by adding in a final entry here, but I can have a four or this is for three different types of heat exchange systems.

1:07:06

The first would be vertical plates or vertical cylinders here for the two different ranges.

1:07:11

And this is the product of the Grashoff and Prandtl number.

1:07:14

So I need to calculate those first.

1:07:17

If you were an engineer deploying us saying, well, look, there's a range of temperature differences here that I need to account for, that's where you take an average, you know, per time.

1:07:27

So what's the average ΔT throughout a day and then what's the average across 365 days a year in and out of different seasons.

1:07:36

So you're getting a representative distribution.

1:07:39

We would then calculate the product of these Prandtl and Grashof numbers and these are the two ranges to which they can apply.

1:07:45

So products it's a product multiplying the two between 10^4 and 10^9 or 10^{10} to the 10^{12} .

1:07:51

The the point is, is that I go to a higher turbulent degree of natural turbulence.

1:07:57

So a higher Grashof and Prandtl number product, I get a smaller B, so a smaller pre factor, but a higher power, right.

1:08:06

So these two variations, these are exactly what I would expect as I go from say the example of laminar flow to turbulent flow inside of a pipe.

1:08:15

I can see a change in the pre factor and a change in the powers and that's just reflecting here.

1:08:19

But for a naturally occurring system or naturally driven system, I can also use horizontal plates.

1:08:25

And there I get a little more nuance because the directionality of the plate and the type of operation has a bit more impact.

1:08:33

So if I'm heating facing upward or cooling if, if the plate faces downward, I'll use this set of correlations for different Grashof and Prandtl numbers.

1:08:42

Or if I'm cooling with the face upward or heating with the face down, I use this bottom correlation here.

1:08:48

And then finally, if instead of vertically orientated cylinders, I have horizontal, so these are horizontal cylinders as I've shown here.

1:08:56

Now we have the condition for the natural log.

1:08:58

So this is the base 10 log.

1:09:00

The Grashof and Prandtl numbers needs to be greater than four.

1:09:03

Or another way I can write this is the product of the Grashof and Prandtl numbers is greater than the power of 10^4 .

1:09:10

I use AB of 0.53 and an N of 0.25.

1:09:17

OK.

1:09:17

So what we've gone through here is looking from our flat plate to a cylindrical pipe to an external I forced convection to an external natural convection.

1:09:29

What are each of the Nusselt number correlations that I can deploy to be able to solve for the convective heat transfer coefficient on the inside and or outside of the system of interest?

1:09:43

Where we're going to bring these together is into our next lecture where we're talking about the design and structure of heat exchangers, right?

1:09:52

So the point that we want to make, and I'm not going to get too deep into this yet, but the point that we want to make, and this is starting to pick up into chapter six of the reader and, and partially Chapter 7, the Delta T that we just saw in the Grashoff number.

1:10:08

We talked about the importance of understanding how that Delta T evolves because nature is going to change its air temperature from day to night, from summer to winter.

1:10:19

There's this natural variance in delta T that I have to account for as the engineer.

1:10:25

Now, if I don't want to use that kind of system and I say no, no, no, I'm going to use a completely internal heat exchange system to move thermal energy from one fluid to another, and it's never going to touch the outside environment.

1:10:40

OK, that's also another approach.

1:10:43

But when we do that and start designing these heat exchangers for inside use, we have the same consideration.

1:10:50

And that's that the heat exchange system is naturally going to vary from the first point of contact, thermal contact, to the final point of thermal contact.

1:11:00

The delta T from the front to the back of the heat exchanger will be different.

1:11:05

And so I, as the engineer, need to think about how I Orient these things and how I choose the direction of flow so that I maintain an optimal driving force.

1:11:15

Now, what do we mean as an optimal driving force?

1:11:17

So as you get into chapter six of the reader, it goes through the nature of how this is a shell and tube heat exchanger and then on the bottom is a double pipe heat exchanger.

1:11:28

So let's focus on the shell and tube heat exchanger first.

1:11:31

Here I have an inlet liquid, and this is going to be say, a liquid of interest.

1:11:35

I have an inlet liquid that's going to come into this channel and it's going to flow through each of these tubes, collecting a second channel and exit out.

1:11:44

I then have a second heat exchange fluid entering from the top that's going to flow around these tubes.

1:11:50

It's going to immerse these tubes and flow around them, kind of like what we just saw for the external heat exchanger, but done internally with the shell around it.

1:11:59

And so in this process, the heat transfer fluid, the external fluid, the shell side fluid comes in here.

1:12:08

Well, I'm going to get a very different heat change profile on this first row that I'm going to get at the exit point down here.

1:12:17

In this example, we would be using something like a warm fluid, a steam vapour that would be condensing to say a partially condensed steam on the outlet here for the purpose of then heating up some working fluid of interest.

1:12:31

So at the if I were to plot this and say we'll cross the length of the tube from the initial point.

1:12:38

So here my working fluid is entering the tubes at its original temperature and it's exiting after having been in intimate contact with steam.

1:12:48

So at the initial point when it first enters the tubes, I have a very large ΔT and at the exit point where it leaves the tubes, I have a very small ΔT relative to where it began.

1:13:00

And so the ΔT that I would use in my calculations needs to be an average of these two things, right?

1:13:07

In the same way that if I were taking from an external system using natural air or water, I would use an average of every hour in the day because the thing is going to be constantly exposed to the environment if it's operating 24 hours a day.

1:13:23

And I would take an average of every day of the year because it's going to change a little bit every day.

1:13:28

I need to take the same consideration here from the front to the back of the tube bundle.

1:13:33

I have a variable ΔT .

1:13:34

And so I'm going to take an average linearly in this case across the tubes to get these two.

1:13:40

Now, as we'll go into the next lecture, and I'm, I'm not going to go into detail here, but these are called the approach temperatures, right?

1:13:47

So this is dictating the the how the approach temperature changes throughout my heat exchange process.

1:13:55

Now the other type of approach that we're going to look at in the next lecture is what's called a double pipe heat exchanger, or we might also call this a jacketed heat exchanger in different industries.

1:14:06

Here the concept is very simple.

1:14:08

I have some pipe containing my working fluid.

1:14:11

Maybe it's hot, maybe it's cold and I want to reverse that.

1:14:14

I'm going to put another pipe around that with a fluid of the opposite temperature profile.

1:14:20

So if I want to cool the thing down, I put a jacket around it and flow through the annulus a cooler fluid.

1:14:26

If I want to warm my fluid up, I put a jacket around and flow a warmer fluid through.

1:14:32

So a very, very simple design.

1:14:34

And even though we show this as a, a weaving a snake like configuration here, in fact, that's just for convenience.

1:14:42

These things can be perfectly linear.

1:14:45

They can be S shaped, they can be anything you can imagine, right?

1:14:48

It's a jacket containing a different temperature so that I can control the temperature of my internal fluid.

1:14:55

So naturally, if my fluid is flowing through the internal pipe, right, So I can see here, I can trace the inside of this pipe.

1:15:04

Well, if either my working fluid and my heat exchange fluid are flowing in the same direction or they're flowing different directions, it's a pipe and pipe cylinder, so that there are only two directional choices here.

1:15:21

If I choose a parallel, this means they're both flowing together.

1:15:25

I begin with a very large temperature discrepancy or a very large driving force for heat exchange, a very large approach.

1:15:33

And by the end of the process I have a very small driving force for heat exchange.

1:15:38

Whereas in counter current flow means my jacket fluid is flowing the opposite direction of my my internal working fluid.

1:15:47

Here I don't begin or end with an approach that is equal to in magnitude that of what I started with in the parallel, but I maintain a much more consistent driving force for heat exchange throughout this process, Right.

1:16:04

And the reason that we care about this so much is that when we're designing these materials that we have ΔT in our calculations that we can use, right.

1:16:16

So we need a ΔT that's representative.

1:16:18

But then we're sizing the materials, the compressor, all of this, we're sizing that based on that ΔT .

1:16:26

So we need to make sure we have a consistent ΔT or we end up, if we end up with this large range of ΔT s accessible to us, we end up with excess materials, unnecessarily spent energy, unnecessarily loaded emissions, the whole thing.

1:16:43

And so maintaining a consistent driving force for heat transfer is critical to maximizing the efficiency of such a unit operation.

1:16:53

OK.

1:16:53

So in the next lecture, we're going to look at the specifics around these heat exchangers

and in particular, what happens in practical heat exchangers where we start to change phases or we utilize that latent energy of phase change for the purpose of heat exchange.

1:17:10

Have a wonderful rest of your day and we'll see you in the next lecture.

1:17:12

Bye.

Lecture 04

0:10

OK, welcome to Welcome to lecture #4 This is our second of two lectures on heat exchangers.

0:18

Specifically in this lecture, we'll be delving a bit more into the nature of how heat exchangers work, but specifically we'll be taking a look at the type of heat exchangers that utilize latent energy from a thermodynamic perspective, that is the energy of phase transition for the purpose of improving our heat exchange network.

0:38

Now a few notes before we get started.

0:40

This lecture corresponds to Reader Chapter 7.

0:42

That's boiling boilers and condensers.

0:46

And again, if you found that you'd want a bit more revision, a bit more discussion, and maybe some example problems on heat exchangers and specifically boilers and condensers.

0:57

This corresponds to the class textbook 7th edition of McCabe, chapters 15 and 16.

1:03

Now, before we get started with the content for today, there are a few points I want to make.

1:08

First, when we look at the layout of content in the class, you will notice that we are now more than halfway through the reader, right?

1:17

So in the first four weeks, we've zoomed through seven reader chapters.

1:22

So a majority of our prep work is now done to really begin working on these lab problems and these process unit operation problems.

1:32

You will notice that for the rest of the semester, we're really, with the exception of a, a

revision chapter on mass transfer next week for those that want it, we're really dealing with about one reader chapter a week.

1:45

I'm sorry, one reader chapter a fortnite as we move forward and anywhere.

1:50

Sorry, two McCabe textbook chapters that would be corresponded that I've brought into one reader chapter and rewritten.

1:58

So, you know, I appreciate many people will be doing this class the assignments at their own pace to fit their own schedule for the purpose of making sure that we don't get too far out of an alignment as a class.

2:13

You know, this being the 4th week of class.

2:15

If you're noticing that you're really far behind in the reader and or the textbook by this point, this is really this week.

2:23

And next week is where I would strongly encourage you to make sure you're able to set aside some time to catch up in those reader chapters because for the next 8 weeks that we spend in class together, we are going to be focusing heavily on the laboratory and design problems that we're going to be working through.

2:42

So we're going to be shifting focus from all of this prep and background into deploying all of it.

2:48

And that's where we want to make sure we don't get too far out of alignment.

2:52

The second point I'd like to make is that when it gets to the design of heat exchangers, this is not something that's really well suited for a didactic type lecture, right?

3:03

We're looking at, you know, calculations where we're varying the number of tubes or the number of tube bundles.

3:09

We we start to get really detailed calculations and those are best deployed as an offline type of asynchronous learning.

3:16

So in the reader chapters, you will notice there's exercises as to how we go about the design of these heat exchangers.

3:23

And even more detail and more depth is given in the class textbook and the relevant chapters associated with them.

3:31

So I would really encourage for the heat exchange chapters, make sure that you've spent some time with the reader.

3:37

If you need to, you've spent some time with the textbook to work through those problems that they show of how we decide on each of the OR how we take each of the engineering decisions that make up a final heat exchange system, right.

3:53

So one of the things I wanted to circle back toward and talk about a bit are these air cooled heat exchangers.

4:00

And the reason that I, I brought this up last last time was really around, you know, the, the evolving considerations that the engineer needs to take in the 21st century, right?

4:11

It's not, you know, every engineering discipline emerged because society had a constant problem.

4:17

Society kept raising a problem decade after decade.

4:21

And after you can trace it back, but anywhere from 2:00 to 3:00 decades, you sit down and say, OK, this problem is likely never going to go away.

4:31

So we're going to invent, we're going to evolve a new engineering discipline to deal with it.

4:36

In the nature of chemical engineering, that was the emergence of the late 19th century, of realizing we can manipulate materials to solve problems.

4:45

So we needed people who were skilled in the manipulation of energy and materials or materials being energy for the purpose of fitting any one of these society needs.

4:55

This could be things like Teflon for cookware, right?

4:58

That makes it much more efficient.

5:00

So people aren't spending an hour after dinner every night scrubbing pans.

5:04

They can spend that time with their family or working.

5:06

It relates to pharmaceuticals, right?

5:09

If we invent a pharmaceutical, we need a way to manufacture it with absolute purity so that we can then pass it to the folks who can use it.

5:16

Each of these domains lead to the emergence of chemical engineering.

5:20

And as a consequence, we've had to evolve with those demands that are placed on each of these needs.

5:27

So initially, as with every engineering discipline, the first goal is always figure out how to solve the need.

5:36

As these things evolve.

5:37

We now consider economics, we consider environmental pollution, which I'll label as separate to emissions.

5:44

We have to consider things in a pollution sense of are we dumping things into the environment or do we have the potential to leak things to the environment unknowingly?

5:53

But then we also have the emissions problem.

5:55

That is a, you know, pollution of a different kind.

5:58

So the energy that we're using has emissions of any kind of energy.

6:02

There's an emissions profile, the emissions of the materials that we're bringing together.

6:06

So how are we balancing all of these?

6:08

And for that reason, as the field evolves, we're going to see things like emission constraints play an ever increasing role.

6:16

Now, they're not going to replace the other constraints that led to the emergence of the discipline.

6:20

They're going to join them.

6:22

And so when we look at that, we realize one of the easiest things we can do to maintain the integrity of our solutions as engineers, but to reduce the capital and carbon intensity of how we get there is by leveraging those points of the natural environment where we can use it as a point of heat exchange, right?

6:42

And both the atmosphere and the ocean is a phenomenal infinite heat sink.

6:47

And so it gives us this ability to significantly reduce capital and carbon intensity.

6:53

So air cooled heat exchangers are one of those things that I would expect over the coming decades we'll see a massive uptick in use.

7:00

And so I wanted to spend a few more minutes talking about how we can deal with and predict performance in those types of heat exchangers.

7:11

So with the increasing use of air, now we would think about, OK, oftentimes the fluid that we're trying to heat or cool, usually cool is going to be placed in tubes.

7:22

Now these heuristics here in the second line, these come from McCabe's textbook.

7:26

So they're a few decades old.

7:28

But the heuristics themselves being common rules of thumb tend not to change very often, right?

7:33

Maybe they change on an every five to six decade time scale, but not usually inside of that.

7:38

So for an air cooled heat exchanger, we would typically expect that we'll be working somewhere between one and 10 inches in tube diameter, sorry, with a bias towards smaller tubes.

7:49

Why is that?

7:50

Well, we typically want to to maximize the effectiveness of heat exchange and with an air cooled heat exchanger we're going to use more materials.

7:59

So we're going to over design the system meaning we have more emissions and more mining and more material utilization, but upfront as a capital expenditure or a capital emissions expenditure for the purpose of reducing continual Optima operating emissions or capital or cost expenditures.

8:21

So we tend to to bias toward the small side of of a one inch tube.

8:25

We can see some of these as large as 10 inch if we're trying to have a very slow process, right.

8:30

The larger we go in that tube, the slower the process will be.

8:34

But either way, we're on the order of inches in terms of a typical air cooled heat exchanger.

8:39

And most of the time we're not going to see them be more than say three to 10 meters long.

8:47

With that in heat exchange, you would have learned about fins, so or extended surfaces as another nomenclature these go by.

8:55

Basically, if we're trying to accelerate the heat rate of heat transfer, we can increase the surface area, the external surface area of the pipe, right?

9:04

And there are a number of geometries that we can use to increase that.

9:07

The simplest being if we have a cylindrical pipe, then we'll put large circular fins around.

9:13

It's almost like a fish's fin, right?

9:15

Every so many millimetres so that we have a much, we can conduct heat all the way through that We use a good material and then we have a much higher surface area on which our external convection is acting.

9:27

We like things because they're going to increase.

9:30

We can increase by some number of integers in magnitude.

9:36

And if we're then using external air, but we're putting a fan behind it, which is a very, very practical thing to do, right, The fans draw very low energy.

9:47

So very practical to use a fan forced external air, we can go above the natural air current.

9:52

It gives us a bit more control as to the overall heat exchange.

9:55

So the natural variation in atmospheric temperature, we can minimize the impact of that variation by adding a fan up front, right?

10:04

Because we're increasing the rate of heat exchange.

10:06

So even if the ΔT is not optimal, by using a fan or particularly varying the intensity of the fan, we can try to balance these things out to maintain a relatively consistent behavior in the heat exchange.

10:20

So this is the Nusselt number correlation that would be deployed in that scenario.

10:24

Here I have my external heat transfer coefficient h naughty, and of course, this is equal to the Nusselt number.

10:30

Same thing.

10:30

I have my pre factor here will recognize this is my Reynolds number to the .61 power and it's my external Reynolds number because I have D naughty here and this is the velocity of the air driven by my fan.

10:42

And here's my Prandtl number again, these properties relate to the external air.

10:47

Now if I'm using a tube bundle like we looked at in the last lecture, then we would also consider the arrangement of these tubes, right?

10:56

So what's the the arrangement factor $F_{sub A}$ if I have cross flow, meaning I have normal flow and we saw earlier why that's so important.

11:05

So if I have normal flow, then what's the pitch of the system relative to the external diameter?

11:12

Meaning effectively what's the spacing between the tubes relative to how big the tubes are?

11:19

So when those are one, spacing is 1 to one.

11:22

When there's two, there's effectively every other tube is missing.

11:26

And here what we're looking at are arrangement factors from external Reynolds numbers from 2 to 42,000 to 40,000, right?

11:34

The point we're making here is that we're correcting this Nusselt number correlation with a factor $F_{sub A}$.

11:40

So this $F_{sub A}$ that we're showing here in this table is the correction factor.

11:44

It's effectively an efficiency term, right?

11:48

It's giving me an efficiency.

11:49

It's, but it's a very ballpark efficiency.

11:51

So I wouldn't use it as a formal efficiency, but it's, it's incorporating the efficiency of having an external natural or sorry, external atmospheric air.

12:01

And so I'm probably not going to get well above 100% in terms of that arrangement factor.

12:06

Although as I go to extremely high Reynolds numbers, I can peak that somewhere between 103 and 106 percent of its base design.

12:14

But if I start to get into very low flow conditions, I might add a 10 to 15% drop and it's potential performance.

12:22

So something important to account for.

12:24

This is one of the reasons if we don't know exactly what these arrangement factors are going to be or if we've not measured or have data for what the atmosphere is going to deliver from day-to-day or from day to night and season to season.

12:37

This gives you an indication of the type of over design factor that you might apply, right?

12:42

And the worst case scenario, you're looking at a 15% differential up across the base.

12:48

So you might over design the length of the tubes by 15 or 20% just to ensure that you're not setting yourself up for inefficient or suboptimal heat exchange.

13:00

And then from that, we're able to directly calculate the Nusselt number.

13:03

And from that Nusselt number get what is the external heat transfer coefficient for my air cooled exchanger.

13:09

So coming back to now, internal systems wanted to spend a little bit on talking about shell and tube exchangers.

13:17

Now the both the reader and in greater detail in the textbook.

13:23

And there's some of this that will also come into the lab.

13:25

One, prompt materials, we're going to be looking at the design considerations of a show.

13:30

And two, heat exchanger.

13:31

Now I've not gone into a high degree of detail here again, because it's picking up on heat and mass transfer and because our asynchronous materials or the reader and textbook have much more work in depth worked examples.

13:44

So what I want to focus on it's how these systems work and what the design decisions of the engineer are, right.

13:52

So first in the single, so in a typical shell and tube heat exchanger, and let's ignore the fact that these are condensing for a minute.

14:01

These are just, we're going to treat them as normal heat exchangers.

14:04

And then we're going to look like look at what happens when I start condensing.

14:09

So initially, I have some inlet liquid of interest that's entering through Port H and it's going to collect on one side and it's going to flow.

14:17

We can see the opening in these tubes.

14:19

It's going to flow through these open tubes, sorry, flow through the inside of these tubes and collect in the second reservoir.

14:27

So at point reservoir D2 is beginning with its initial temperature and across these tubes I'm entering some heat exchange fluid or heat exchange medium.

14:38

Now that could be steam or it could be a molten salt, right?

14:43

It could be any warm or cool fluid of interest to facilitate my heat exchange.

14:48

Most times I'm going to see from either saturated steam through super heated steam, or I might see a single phase where I have a maybe a warm ionic liquid or a warm hydrocarbon liquid like a warm heating oil.

15:03

But I've warmed up through a boiler.

15:05

And then I'm going to pass it through this shell side such that it's going to contact across each of these tubes and warm the fluid passing through it before it collects in the outlet reservoir.

15:15

D1 finally exiting the heat exchanger.

15:19

So the number of decisions that the engineer has to take is first, what is the size and the number of tubes.

15:27

So in we can calculate for based on the size of the tube.

15:32

It's going to give us if we go back to the Nusselt number correlations, But the diameter of the tube is going to dictate the internal convective heat transfer coefficient.

15:42

The thickness of the tube wall is going to dictate the convection or the conduction and the nature of what's happening on the shell side.

15:51

What is my material?

15:52

Is it a single phase or is it transitioning phase?

15:55

So if I'm using a heating oil, a warm heating oil, then that's going to remain single phase.

16:00

A super heated steam is probably going to remain single phase.

16:03

But if I enter the shell side with a saturated steam, then it's going to be transitioning from a saturated steam to a partially saturated or condensed liquid.

16:13

And so I have to think about that energy as well.

16:18

So the engineer must first decide if I'm using a single pass and we'll come back to what happens if I have a 2 pass, but how many passes?

16:27

So if I choose a single pass, what is the number of tubes?

16:31

And the way that I get there is by considering the impact of tube diameter on the overall heat transfer coefficient.

16:40

What I'm trying to optimize here is the heat transfer coefficient, the overall heat transfer coefficient hue.

16:48

So as my heating fluid enters through the shell side on the top, it's going to flow across this tube bundle and exit through the bottom port label G, which in this case, if we're using condensing steam, we would call the outlet after it's transitioned from a saturated steam to a combination of saturated liquid and saturated steam, we'd call that a condensate.

17:10

It's a combination of the two.

17:12

If I've completely removed all latent energy from that saturated steam, I've fully transitioned it to a saturated liquid.

17:20

So it means in the thermodynamic parlance we have crossed that two phase region fully.

17:26

We then have a fully condensed outlet in terms of that nomenclature.

17:32

Now one of the things, if we look or recall back to the previous lecture, we looked at the the ΔT at the beginning of the tube and the ΔT at the end.

17:43

And one of the things we would have observed is that the ΔT changes, right?

17:47

And we identified at that previous lecture that when we have a variable ΔT , we can get into a situation where we don't really have an optimal heat transfer going on.

17:59

We would love to have at every point along these tubes as we go from left to right.

18:04

What we'd really love to have is a constant ΔT .

18:08

That means I'm maintaining a constant driving force for heat transfer and as a consequence thereof, I can get a much more efficient system.

18:19

Now if I only have one pass, meaning my fluids come in, they transit across and they exit, well then I'm not going to be able to modify that unless I think about a multi pass system.

18:32

Now let's ignore this floating head thing for a minute.

18:34

We'll come back to that, but in the multi pass heat exchanger.

18:38

So this is a 2 pass shell and tube heat exchanger here we're going to look.

18:42

So we're looking now from above.

18:45

So the vapour, in this case the steam will be entering from above the tube bundle or across the tube bundle either way and flowing through both sides and exiting on the left is a condensate outlet.

18:58

But I then if I'm trying my second heat exchanger to be my internal fluid is going to enter through the first shell side right is going to then transit across, flow around and exit back down the cool or the 2nd reservoir.

19:15

So what this is effectively giving me is that I'm directing the shell side fluids around two different passes.

19:25

So I initially have one approach as they first enter the tube bundle and the shell side fluids transit to the other side.

19:33

And I maintain a similar approach there when I compare it to my single pass before the shell side fluids are turned around and run the other direction, after which point I maintain a similar ΔT or driving force through this second pass.

19:52

So when I then apply this concept beyond just a basic shell and tube heat exchanger, but I'm applying it to the purpose of a condenser.

20:01

When we say condenser, what we mean is that we're taking either a saturated or a slightly super heated fluid.

20:08

And the purpose of the heat exchanger is to condense that into its liquid phase.

20:13

All right.

20:14

So for this reason, we remember back from thermodynamics, the amount of energy bound in the phase transition is usually extraordinary compared to the energy, the sensible energy of changing temperature back and forth.

20:30

So as a consequence, in designing these types of heat exchangers, if our purpose is to condense, then we need a system as efficient as possible because we know we're going to have to extract a phenomenal amount of energy out of this thing.

20:44

So to do that, let me grab my laser pointer here.

20:50

This would be our normal shell and tube heat exchanger.

20:53

We're just calling it a condenser because now we know one of the fluids we're using is a steam that's going to condense through this process and exit as a condensate.

21:01

Or if I put it into a 2 pass system right where I have here my cooling liquid that's going to take it on and then take that heat on and come back out at a much warmer temperature here I'm able to condense more efficiently.

21:14

Now the reason we call this a floating head is that I'm going to end up with a wide variety of material temperatures in the shell and tube heat exchanger itself throughout this process.

21:27

And as a consequence of that, I need to give one of the size of these Weir's the ability to expand and contract ever so slightly.

21:36

This is what this floating head looks like.

21:38

So you can imagine this left hand side that I'm highlighting here is bolted in.

21:45

Sorry, not bolted in, this is bolted to.

21:47

So part of this Weir is bolted to the tube bundle, but only on one side.

21:52

So as these tubes that are experiencing a wide variety of temperatures across the material itself, I'm going to get differential contraction and expansion in the tube bundle, which means I need to give it one side the ability to float a little bit so that I don't end up breaking the metal itself or or putting it such a thermal gradient across it that it breaks.

22:16

So we typically find that these single pass condensers, as we've said, because they're not optimal, they are also uneconomical, right, or sub economical.

22:26

So they tend to have relatively poor overall heat or convective heat transfer coefficients.

22:31

And then to make up for that, I end up purchasing a very, very large size.

22:36

So if they were uneconomical to begin with, just imagine when we start considering the emissions and cost of the materials used to manufacture them, they're going to get even more uneconomical over time.

22:46

And so we tend to then start thinking in industrial processes about multi pass heat exchangers or in the example of a 2 pass a floating head just as a design protection to ensure that we're not spending any unnecessary money or emissions on the process.

23:03

Now the reason we spent last slide talking about external convection in cross flow is that I can apply that same approach.

23:12

I can apply to a shell and tube heat exchanger with the exception that I do not need to worry about that F sub G correction factor, right?

23:22

I'm not worried because I'm directing the fluid in across both directions.

23:27

I'm ending up with an average heat exchange that's consistent with that Nestle correlation.

23:32

So that on slide 4 of this lecture, I can deploy that Nestle correlation to get the external heat transfer coefficient around each of these tubes.

23:42

And I know from my Adidas Bowler or Cedar Tate correlations the internal heat transfer coefficient that I can deploy to each tube.

23:52

OK, so now if we're deploying this as a condenser, and we'll come back in a few slides to talk about different types of condensers, but this is our classical 20th century steam condenser, right?

24:05

If we're trying to pull that energy back out.

24:07

And the reason why could well be because we've deployed steam as a part of our process and we don't want to be venting steam into the atmosphere.

24:16

We would much rather have a closed loop and so we need to do something to condense the steam to prepare it to re enter the beginning of our process plant again.

24:24

This is where we would get something like a shell and tube condenser from and we'll look at what a different type of condenser, which is wildly different that can do.

24:37

OK, so what's going to happen now if we invert this scenario and we start to think about our heat exchanger not just as a vehicle for condensing, but as a vehicle for boiling?

24:47

Well, there are a few different considerations we need to take, and the first is going to be what's the if we bring the whole fluid to its boiling point.

24:55

So this would be, say, water at 100° C.

24:59

The type of boiling that we're going to observe is dependent on the driving force for the boiling itself, meaning the temperature difference between the surface heating and the fluid.

25:10

So if the fluid is always going to be at 100° C, and thermodynamics tells us that because it's transitioning from a liquid to a vapor phase, in this case water transitioning from water to steam, then I'm going to have an option as an engineer as to how warm my heating surface is going to be.

25:29

Now these plots come from the caves, so they were done in the States, which is why we see Btus for flux and Fahrenheit for driving force.

25:38

For point of reference, of course, you know, 1.8 Kelvin in sorry, 1°F driving force is 1.8 Kelvin in driving force for differential.

25:48

So that allows us to do quick calculations, basically 2 to one.

25:52

So if we have a 10 Fahrenheit driving force, so if you go to something like 10 Fahrenheit in driving force, we would be looking on the order of say 5 to 5.5 Kelvin in driving force.

26:07

So the point of these regions that we're trying to tease out here is that more, more driving force for boiling, meaning a hotter heating surface does not always equal better or more efficient.

26:20

So we're going to break this into five regions for assessment, right when we're at from point A to point B.

26:26

And this right hand graph is just cutting it off so we can focus on this, this tighter region here.

26:32

But as we go from point A to point B, we're in a region of relatively low differential temperature where the heating surface.

26:40

So this would be the the bottom of my pot of water on the stove or the bottom of the tea kettle.

26:45

If it's one that heats from the bottom, you know, it's within say well within one to 10 Fahrenheit difference.

26:53

So again, 11 to about 5 Kelvin or .5 to 5 Kelvin driving force where my the heating or the boiling process, the heat transfer.

27:05

If I'm going to need to continually supply energy to boil off more and more water, well that heat transfer is dominated by natural convection within the liquid phase itself.

27:16

OK, Now we know from the past, you know, couple lectures in the reader sections, that natural convection can be very useful if we're trying to minimize cost or emissions profiles, but it also tends to be not very efficient.

27:28

And so if we're designing a process to boil and we're using a lot of heat energy to do that, we probably want to increase the efficiency past this point A to point B.

27:38

So that's more than say, 10 Fahrenheit of a differential driving force or differential boiling, a driving force for boiling.

27:47

So as we go from point B to Point C, now we're increasing from say 10 to on the order of 40 to 50 Fahrenheit driving force.

27:55

That means that in my tea kettle, the bottom surface is 40 or 50 Fahrenheit warmer than the liquid itself.

28:02

Or conversely, on the the stove, my bottom, the the point of the pot that meets the the heating surface, whether it's electric or gas, is around 40 to 50 Kelvin warmer than the the boiling fluid at 100° C.

28:20

So as I go to the left to the right on these plots, what I'm doing is adding or using rather more and more and more energy in the process whilst my liquid, because it's transitioning phase is remaining the same temperature.

28:34

So I'm creating a greater driving force.

28:37

So when I go from the region from point B to Point C, now instead of having just a few bubbles here and there that are emerging and the majority of that, that mixing and turbulence in the liquid driven by natural convection, now I get more and more bubbles forming from point B to Point C.

28:57

With each of those bubbles, two things can happen.

29:00

Now the bubble can collapse back into the liquid phase as it starts to rise, or it can survive and make it all the way to the very top of the gas liquid interface, which is less common.

29:13

So the formation and collapse of these bubbles is a really noisy business.

29:17

In fact, it's the same process that would have been discussed in fluid mechanics around gas cavitation and liquid systems, right?

29:25

We get a lot of noise when bubbles collapse back into liquid.

29:30

So is this is precisely why this is the region that our electric tea kettles work in.

29:35

This is why they're so noisy because I'm working at the point in which I'm producing a maximum number of bubbles and many of them are collapsing inward until the whole thing becomes highly turbulent.

29:47

And I'm in a, a region where I have bubbles constantly rotating through the system.

29:53

So at Point C where I'm sitting in about, you know, 4050 Fahrenheit and driving force is where I start to see that the local maximum in terms of the efficiency of the heat transfer process from that heating surface into the liquid that's going to constantly need energy to support its phase transition.

30:12

If I try to turn up the power right, whether I'm turning up the power of the electric kettle or turning up the amount of gas that's being combusted.

30:21

Either way, if I go beyond that point, I'm going to get a decrease in the efficiency of the overall heat transfer from the heating surface to the liquid that I'm attempting to heat.

30:32

And the reason why is that I'm the bubbles are forming quickly and they're turning into a jet.

30:38

So instead of the formation collapse of the bubble from Point C to point D, I'm getting an increase in the survival of these bubbles that form and eventually drag the.

30:51

So as the bubble forms, stabilizes, breaks off to go toward the gas liquid surface on the top, it's going to pull additional bubbles with it.

31:00

And so I get these local jets effectively that are going to form of bubbles that are supporting each other and dragging each other up from the heating surface on the bottom for the gas liquid interface on the top.

31:13

So from Point C to point D, this process we call transition boiling or or jet boiling.

31:19

And it begins a less efficient flux than if I were at the peak of that nucleic boiling where I get the loudest noise possible.

31:29

And point D is where it's going to inflect again.

31:32

And after that, I'm going to increase again in heat transfer efficiency, although whether or not I recover back to the original maximum of nucleic boiling depends heavily on the heating system, it's heat transfer characteristics and so forth from point D to point E, which I won't go into too much.

31:51

But this region is one that most engineers try to avoid unless we really have to work within it for for some process consideration.

32:00

And I should mention point D is what we call the Leiden frost point.

32:03

So above this Leidenfrost point, now my heating surface, I'm forming so many bubbles that instead of having a a constant formation and collapse or formation and and drag upward of the bubbles themselves, I'm able to to support a consistent gas pocket that's holding up that liquid.

32:27

It's almost floating the liquid on top of it.

32:29

I'm forming gas so fast that it's able to constantly be there and it's actually a buffer between the liquid that I'm attempting to heat right and the the heating surface itself.

32:44

So if I have a a small phase of gas that's acting as this kind of a lubricating pocket between the liquid on top and the the vessel in the heating surface on the bottom, that gas pocket or film we would call is now itself a new resistance to heat transfer.

33:03

So in the case of my stove, if I'm using a gas stove, I have to go from the point of combustion, right?

33:09

And I have a natural convection around that conducting through the metal.

33:13

Now I have to conduct again through a gas film and into or convect through that gas film before I can then convect the energy into the liquid phase.

33:24

So this is the reason why from point D to point E we can sometimes if we have a cleverly designed system or a highly efficient set of materials, we could certainly get a higher overall flux than was occurring at Point C.

33:37

So the the maximum nuclear boiling point.

33:40

Or we can get a decrease over quite some range of driving force where we get less efficiency because we're now having an additional heat transfer resistance that's emerged in the system in this film boiling region.

33:54

So the, the take home messages from this slide.

33:57

Then there's This is why our our electric tea kettles cause so much noise as they're first coming into boiling.

34:05

And in fact, you know you can, if you turn on the tea kettle from cold, you can hear it when it starts to get to the boiling point because it gets louder and louder, almost like it's announcing to everyone that it's about to begin boiling.

34:18

But the second of that thing transitions into now rapid boiling because it's it's warm enough that the driving force across it is putting it past the point of nuclear boiling.

34:29

The noise goes away and we get into transition boiling.

34:33

And we can hear if if we can't see through the kettle, we can hear in the kettle transition boiling as it's or jet boiling as it's happening because it sounds it's, it's quite a lower decibel noise, but it sounds quite turbulent.

34:47

And if we were to perform the exact same experiment of a pot of water on the stove where we can visually observe it, we would also see this behaviour going, you know, as the heating surface in ever increases in temperature relative to the boiling fluid.

35:01

We can watch this, this original domination by natural convection with a few bubbles transitioning to more and more bubbles forming and collapsing.

35:09

Now we tend not to get the same noise on the stove, largely because we're using combustion, which is deploying a heck of a lot more energy at that heating service.

35:19

So we're jumping past the point of nucleus boiling and we're seeing the rapid emergence and onset of transition boiling on the stove.

35:29

Now in an industrial process, then what we're thinking about for steam, we would deploy something like a shell and tube heat exchanger for the purpose of boiling.

35:41

And so this is one of the points that we want to drive home is that weaken our shell and tube design itself.

35:47

These are simply an idea of I'm going to have a whole bunch of tubes that are encapsulated in a shell.

35:54

I can drive it in One Direction and it becomes a condenser.

35:57

I can drive it in another direction and it becomes a boiler.

36:01

And so if we have something like a kettle or a kettle type reboiler here we would be looking at our heating fluid.

36:12

So this would be the steam, it would be flowing through the tubes and this would be exiting the system as two phase.

36:18

Our cool liquid is going to enter the shell sign.

36:20

So here's our liquid feed.

36:22

It's flowing through the shell sign and it's going to exit as a vapor on top.

36:28

Let's trace this through.

36:29

My steam is going to enter here and it's flowing through these tubes.

36:34

I have my same floating head design because I'm going to have a very high thermal gradient in the material, presumably metal, but the material across these things.

36:43

So I can see that floating head design showing up on the right exits these tubes into a second reservoir, turns around and flows back out, and I'm taking warm steam and condensing.

36:55

So it's the tubes themselves that are hot in this scenario as opposed to putting the steam on the shell side.

37:01

So around this hot tube bundle, I'm injecting a warm or sorry, a cooler liquid from the bottom.

37:08

So as this cool liquid comes up, it is occupying and let me see if I can, OK, I'll shade this in yellow hash marks.

37:15

The liquid is occupying A level here where we don't want to inject liquid so fast that it fills up the entire thing.

37:27

But if I grab my marker again, we're filling liquid to about the level and I can imagine it's a bit turbulent.

37:34

So it's bubbling up and down where it's sitting at this Weir.

37:38

So this Weir is basically a wall where where I'm I'm boiling.

37:42

So I'm getting a little nuclear boiling all over these tubes.

37:46

These tubes are causing the boiling in whatever liquid feed I have.

37:50

So as the boiling process takes place, I get a lot of turbulence in this upper region, meaning I can have some warm liquid spill over and that's where I get the hot liquid outlet from or can at the same time, the gas that emerges from this that boils is going to exit through the vapour outlet.

38:07

And so for the the hot liquid exiting, what I would normally do is put this through a blending process and mix it to turn it back into the liquid feed.

38:16

And this would then produce a system where I'm using steam or or another working fluid that's hot and I don't have to condense the steam, right.

38:24

It could be a super heated steam that's just going to enter, maintain constant phase, warm the tubes and back out it goes.

38:31

But I'm able to inject a constant rate of liquid feed and through a recycle system, I'm producing a constant rate of vaporized outlet, right?

38:43

So what makes this a reboiler and not a proper shell into the condenser is that the shell has this massive vapor space, right?

38:51

So I'm effectively the bottom half of this is what we would traditionally call a shell into the heat exchanger.

38:57

When I put this large vapor space on top of it, it becomes a reboiler, right, for the purpose that I'm able to collect that that vaporized material and and put it through the outlet without taking liquid alongside.

39:11

So if I then think about what's the effectiveness of heat transfer.

39:15

So this is again, the heat flux that you're just looking at as a function of the driving force.

39:19

The difference between this on average difference it would be and especially if I'm condensing steam, but between the surface of my tubes and the shell containing my liquid to be heated and this driving force is in delta degrees Fahrenheit difference.

39:37

Then I can see well, I might have a a single tube bundle or a multi tube bundle.

39:42

But effectively I can see the same phenomena emerging right where if I go from a very low driving force on the order of a single integers in in Fahrenheit difference.

39:53

As I increase past that point on the order of 40 to 50 Fahrenheit difference, I get a much more efficient system.

40:01

Until I hit a region of maximal efficiency, after which point I'm going to transition back downward in efficiency until I get the onset of film boiling.

40:11

OK, Now we're not going to be looking at re boilers in any of our labs, but again, both the reader goes into these and in particular the process around these.

40:23

So I'd really, really encourage, particularly by this week, everyone to have sat down and gone through readers chapters 6 and seven.

40:30

So the basics of heat exchanger design and the boiling and condensing process in particular.

40:37

If the design process around this is something that is uncomfortable or, or needs a bit of revision after heat transfer, then absolutely.

40:46

The the number one reference is the required unit textbook and the relevant chapters for basic heat exchangers are 10/12, 11:12 and 13.

40:55

And for the boiling and condensing systems, chapters 15 and 16.

41:01

OK, so let's look at two additional, well actually three final types of phase change systems.

41:11

And the first of these is a dehumidifier.

41:13

So in particular, if anyone's put a, a like a clothes dryer inside the house on a, a humid winter's day in Perth, you would have noticed that it's not particularly hard to cause it to rain inside the laundry room.

41:29

And that would be because we have such a high humidity in the air that we're able to condense that outward.

41:35

And so one of the fixes for that is to put a dehumidifier in the system that is effectively built to pull the water out of the air.

41:41

And this is water content that's been dissolved in the air.

41:45

So a dehumidifier operates effectively as a vertically oriented shell and tube system, right?

41:54

So I pull in my vapor.

41:55

This is if I'm using the analogy of a dehumidifier in the laundry room, this vapor inlet is the air in the room, right?

42:02

And the reason of course, in the laundry room that air has water vapor in, it's from the clothes dryer that's saturating the air that it pulls in with water from the clothes.

42:10

So quite an elaborate system to go from putting clothes in a washer where we draw water in to saturate the clothes and wash them.

42:16

We take them out of the washer when in the dryer to push that water content from the clothes into the ambient air in the room.

42:24

And then realizing that we should not be condensing and raining water in the laundry room, we'd have to put in a third operation of a dehumidifier to pull that water back out of the air and put it back into a liquid phase.

42:36

Now, instead of having these three operations independently, right, if we were trying to be efficient and, and conscientious about the approach, we'd probably use that dehumidified water as an inlet to our clothes washer, right?

42:48

And we can put the thing around and around in the loop, all of which is meant to, to take, take the dirt out of the clothes.

42:55

So this vapor inlet, this is the humid air from, in this example, the laundry room.

42:59

But it could be any process operation.

43:02

And as we put it through the system, we note that this vapor is warm, right?

43:06

So if I think about how do I get water vapor out of air?

43:10

Well, the number one way is cool the air down.

43:14

In fact, I can go to something like multi flash or another Thermo physical tool and I can plot the equilibrium.

43:20

So the saturated water content in vapor as a function of temperature.

43:24

So if 90% relative humidity RH, this means 90% of the potential water that I could saturate in air is present, 50% I have 50% of the saturated content, 10 percent, 10% so on and so forth.

43:41

So if I'm sitting at some place in constant temperature, if I get to the point that I'm raining or I see rain emerging in the laundry room, I'm probably upwards of 90 to 100% relative humidity.

43:54

But all three of these curves, as we can see drawn, are sensitive to temperature.

43:57

So if I can take that warm humid air and expose it to something colder, say down here, right, then the difference, let's say here is my cold water might be coming from atmosphere.

44:11

So it's sitting at 20° C, and maybe the air in my laundry room is warm.

44:17

So what I'm looking at the difference between these two points, imagine that those connected ones drop from the other way here.

44:25

So the difference between these two points is what I can then extract back outward, right?

44:33

It's the delta relative humidity.

44:37

This is what I can pull out of that humid air.

44:40

So the way that we're going to do that is by exposing the warm air to a cool system.

44:45

So this vertically oriented shell and tube exchanger pulls that warm air in, containing this water vapor, and pulls in liquid water that's much cooler.

44:54

So the liquid water is going to flow.

44:56

In fact, let's draw this out here.

44:58

It's going to flow sequentially through each.

45:02

In fact, I should use a blue color to indicate the cooler water it's going to flow through each of these shell sides, right, to basically maximize the efficiency of the heat exchange process that we would have seen up until now.

45:20

And the warm air that flows in here is going to transition downward and flow through each of the tube internal tube bundles.

45:27

So it's going to make its way and cross with this air as, I'm sorry, cross with this water as the water's heating up.

45:34

And in the process it's going to cool this warm vapour down.

45:38

So when I cool the vapour down, I get the emergence of liquid water that's this Delta H or Delta RH right here.

45:46

So this liquid water is going to right make all its way down here and exit as a condensate on the bottom.

45:55

And we're just putting in here a very simple Ducantin design allowing the water vapor or

sorry, the result, the remaining water vapor or remaining air containing much lower humidity to be exited out of the system.

46:09

So most of the types of household dehumidifiers we would use, oh, I and I have drawn, sorry, I have drawn that water going in the wrong direction.

46:20

Water's going to come in from the bottom here.

46:22

So we're operating in counter current, right?

46:25

And it's going to make it swift to the top of the outlet.

46:27

Sorry.

46:28

So most of the the household type systems that we would observe are going to take a step further and they're going to use this condensate outlet as a recycle to the water inlet.

46:39

So they're going to connect this water inlet and condensate outlet, basically meaning that we're going to use the water we've already condensed as a vehicle to condense more water and therefore not require an open system that's connected to water.

46:52

If I were deploying a dehumidifier in a process plant, I may not be able to operate with that type of recycle system as a primary.

46:59

Like sure, I could use the condensed water as a a partial, but I may need to use a feed system to push this water through at a fast enough rate.

47:10

So thinking about condensing for a minute then, right, We've seen two different approaches.

47:14

Either I can use a big shell and tube heat exchangers.

47:17

That itself is kind of the size of a car.

47:20

Or if I'm thinking of a dehumidifier, I'm going to basically take that shell and tube heat exchanger and turn it 90° vertically.

47:27

But they're both operating on the same point, right?

47:30

The, the, the condensation process, whether I care about humid error, right?

47:36

That's in the presence of sorry, high humidity error that's going to be contacting cool water or some other kind of condensation process from a different material.

47:46

I'm still using a variation of the same shell and tube heat exchanger, So there's one more type of heat exchanger that I can use for condensation that is in an entirely different design principle, and that is a contact condenser.

48:02

So these are smaller and cheaper than shell and tube systems by a country mile, right?

48:08

These are very, very efficient designs and they're elegantly simple in their execution.

48:14

The approach is that I'm going to take some vapor here that needs to be condensed and I'm realizing that well and and I can deploy these contact condensers if and only if I do not mind I have chemical contact, meaning intimate chemical contact between both of my working fluids.

48:34

So the vapor to be condensed and the liquid water or liquid, whatever that's going to condense it.

48:40

If I have no problem from a an environmental safety hazard standpoint contacting these two things, then I can do a heck of a lot better than a shell and tube design by using a contact condenser as this vapor enters from the top of the system.

48:55

And I can imagine, and here I'm going to put this in red, this water in, I've shown it as a water, but it could be any inlet liquid is sprayed through a nozzle.

49:05

But these nozzles are arranged around the entire circle, the entire circumference of the vessel.

49:12

So they're spraying and aerosolizing water into all of these droplets here.

49:18

Now, the net effect is that I have a cool liquid.

49:22

It can be water, as in this case, or something else.

49:24

I have a cool liquid with a very, very high surface area, right?

49:29

If I aerosolize a coffee cup of water, I could create thousands of square meters of surface area.

49:36

All right or sorry, not aerosolized, but disperse as a small aerosol, meaning not to aerosolize as in to vaporize.

49:45

So if I turn this even a standard coffee or teacup into an aerosol, meaning a small dispersion of liquid droplets, I can create thousands of square meters of area just from one coffee cup.

50:00

Now if I'm my, if the liquid that I'm spraying is quite cold relative to the warm liquid that's entering, I am going to rapidly cool down the vapour inlet.

50:14

So as this warm vapour containing a liquid to condense contacts this incredibly high and cold high surface area that is very cold, I get the condensation process happening immediately here.

50:28

And so naturally, I'm going to have some amount of air that's exiting out of this thing, and the liquid that's flowing down from this, I'm going to use a little additional liquid.

50:38

Now again, this is shown as water, but it could be anything, but I'm going to use an additional amount of liquid to plunge that downward as a jet and force this out.

50:47

So the process of this liquid jet plunging downward, as we can see diagrammed here, means that I create a natural vacuum on the bottom side of this vessel that draws more vapor in, right?

50:59

And in fact, if I've designed it correctly, minimizes the amount of pressure I need to put in those aerosolizing liquid jets or water jets, as we've shown here.

51:10

So these contact condensers use the an intimate, I call it an intimate chemical contact because if we're not careful, we need to be very aware that using this means we're going to exchange mass, We're going to exchange chemistry between whatever liquid is sprayed here and whatever vapor is drawn in and subsequently exits on the right hand side, right.

51:32

So if we have any propensity for say if the liquid is going to contain a contaminant or the vapor, we need to appreciate that use of a contact condenser is going to cross contaminate the system by the time we're done.

51:45

But these are much simpler physic, well complex physics yielding a much simpler construction and operation where the one constraint is that we have to be careful of chemical contact.

51:59

And then finally we want to look at can we take that same kind of clever approach of a contact condenser?

52:06

Well, are there any variations to the approach of boilers or another parlance of the evaporators that we can use?

52:14

And this is what's called an agitated film evaporator.

52:19

So if we imagine here on the the right hand side now this motor is just meant to rotate.

52:25

We'll come back to in a minute to what this rotation produces.

52:29

Let me grab my mark here so that the feed that we're trying to vaporize is entering here and I can see this is going to enter into the center channel of the vessel right now.

52:41

Remember, if we're vaporizing this, the idea of an agitated film evaporator is that we can make further use of the density difference between a liquid and its equilibrium vapor.

52:57

We know the vapor will always, always, always have a lower density.

53:02

So we can use that to our advantage.

53:05

And as a consequence, as we inject this liquid to be heated, well, if I have steam flowing through this jacket here, right as this liquid flows downward, it's going to be warmed by the steam jacket.

53:19

And in fact, if I'm rotating this system here through a central shaft, I can see that same rotation is going to pass down through each of these blades.

53:28

It's going to to flick that liquid to the outside so that it's in intimate contact with a steam Jack.

53:36

Not intimate as in chemical contact, but intimate as in they're at the same solid interface.

53:44

So it's this centrifugal motion, the same principle that we started with at the very, very beginning of lecture one, that's going to force all of the liquid droplets in my system to the wall, at which point they vaporize.

53:57

Well, as they vaporize, they're going to rise, right?

53:59

They're they're much less dense than the liquid.

54:02

And so this warm vapor turns around and it's going to migrate upward through this system before it's collected here and exits through the top.

54:12

Meanwhile, the steam that entered right through the bottom is going to then turn around and as that steam condenses downward, exit through the shell side as a condensate where any residual liquid that's not vaporized exits as what McCabe's parlance calls a concentrate versus the condensate, meaning that I've vaporized.

54:38

If I have a multi component system, I have vaporized some portion of the feed inlet and thereby concentrating the remaining chemistry in the resultant liquid phase.

54:49

So you might wonder to yourself then, OK, well if I were to try to calculate a heat transfer coefficient for this evaporator, how on earth can I do that given I have centrifugal motion to think about?

55:00

I have droplets that are being spun around and forced toward the wall, right, that are being broken by the turbulent field or by the turbulence of this rotating motion.

55:11

And the, the approach then is shown is an estimate of the internal heat transfer coefficient for this, this.

55:19

And we would use this for something like a viscous fluid, right, where we, we can't put it into an average reboiler because it's not going to be able to, to heat up quickly enough and it's not going to move around with the right natural convection.

55:32

And so this, this internal heat transfer coefficient we're going to use will depend on the same Thermo physical properties we've come to appreciate.

55:39

So the thermal conductivity, the density and heat capacity, But we now also incorporate the number of blades, so the agitator speed N and the number of blades, right?

55:49

And Π is obviously the correction factor or the fact it's circular and rotating.

55:54

So we can use this approach if we know something about the number of blades or the where we set design the number of blades and the agitator speed to produce a relatively effective heat transfer coefficient, convective heat transfer coefficient for these vaporators.

56:11

OK, so that's the the last bit of content I had here.

56:15

So the, the take home message we're trying to instill then is that most of the time what we will use is a shell and two heat exchange, right.

56:24

Well, there are the shell and tube heat exchangers and there are the plate type heat exchangers.

56:28

The the very reason I don't go into depth and plate type heat exchangers as I appreciate Professor Huitong does and heat and master ONS.

56:36

So I'm trying to spend more time on shell and tube heat exchangers.

56:38

So you can appreciate the diversity of these applications of course, right.

56:43

We would see both plate type and shell and tube heat exchangers showing up in a majority of chemical engineering unit operations or process plants.

56:52

And I know Professor Kuatong has gone through the advantages of plate type heat exchangers.

56:56

These are excellent for small applications, small businesses, you know, where we're not working at like a a, you know, city scale process plant, but maybe something where it's a, a small startup and we need a highly adaptable, you know, very, very versatile system of heat exchange.

57:16

When we get into the larger process plants, we tend to be dominated by shell and tube type designs.

57:21

Now these can take the form of where I can deploy these designs for the purpose of simply transferring heat between two phases that remain constant for the purpose of boiling or the purpose of condensing.

57:35

And in either one of these limits, I can look at manipulations to the boiling and condensing system, right?

57:40

Things like a dehumidifier that allow me for some of the niche applications we've talked through.

57:47

So the purpose of this lecture and it's adjoining reader chapters is to ensure that you're comfortable and that you exit with a degree of comfort around the types of heat exchangers that can be possible, right?

58:02

And, and where these tend to fit in the types of applications, they're appropriate for the, a portion of the reader chapter, but it's really within the laboratory materials and the critically, the required unit textbook for this section is where you'll get a lot of the, the great detail on if you wanted to design A shell and tube heat exchanger from scratch.

58:25

Right now, we're not going to be doing much of that in our lab because we're more focused on the performance and characterization in comparison to ISIS.

58:34

But this is one of those reasons that I recommended if you plan to go out and be a chemical engineer, right, that working for the next 40 years in the field, having McCabe's textbook is an incredible resource to have with you, right?

58:49

This is a very, very useful book because it will walk you through the detailed foundational design process for each of these types of heat exchangers.

58:59

Have a wonderful rest of your day, everyone, and we'll see you in the next lecture.

59:03

Take care.

Lecture 05

0:10

OK.

0:11

And welcome to lecture #5. From here on out, we are now transitioning into the mass transfer unit operations of which we're going to look at three.

0:22

And part of the reason why the class of unit operations is biased toward mass transfer is that you would have had more experience on heat transfer operations from thermodynamics and the heat, the class heat and mass transfer.

0:36

And we've revised that with one additional laboratory assignment in heat transfer.

0:43

So really what our purpose here then is to look at 3 distinctive mass transfer operations that are found across the spectrum in chemical engineering process plants.

0:56

And we're going to in each of these labs look at at really cool applications of mass transfer unit operations that power a majority of the modern materials liquids vapours that we deal with.

1:11

These are the operations that are really sitting at the core of most processed plants.

1:17

So each of these three, well as we go from absorption AB, so absorption first that is the simplest of our three mass transfer operations.

1:31

Distillation is a level up in difficulty, but both absorption and distillation preferably operate at steady state.

1:43

And so for that reason, they are both easier to deal with than adsorption ad, because adsorption operates with time dependency.

1:54

And So what we're doing is starting with the simplest of the three and we're going to frame our discussion of mass transfer operations around that.

2:02

Then in the next module, we will progress to distillation, which is effectively what we're going to see multiple absorption systems put together.

2:13

And then we progress to absorption, where things are going to be changing in both space and time.

2:19

OK, so to start our module on absorption, we're going to look at two different lectures.

2:26

So lecture #5 now I flipped these around a little bit because I appreciate to begin this module, we're beginning the absorption lab.

2:34

And so I want to make sure up front you have the key design parameters that power absorption columns.

2:41

And then in lecture number six, I'm going to back up a little bit and try to revise and refresh and make sure we're comfortable with where do these mass transfer foundational concepts come from.

2:52

If we take it all the way back to thermodynamics so that we can look at a bit more of the practical considerations around mass transfer before we progress to the more elaborate systems.

3:02

So for this lecture, we will be going through the basics of how an absorption column works.

3:08

This is now related to Chapter 8 in The Reader.

3:11

This is a summative kind of revision of general mass transfer.

3:15

And Chapter 9 in The Reader is all about absorption.

3:19

So particularly to begin this lab, make sure that you've had a chance to if you weren't comfortable with mass transfer in full.

3:27

And to be fair, I wasn't as a student, it's one of the hardest concepts that we can teach in chemical engineering.

3:32

Chapter 8 hopefully is able there or there to hopefully able to provide a bit of revision through that that content.

3:39

But Chapter 9 is really the meat of this module of where we're going to get to and how we work on the Latin together.

3:45

OK, so we're not going to go into the detail behind mass transfer coefficients in this lecture.

3:55

That's what our next lecture is going to be approaching.

3:59

But the take home message is that instead of using something like mass fluxes, our mass transfer coefficients are a general representation of the ease with which we can transfer mass between phases or the ease with which a particular component is going to transfer through phases.

4:22

So the mass transfer coefficients are also referred to as MTCS.

4:28

We will use K_X and K_Y .

4:32

So X representing my liquid phase and Y representing my vapor phase.

4:38

Now for both absorption and distillation, our phases of concern are liquid and vapor together.

4:46

We're transferring mass between them and we'll look at both in this lecture and over the coming few weeks why that is such a necessary thing to do and how we can leverage that to really solve really common societal problems.

5:01

The mass transfer coefficients are a generalization of the overall mass transfer process, right?

5:08

So they are accounting for a number of factors, which is why lecture number six is going to come back and delve deeper down into to what they physically represent.

5:18

The mass transfer coefficients themselves much like, and you can almost think of this as a proportionality to a convective heat transfer coefficient, right?

5:27

It's a balance of the volumetric diffusivity.

5:30

So the ease with which I can diffuse mass or diffuse material through a volume relative to the distance with which I'm trying to diffuse that mass through a volume.

5:43

So we give these little K terms, my mass transfer coefficients.

5:50

These are the objective of our calculation, OK, now, And we'll look at an example later on of where these come into play.

6:03

Just like with heat transfer, right?

6:06

The difficulty that we have is in taking a complex system where we're thinking through the thermal and the hydrodynamic boundary layers, the properties of the fluids, the type of material, the nature of the convection.

6:19

And we're trying to turn that into a convective heat transfer coefficient.

6:24

And the reason that we like these types of correlations, frankly, is that we can put them together in a spreadsheet and then we, the engineer can run a whole variety of cases very quickly to say, well, what happens if I use different material or if I turn the velocity up over here or I change the temperature there at the inlet, I'm going to get a different heat transfer set up.

6:44

We want to take the same elegant approach to solve mass transfer problems.

6:49

And the way that we're going to do that is using Sherwood correlations.

6:53

So Sherwood correlations and these are given or the Sherwood number is capital SH.

7:02

So the definition of the Sherwood number is shown here.

7:06

This is defined as the mass transfer coefficient.

7:11

So this Sherwood number is defined as the mass transfer coefficient $K_{sub C}$, right?

7:19

And so this little K_C is what I'm trying to get out times the D , the characteristic length of the system.

7:27

So in this way, it's it's analogous to my use of h or my analogous to my use in heat transfer.

7:35

And but it's divided now by $D_{sub V}$ So this is the volume D_V is the molecular diffusivity of the system now.

7:45

So I can appreciate this, this K_C , this mass transfer coefficient, this is the objective that I'm trying to get to delete that.

7:53

So it isn't.

7:54

And the way that we're going to do that is it's going to take the same form.

7:59

We're going to look at a a variety of correlations for the same types of applications that take the same form as the Nestle correlations.

8:08

And in some ways, we're actually going to see the very same bounding behavior emerge from them.

8:14

So in general, my correlation for Sherwood numbers will look like some pre factor here, I'll call it C times the Reynolds number to the power some power A .

8:26

But now instead of the Prandtl number, because again the Prandtl number is defining my heat transfer characteristics.

8:35

Now I'm going to employ the Schmidt number.

8:39

OK.

8:39

So the Schmidt number fundamentally is representing the momentum diffusivity.

8:45

So that's the momentum of the flowing system of the fluid dynamic momentum relative to the molecular diffusivity, right.

8:55

So I'm writing this here as dynamic viscosity divided by density times molecular diffusivity.

9:02

However, I could equivalently write that Schmidt number as the kinematic viscosity, the Greek letter small ν divided by the molecular diffusivity.

9:13

So the Schmidt number represents an analogue, a mass transfer analogue to my Prandtl number.

9:19

So Reynolds number stays the same again, because This is why fluid dynamics is a foundation for unit operations, because we're in flowing systems.

9:28

I'm again have the same power of the Reynolds number and a pre factor, but now I'm replacing the Prandtl number with the Schmidt number and the result of such produces the Sherwood number.

9:39

OK.

9:39

So the goal that we're going to start looking at and we're going to firstly focus this in pretty clearly on absorption columns and look at the correlations in the approach for them.

9:48

But over the coming next lecture, we're also going to look at a variety of correlations for this Sherwood number to help me predict mass transfer coefficients.

9:59

So an absorption column right?

10:01

Now in the first couple lectures, we were talking about a packed bed, right?

10:06

And if you recall lecture two, we went through the process of what does a packed bed material look like?

10:12

Why do we call it a packed bed?

10:14

And what are the different states that it could occupy?

10:16

So if I was taking a, you know, if we go back to the, the idea of Ottawa sand, right, and I have Ottawa sand packing through this bed and I'm blowing air up from the bottom.

10:26

Those were the examples we were looking at where the faster that air flows through the bottom of it, I can hit a point of minimum fluidization where those particles begin to rattle and they're effectively floating on air as opposed to transmitting their stress directly through each other.

10:42

And if I continued increasing that air velocity, I would hit different conditions of fluidization.

10:48

So an absorption operation is the same concept.

10:52

It's the same approach, but now instead of one fluid phase, in that case the air, now I have two.

10:59

I have air and I have liquid.

11:01

Or more generally, I have a vapor and I have a liquid of interest and or sorry, a vapor of interest and a liquid of interest.

11:10

And I'm using the nature of the absorption or absorption column and apologies in advance because I will occasionally talk too fast and my tongue gets tied between ADD and absorption.

11:21

So the absorption column that is very simply a cylindrical column containing a whole bunch of packing material, right?

11:30

We show with this little cutaway here because it can be of any length of interest, right, depending on how much material we have to transfer.

11:38

And we'll come back to why that can get very large very quickly in terms of the size of these columns.

11:45

So now what what differentiates this absorption column from what we were looking at with a fluidized bed is that we have two fluid phases.

11:54

One is a vapour and one is a liquid.

11:57

Now, just like we were looking at before, we take this packed section.

12:00

Now the first choice the engineer makes is what is the material I want to use in this packing?

12:05

Right Here are the ratchet rings that we looked at before and you'll remember the barrel saddle.

12:11

It kind of looks like a saddle or a manipulation of a saddle that would be across for a horse.

12:16

We also have different types of ring systems that we can put in.

12:20

So this is a take off on the ratchet rings, but we have internal internal portions to the ring that help break up flow across it.

12:28

So this can be metal versus plastic, but effectively a variety of materials can be used.

12:34

And these Interlock saddles are a take off on the barrel saddle that has a slightly different geometry meant to produce more fluid turbulence locally, right?

12:43

And they also can come in a variety of design manipulations and materials.

12:48

So I, I'm going to pick a packing material now for the purpose of our lab, we're using ratchet rings, plastic ratchet rings.

12:55

These tend to be quite simple, right and quite cheap to use in early versions of of the world's first absorption columns, we would be using autosan, right?

13:06

It's a very controllable, it's, it tends to be chemically inert for most things and provides a relatively consistent design basis to work across.

13:16

And in fact in the, the Preheat design of absorption columns before they were well

defined, we would just use a rock dump, right And put a whole bunch of rock packing through this column and use that surface area for our purposes.

13:28

But you know, we now in a chemically controlled environment would be a bit more judicious in what we're choosing.

13:36

So the engineer would first choose what's my packing material.

13:39

So I put this packing, I choose my packing material and alongside that choice is a choice around the diameter and height of the overall packed section.

13:49

So how much surface area do I want to use?

13:53

Gas is going to flow in through the bottom and being buoyant is going to bubble up through this packed section liquid.

14:02

And so the gas will exit and flow out through the top.

14:05

The liquid will flow in the top and there will be a little spray system here that's going to call it a distributor, but it's basically a whole bunch of spray caps.

14:12

So it's going to spray this liquid downward the whole point.

14:16

This type of system is built to maximize surface area.

14:20

Therefore, we want to start with the the most optimal condition.

14:24

If we distribute the liquid as droplets flowing downward through the pack section, the liquid will then coalesce in this this bottom reservoir and flow outward.

14:37

OK, So the purpose of my absorption column is to provide a system in which I have a large and controllable interface between two fluids.

14:50

That's it.

14:52

That's the absorption column.

14:54

It's 150 years old and it's in.

14:57

Yeah.

14:58

We'll get to what's next in a minute.

15:00

So the question for the chemical engineer is then what I need to do is figure out when I bring my 2 fluid phases together, what's going to happen, right?

15:14

I have one liquid and one vapor.

15:15

In this case, what's going to happen when I contact this liquid and vapor?

15:20

Chemically contact, intimately contact, meaning I'm going to have the ability to transfer mass between them.

15:28

Now if we go all the way back to thermodynamics, we can sit back and think about, OK, well, if that liquid was already in equilibrium with its vapor and I'm using, let's say you know of my simple flash vessel, maybe I've vaporized ethanol.

15:44

So I have an ethanol vapor space and an ethanol liquid space and I'm in a two phase flash.

15:51

If I brought that system to thermodynamic equilibrium and then put the liquid and vapor across an absorption column, should anything happen?

16:01

And the answer is absolutely not because thermodynamically I have already brought the liquid and vapour to its equilibrium point.

16:10

And so as a consequence there is no Gibbs free energy driving force.

16:15

There is no chemical potential driving force within this that's going to allow molecules to migrate from one phase to another.

16:24

So when I employ an absorption column, the first thing I need to think about is OK, I need to make sure my liquid and my vapor are not already at equilibrium with one another.

16:37

And if they are not, then the degree to which they are not in equilibrium.

16:42

So the degree to which they're out of equilibrium.

16:45

That is another way of saying the chemical potential or Gibbs free energy driving force for mass to move between either from one phase to another is going to dictate not only how much mass is going to change phases, but how quickly, right?

17:01

The further out of equilibrium these two different phases are with each other, the faster my initial rate of mass transfer.

17:09

So where does this start to come into play?

17:13

Well, you probably would have seen, I hope you would have seen in the news, especially over the past few years, the significant funding that's going into what's called direct air capture or DAC systems for emissions control.

17:28

And there are a few sci-fi films that are TV shows that have done a fun job kind of looking at a potential future of scaling these up on a a very large, large scale.

17:37

I think Peripheral was one where in that TV show they had direct air capture or DAC systems that were something like 10 times the height right of the Empire State Building.

17:50

And we're going to come to why as we go through the absorption design process.

17:54

But effectively, if my goal was to remove CO₂ from the air, right?

18:00

And so we're sitting at somewhere north of 350 PPM, if my goal was to remove that, I need to contact that CO₂ rich air with a liquid phase in which the CO₂ molecules would rather be.

18:16

Now, the nature of thermodynamic equilibrium is such that I don't.

18:19

I can't assume I'm transferring 100% of the CO₂ molecules, right?

18:25

Unless my liquid phase is which one in which the CO₂ would absolutely and always want to be instead of the air.

18:34

And that's not the case, right?

18:36

I will never be able to fully strip CO₂ from air, which means I have a partial driving force.

18:43

So if I take liquid water and I contact it with CO₂ rich air, there is a fraction of the CO₂.

18:51

If I say that there's three, let's say we take on on a very small basis, there are 350 molecules of CO₂ in the airspace.

19:00

Well, somewhere something more than one and less than 150 of those molecules is

going to want to be in the liquid, depending on the type of water that I choose and the temperature and pressure to which I'm operating, right?

19:15

The higher the pressure because CO₂ has a much lower vapour pressure than nitrogen or oxygen.

19:21

So the, the higher the pressure I operate at, the more preferentially the CO₂ is going to want to drive into the liquid, right?

19:28

Because it has the lowest vapour pressure of the three components in the air I'm considering.

19:34

So in fact, direct air capture systems as they're now being wide scale funding, I think Norway took a huge investment in the past year.

19:43

These are large, large, large absorption columns.

19:48

All right.

19:49

And there's a really fun exercise we can go through to think what we're going to do in our lab together is a pilot scale direct air capture system, right?

19:59

And one of the things we want to look at is if we were to take a large investment and build a very large unit operation, what would it take to make up for the emissions of Perth?

20:10

How big of a system would we need to to build?

20:13

And in fact, the result is exactly the scale of system that, if you've seen the TV show *Peripheral*, is exactly the scale of system shown in that TV show.

20:24

It is something like a number of integers of the Empire State Building in its size.

20:30

So this is a very tractable problem and one in which, you know, right now we're using relatively inefficient liquid phases to capture the CO₂, which is why we don't get as good of an uptake.

20:41

But even if we could capture 99% of the CO₂, we're still talking about really, really, really big systems, OK.

20:50

Now I can also envision absorption from a different angle and that is post or as a post, well post process unit operation applied to a process that's creating a very CO₂ rich gas phase.

21:07

So if I have something like a combustion system where I'm producing not 350 PPM CO₂, but I'm producing 50% or more CO₂ that I can concentrate in my gas phase, then all of a sudden absorption becomes extremely attractive, right?

21:24

Because with a little bit of pressure and the right choice of liquid, I can pull most of that CO₂ out.

21:31

And if I were to stack multiple absorption systems back-to-back so that the exit of one is the entry to another for the gas phase, then I can sequentially strip CO₂ directly out of that vapour phase.

21:42

And this is one of the key technologies that will be persistent over the coming 100 years.

21:47

There is no doubt around CO₂ capture and the innovations to be taken, right?

21:53

Not so much in the packing material, right?

21:57

We've even though we're just turning the page on AI now, we've experimented with pretty much every variation of packing material and geometry that we can think of.

22:06

It's really in the chemistry of the liquid.

22:09

That's where we're going to start seeing some really cool progress in my personal opinion.

22:14

OK, So the purpose of what we're trying to look at then is if we want to design a system to pull, and usually we'd want to pull a toxin out or a negative byproduct.

22:24

So CO₂ is the most common example, but H₂S, right?

22:28

As chemical engineers, we must be familiar with H₂S and its toxicity.

22:33

One breath of 100 PPM H₂S is instantly lethal and instantly on the order of 10s of seconds.

22:40

So when we work with systems where sulphur is present and we risk having chemical reactions, we must always think about is there a possibility that any H₂S can be evolved from this system?

22:53

And if it can, we must take not just one, but multi layered precautions to prevent that from happening.

23:00

And if H₂S is evolved, perhaps that's an intended byproduct.

23:04

We need to to, we'll use something like an absorption column to capture all of it.

23:10

OK, So the purpose of our lecture today then is to get deeper into how do we design, size and operate this absorption column, right?

23:21

Our choices as engineers, as we've talked about the packing material and it's, it's overall dimensionality.

23:28

We usually the gas is the thing we're working on, although technically that is a choice.

23:34

So our real choice is the liquid, the liquid, it's flow rate in the packing section or the packing material.

23:41

So the liquid and how it flows and the packing material and how much there is.

23:45

So those are the two domains that we would typically be able to control.

23:52

Now you would have remembered when we talked in Lecture 2 and we were going through the Ergun equation, right?

23:59

And this contains some insight around pressure drop across this packed column because if we're going to be using our gas phase and injecting it into the absorption column, we had darn well make sure that we have enough pressure to drive that across the entire column, right?

24:14

We don't want our our gas phase molecules to slow down and more or less come to a stop at halfway through the column because then all of the money and time we've spent on the second-half of the column or the the 2nd 50% becomes useless.

24:29

So we need to make sure that gas enters with enough momentum energy to make it all the way through.

24:34

And if you recall, what were the characteristic things we had to think about?

24:39

Well, the first was the the effective characteristic length.

24:43

So these are the nominal sizes, right or characteristic length of different types of packing materials.

24:49

So ratchet rings would be the common one that we're using in our labs.

24:54

This is its total surface area in feet squared per feet cubed, which we can quickly convert to meter square per meter cubed.

25:01

The porosity of the material, this is epsilon.

25:04

So this is the same kind of void fraction that we looked at in the Ergun equation and the packing factor.

25:11

All right.

25:11

And these packing factors are effectively giving me a reductive view of what is that overall porosity in surface area.

25:20

So I can find a table like this in the class textbooks in the Caves 7th edition, but I can similarly, right if I'm going to go to a material vendor, all of these properties are readily provided by material vendors simply because they're trying to sell their packing materials.

25:39

And this is what they have to provide the engineer with for the engineer to decide is this the right packing material for my application.

25:47

So with these properties, I'm able to successfully calculate the pressure drop across the column through the Ergun equation, or conversely, through its components, the Cosini, Carmen and Burke Plummer equations, depending on what velocity I'm operating at, all, right.

26:03

And when we do so, we need to think about, well, how does the nature of flooding change, right?

26:07

You were worried about early on if we only had one fluid phase, we had to be real careful not to let the system flood.

26:14

Well, now what's going to happen if we have two fluid phases, 1 liquid and one gas is how does that change the nature of flooding?

26:22

OK, so now what we want to look at is an example of how this this plays out for A1 inch interlock system.

26:32

So first and foremost, I need to think about the relation of pressure drop, right?

26:36

Because I no longer have a single phase and a single, a single fluid phase and a single packing material.

26:43

Now, in fact, I have two fluid phases.

26:47

So we're going to start by considering this dry line.

26:51

Let's see if I can highlight that there.

26:53

So with this dry line here, we're looking at the pressure response of the system.

26:58

And this is in inches of water.

27:00

So it's a different measurement of pressure, kind of like millimetres of mercury, inches of water per foot of height and packing material.

27:10

So the dry line is going to give me an indication that would be consistent with the Ergen equation because I have only one fluid phase present now and I can see in in log, log space, this returns a linear correlation or a linear behavior.

27:31

As I start to increase or as I start to inject liquid in the absorption column, I think what should happen?

27:41

Well, as I, as I first put liquid across it, my pressure drop's going to start increasing, right?

27:48

And it's going to start increasing because I'm now have more things that that gas has to flow past before it gets to the exit.

27:56

More interfaces means more friction, means more pressure drop.

28:00

So if I'm starting with something like 2000 lbs per foot squared per hour of air mass velocity, all right, I can, I can see here I need something, I'm going to get something between 1.5 and two inches of water per foot of packing material.

28:15

In terms of the pressure drop is that dry line.

28:18

Now if I start adding liquid spray to the top of that adsorption column, so just a little bit to begin with, you know, maybe one 100th of my air mass velocity, I'm not initially going to really see a departure from that dry line.

28:34

Now, if I zoomed all the way in, I would see that the actual operating pressure drop

curve is going to pull off the dry line ever so slightly, but it's still going to retain this linear feature in log log space, right?

28:48

So in fact, the more liquid I add, it's going to continue shifting that dry line to the left, but it's going to retain linearity.

28:58

At some point, I'm going to begin seeing a departure in the pressure drop profile from linearity.

29:05

And again, it's linearity in log log space, which I appreciate is not convenient.

29:10

At some point I put enough liquid in that I see this departure behavior from linearity and I'm going to start seeing right this curve starting to show up.

29:21

And in fact the severity of the curve.

29:24

If I go from 3000, this is a liquid mass velocity of £3000 per foot squared per hour.

29:30

If I go from there to £30,000 per foot squared per hour, I can see that the severity of that curve in log log space is increasing.

29:41

So the initial departure point at which this thing pulls off the dry line in terms of its linearity we call the loading point.

29:50

So what does this loading point represent?

29:53

This is the point at which I now have all of my, well, majority, presumably all we're going to assume all of my solid surface area coated, right?

30:04

And let me grab a blue color here, but coated in a very thin film of liquid, right?

30:14

So now with that thin film of liquid I across all of my solid surface area, I now have achieved a condition of maximal mass transfer between the liquid and the vapour phase.

30:32

Now, if I increase the liquid above that or into the liquid mass flow rate above that, I am going to start seeing a condition in which that thickness of the liquid film is going to increase.

30:44

So the height of the liquid film is proportional in this.

30:48

As I approach the loading point and go beyond, it is proportional to the amount of liquid flow through the system.

30:56

OK, now I can go too far, right?

31:01

The principle of mass transfer that I'm exploiting is that I have some concentration Y sub I right in the vapor phase.

31:11

And so I being the component that I care about in vapor.

31:14

And there is a concentration profile that is mirrored and reflected in the liquid phase.

31:22

I shouldn't say mirrored, it's reflected in the liquid phase, but its concentration profile is different.

31:27

So the thicker that that liquid film is, A , the more of my target component it can take, but B , the more time I need to give it to become fully saturated, right?

31:41

So there is a, a sweet spot in terms of I need to be at the loading point to ensure my liquid or my solids are fully, you know, loaded with liquid.

31:51

But if I put too much liquid in, then eventually the thickness of that liquid film, in this case the way I've drawn is H_2O , but the thickness of that liquid film can become large enough that eventually the entire packing material locally becomes filled with liquid.

32:12

So as I've illustrated here, this could be, you know, of three spheres.

32:16

This would be liquid imbibing all three spheres.

32:20

So when that happens, we call that flooding, right?

32:24

By the just definition of the word flood, we have created a local area in which there is far too much of the liquid and we've not distributed it evenly across the system.

32:35

And this is occurring either because my gas phase is not flowing fast enough or I've chosen to put too much liquid across for the gas phase that I do have there.

32:46

So flooding represents a condition of inefficiency in our system, right?

32:52

It's a condition in which we're not optimally transferring mass from the vapour to the liquid phase.

32:59

Now prediction of the pressure drop associated with flooding and the flooding point in the system is not something that we can do with an analytical approach, right?

33:11

This is not a, we can't deploy a simple algebraic expression to predict this.

33:17

So what we're going to look at on this slide and the next one are a few different examples and some methods for how we might approach this.

33:25

So one, and this is shown in McCabe's textbook and it's reflected in the reader as well as a balance of, of looking at measuring, well, what is the flooding velocity?

33:34

And this is of the vapor.

33:36

So when I let me explain this, the vapor phase here we're plotting in pounds per foot squared per hour.

33:41

So in SI units would be kilos per meter squared per second, but it's a mass per area per time that we're putting across.

33:51

This is the gas mass velocity at which I'm going to start flooding the column for a given liquid mass velocity that I've injected in the same unit sets.

34:03

So the way that we can read this is to say, let's imagine we have for this half inch into locked saddles in this bottom black curve.

34:12

Well, if I have 1000 flooding velocity of 1000, a gas mass velocity of £1000 per foot squared per hour, then let's call this this intersection for convenience.

34:25

Or in fact, we find a better bisection here.

34:30

OK, so if I look here, this is a perfect bisection.

34:35

So 700, all right, £700 per foot squared per hour.

34:40

And the gas mass velocity will be the flooding point when my liquid is flowing at £5000 per foot squared per hour.

34:52

Now this is not to say that the volumetric flow rates aren't very, very similar because remember, my liquid is going to have, you know, on the order of 100 times at least the density of my vapour phase depending on the pressure I'm operating at.

35:03

So I'm dealing here with very similar volumetric flow rates, but a mass flow rate that's on the order of say 10 times in the liquid that of the mass.

35:14

So as I'm reading here and these are coming from experiments that have been performed that McCabe's reporting on, if my liquid is flowing above 5000, I'm flooding or I begin flooding rather it's more appropriate.

35:28

And if I'm below 5000, I'm not flooding.

35:32

So we would tend to want to operate just below that flooding region where we have maximal coverage.

35:37

We have loaded the system, we've increased the surface area, but we do not want to ever allow it to tip into flooding because the overall efficiency of my system is going to drop.

35:48

And I could similarly go through this chart with exercises at the different sizes.

35:52

What I can see is that the bigger the material, the more well, the bigger the material, the more mass I can put across it before I flood for a given air velocity.

36:04

So this is another decision criteria that the engineer would take to think about what is the right size packing material?

36:10

Well, one of the questions we need to answer is for the liquid in the gas phase that denominated pressure, where is the flooding point going to be?

36:17

Because that's largely if I can say something about the type and the size of the materials going to dictate what's the most appropriate for my scenario.

36:27

So in terms of predicting this pressure drop and the pressure drop at the flooding point, there are a few different approaches that we can take.

36:35

The 1st is from Eckert and it corresponds to the graph shown here on the right hand side.

36:42

So here what we're plotting, what we're plotting here on the ordinate or the Y axis is a balance of the gas mass flow rate.

36:53

And here I can see this is being corrected by the packing factor $F_{sub P}$, the liquid phase viscosity $\mu_{sub X}$ G So gravitational acceleration on Earth, the density difference $\rho_{sub X}$ minus $\rho_{sub Y}$.

37:08

So between the liquid and gas phases times again the density of the gas phase.

37:13

So this is a A.

37:19

This is a merged ordinate value.

37:21

That doesn't mean anything physically, right?

37:24

It's just instead of putting forward an analytical expression or an empirical expression, Eckert has taken these terms and merged them as to one ordinate value or Y axis value that I would calculate.

37:38

I do the same thing with the X axis or the abscissa.

37:41

So IGX and GY are respectively the gas and liquid mass flow rates through the system.

37:48

And here again, I see the three densities of the liquid or sorry, two densities of the liquid piece rows of X and the vapor rows of Y show up.

37:55

So to execute this approach from Eckrid, I calculate independently.

38:00

So I'm going to go to Excel and calculate what is the Y value and what is the X value for my system.

38:06

And what I'm going to read off is to interpolate between these different curves, right?

38:13

Each curve represents a different condition of pressure drop in the column at the point of flooding.

38:21

So here and the values here.

38:24

So we have to unfortunately use imperial units, which I know is an absolute terrible approach.

38:30

And GC is not 9.81.

38:32

So make sure you're incorporating GC within this.

38:37

So correction from pound foot to pound force, but here I can see we're measuring out inches of water per foot of packing height.

38:43

So this is a pressure drop per height of the column at which my flooding is going to occur.

38:48

So if for instance, I was, I did my ordinate and Abscess, so Y axis and X axis calculations and it returned an outcome that was sitting right here.

38:58

I would say that my pressure drop at flooding is 075 inches of water per foot of packing height.

39:05

Conversely, if I was sitting right here on the outcome and of the Y&X axis calculations, I would have .5 inches of water per foot of back, which I could quickly transform to millimeters of mercury per meter or kilo pascals per meter.

39:21

Now this approach, the convenience here is that I can put GX and GY in SI units.

39:29

Right now, I cannot do that with GY.

39:32

So the units on this Abscess of the X axis are going to cancel out for both the mass flux and the density.

39:37

I cannot do that with the Y axis.

39:40

I must use pound per foot squared per second for G sub Y.

39:44

The packing factors have no dimension.

39:46

MU is incentive, ironically is the one variable as incentive for both SI and inferior units sets.

39:54

The density that I use in the Y axis must be pounds per cubic foot on the bottom and this is the value of GC that I would employ for the conversion.

40:03

So I have to do the Y axis in imperial.

40:06

I can choose imperial versus SI for the X axis.

40:09

What I'm reading out of this is an also a very, very old imperial pressure drop, but I can convert it conveniently to SI.

40:19

So it's a visual approach.

40:22

Conversely, I can look at a model equation for this based on the packing factors of the materials in plain.

40:28

So these are why these show up in in my material and and packing material selection is effectively and this is very approximate for packing factors between 10 and 60.

40:40

My pressure drop at the point of flooding would be .115 times that packing factor to the .7 power.

40:48

Now these are going to give me estimates.

40:51

So if I can calculate the pressure drop across my column, and I would do that for the dry column based on the Ergun equation, then this approach is going to give me a very, very ballpark, very ballpark approximation of, OK, it's more liquid that I put across this column.

41:11

I'm going to increase the pressure drop.

41:12

And if I hit, you know, that flooding pressure drop, then I know I've put too much liquid across and I need to turn it back down.

41:22

In practice, what you would do is, just as we saw in the previous slide, you would determine this experimentally for your column and for your packing material.

41:31

If you could not find a reference in literature already, you'd measure that dry line and then start putting more and more liquid across it.

41:38

Ensure that you have a physical and experimental boundary of a where is the loading point and B where is the flooding point and so that you know this is the range in which you can operate.

41:49

If you were using either of these approaches to predict that in advance, then I would tend to put a very large engineering margin on those boundaries because you do not want to get to the point where the the column is flooding.

42:03

OK, so now that we have taken a look at the boundary condition for the upper limit of how much liquid I can put through one of these columns, I now need to take into consideration of how do I predict the inlet and outlet compositions of my target component.

42:23

So the diagram that we're going to look at here on the right hand side, and I should mention that this is particularly a section where both the reader and the tick textbook are critical compliments to the lecture.

42:34

So please make sure that you've had some time to look at the reader and go through it for this section to understand how these lines are constructed.

42:42

One of the reasons that we care so much is we are going to take the exact same approach for distillation.

42:49

This distillation is going to add in much more and so we need to make sure this foundation is rock solid.

42:56

OK, so here is again on the right hand side, my nominal absorption column where I have some inlet vapor of interest at the molar flow rate $V_{\text{sub B}}$ and a gas composition of $Y_{\text{sub B}}$ of my target component.

43:11

This is usually the thing I'm given to deal with, right?

43:14

So if we were thinking about a direct air capture system, that would be the CO_2 concentration in air.

43:20

So it's not something the engineer can control.

43:23

What the engineer can control is what they use as the liquid and so the liquid molar flow rate again with the upper limit, the maximal liquid flow rate dictated by the point at which we begin flooding or usually some, you know, buffer and engineering tolerance around that and beginning with some composition X of A .

43:42

So maybe I'm able to use a water in which there is absolutely no CO_2 and it's pristine, or maybe I'm using a recycled water loop, in which case I'm going to have a little bit of CO_2 still residual in that water.

43:54

And so I might begin at a non zero point in X of A as these, as the liquid flows down the column and as the vapour flows upward, we are transferring mass from the liquid to the vapour exiting the liquid with a molar flow rate $L_{\text{sub B}}$ and a composition $X_{\text{sub B}}$.

44:13

So this is the amount of CO_2 in the liquid phase on exit and the molar flow rate of that liquid on exit.

44:20

Now one might imagine to oneself, OK, $L_{\text{sub A}}$ and $L_{\text{sub B}}$, aren't these the same thing?

44:25

All right, I have a liquid molar flow rate.

44:28

Well, not quite because I am moving mass from the liquid to the vapour phase.

44:34

So in fact, if the purpose of this process is to capture CO_2 out of the vapour phase, I'm moving mass from the vapour to the liquid, right?

44:43

So in fact $L_{sub B}$ is going to be larger than $L_{sub A}$ because I begin here with just water and I'm not losing much water, so I'm exiting with water and CO_2 .

44:55

So $L_{sub B}$ becomes larger and $X_{sub B}$ is now the point at which I have saturated or maximally packed my liquid phase with CO_2 for this example.

45:09

Conversely, the vapour phase is going to exit with its molar flow rate $V_{sub A}$ and its final composition of component $Y_{sub A}$.

45:18

Now in the same way, the $V_{sub B}$ - $V_{sub A}$ is equal to $L_{sub B}$ - $L_{sub A}$.

45:33

So the amount of mass I move from my liquid to my vapour is equal to the amount of mass I've lost from my vapor to my liquid.

45:43

So across this total column, if I looked at the entirety of the column, I could write a total material balance for the inlet and outlet molar flows.

45:52

Or I could move the control surface up and cut the column at some point nominally in the middle, in which case I know L_A and I know $V_{sub A}$ because these are still entry and exit points.

46:05

But I don't necessarily know what the L and V_{sub} are going to be in the middle of the column to begin with.

46:12

And so we would leave these V_{sub} & L being an intermediate vapor and liquid molar flow rate respectively.

46:18

Now instead of a total material balance, I could take the exact same approach but write it as a component material balance, either at the terminal condition, so the entry and exit of the column, or cutting it within the column across that control surface.

46:31

In some of the dynamic columns, we would also call it control volume or control area.

46:38

Now the point that we want to recognize is that we can take this component a balance at any point within the column.

46:45

And what if we solve this for Y as a function of everything else?

46:50

And that's what we're showing down here.

46:52

We say Y when we solve this out as equal to now this intermediate liquid molar flow rate L divided by the intermediate liquid vapor flow rate V .

47:01

So that's the liquid and vapor molar flow rates at this exact point here times the mass or the composition X plus what effectively we're looking at is AY intercept right $VAYA$ minus $laxa$ divided by that vapor molar flow rate.

47:19

So here we have an equation in the form Y equals MX plus V where Y is the composition of my target component in vapor, X is the composition of the target component in liquid.

47:33

I have a slope $LON V$ and AB or AY intercept shown on the right hand side.

47:42

So when I begin starting the design process for this, then what I'm going to look at is comparing so I can plot this operating line out.

47:53

Now we call it an operating line, and that's A engineering parlance that stuck throughout the ages.

47:59

In fact, it's a curve.

48:01

And we can think to ourselves, why is it a curve?

48:04

Why is it not perfectly linear?

48:06

Well, it turns out right, because from the very second my, my liquid or my gas is entering the column, it's either losing or gaining mass.

48:15

And the further it goes, it loses more or gains more depending on the phase.

48:19

And so I have this constant monotonic change in the molar flow rate of both the liquid and the vapor, which is why I ultimately get an arc in the operating line.

48:33

So this is the equation for the operating line.

48:35

And this is what it looks like in practice from point A to point B.

48:39

And I can see here if I plot this in YX phase.

48:42

So this means I'm operating at constant temperature, constant pressure.

48:45

And in fact, I'm making the assumption of neglecting the hydrostatic head of the liquid and vapor phase as an effect on pressure.

48:53

Not something I'm going to account for here.

48:56

I can plot this out, and I need to plot it in comparison to the equilibrium curve.

49:02

So this is for my pressure, temperature, and composition.

49:06

What is the mole fraction of component A in equilibrium with the mole in the liquid phase in equilibrium with its vapor?

49:16

This is what that equilibrium curve represents.

49:19

If I set my pressure and I set my temperature and I perform a two phase VLE flash, what is the equilibrium composition of X&Y for my target component?

49:32

This is why we spent so much time in thermodynamics focused on VLE vapor liquid equilibrium.

49:39

Because the purpose is when I'm dealing with a mass transfer system, nine times out of 10 I'm dealing with a liquid in a vapor mass transfer system.

49:47

I must be able to know what is the equilibrium between a vapor and liquid in order to perform both absorption and distillation operations.

49:59

So the solution to my VLE, my vapor liquid, my thermodynamic VLE solution produces this equilibrium curve.

50:11

Now you might ask yourself, how do I get that curve if I don't want to do a manual cubic equation that state I don't blame you, you don't want to?

50:17

Fair enough.

50:19

We would get it through something like multflash or something if we had data tables that we could find from the peer reviewed literature where we had some confidence in the technique, right?

50:30

We either measure it or we use a complex tool like Aspen HYSIS Multiflash.

50:36

To be able to predict when I flash the system at constant pressure, constant temperature, I would vary the amount of components, say in my liquid phase to start with.

50:47

And so for a total amount of component, let's say I start with .1 mole fraction, sorry, point 01 mole fraction in the system, constant pressure, constant temperature and I flash it.

50:58

So I perform that thermodynamic flash calculation.

51:01

As a result, that is going to that point O_1 mole fraction is going to split part of it into my liquid, part of it into my vapor.

51:09

I do the same thing again at point $O_2, O_3, O_5, 1, 2, 3$.

51:15

Every time I flash this, I'm getting a separation in my vapor and liquid equilibrium concentrations.

51:23

So I get an X_1, Y_1 .

51:26

So at $.01$ mole fraction I perform the flash and I get X_1, Y_1 .

51:32

At $.02$ mole fraction I perform another flash, I get X_2, Y_2 .

51:37

So on and so forth, X_3, Y_3, X_4, Y_4 .

51:41

These build my equilibrium curve.

51:45

So now what we've done is been able to architect an operating line or operating curve or an operating line that is a curve that shows me the change or the arc and the change in mole fractions between my liquid and vapor phase throughout the column.

52:07

And I'm directly comparing that to what I've studied in thermodynamics where I can see the equilibrium that the system is trying to reach.

52:17

So when I construct these diagrams, the very first thing I do is I'm going to map out, physically map out these X_B, X_A, Y_B, Y_A values.

52:30

These are my terminal mass material balance positions.

52:34

I'm going to map my equilibrium line.

52:37

And I could very well begin by assuming that L & V are always constant, right?

52:41

If I'm not changing a lot of mass between them, I could start by assuming it's linear, right?

52:47

And I need to write that down as an assumption.

52:49

So I'm just going to draw a straight line of that slope and figure out where it bisects each of these two points, and I can deal with adding the curvature to it later on.

53:01

And as I draw that operating line out, I must be able to draw it next to an equilibrium curve that I get from doing a VLE flash.

53:13

This is also where it's very important when we're using a package like multi flash or high S S that you select the correct cubic equation of state for the components that you have, right?

53:24

So if we're dealing with CO₂ and water, we have a highly polar aqueous system.

53:29

We know from thermodynamics we should never use Peng Robinson for something like that.

53:35

Peng Robinson is a hydrocarbon fitted cubic that's specializing in hydrocarbons.

53:41

So we need to use our thermodynamic knowledge to pick the right equation of state and we perform what we're basically going to manually perform 15 or 20 flashes in multi flash or hyaces.

53:53

And that's going to give us, if we just vary the total amount of our target component in the system, then each flash is going to give us a pseudo random point along this equilibrium curve.

54:04

And when I plot the whole thing out, I can see it here emerging as a continuum curve.

54:10

Now the key point of showing it like this is that the difference, right?

54:15

Well, firstly, for absorption to take place, my operating line must categorically be above my equilibrium line.

54:25

It must be higher in the Y space.

54:28

That is an absorbing system.

54:31

And in fact, if the difference in height between the operating line and the equilibrium line at any given position is the driving force.

54:42

So if Y_B is the mole fraction at at the inlet.

54:46

So this if we were using the allegory of direct air capture, this would be 350 PPM.

54:52

So if this is 350 PPM, what I'm looking at is a driving force that as it's drawn here would be about half right half of the OR.

55:03

The driving force is to remove about half of the CO₂ from the vapour phase, meaning that it's 350 PPM, right?

55:12

I should have a driving force initially, and this is critical at the at the entry point of the column from the vapor to remove about 175 PPM of CO₂.

55:26

Now this is the bottom of the column, this point B.

55:32

As I traverse down or up through the column to point A, this is the top of the column.

55:37

So here I also am above the equilibrium curve.

55:41

Thank goodness, right?

55:43

If I wasn't, no absorption would be taking place in that part of the column.

55:47

So I'm beginning and ending above the equilibrium curve.

55:49

However, I notice here the difference between point A and the equilibrium curve is much smaller.

55:56

It's probably 1/4, maybe 1/5 of the driving force that I began with.

56:04

So at the top of the column I have a much, much, much much lower driving force to move mass, meaning move molecules of CO₂ from the vapour to the liquid phase that I began with.

56:18

So this is a a really important insight that the position and the curvature of my operating and the equilibrium lines tells me from the top to the bottom of the column.

56:29

How does the thermodynamic driving force change, right.

56:35

Another way to look at that is a chemical potential driving force, my molecules throughout the entire column, my CO₂ molecules would rather be in that liquid than in the vapor, but not consistently.

56:49

So that changes throughout the column.

56:53

And so when I talk about the something like innovations in the liquid that we're choosing and you know, particularly we get into more advanced chemistry research, innovations in that liquid allow me to create a system in which I am maximizing the distance between the operating and equilibrium lines throughout the entirety of the column.

57:12

The larger the distance, the greater the driving force for mass transfer.

57:18

Now, one of the points I would make here is that if this Y_B had a value of 350 PPM and we said OK, initially about 175 PPM of CO_2 will be will attempt to move toward the liquid.

57:31

Now that's going to take time and that's where we come into in the next slide.

57:35

We need to think about the rate of mass transfer.

57:38

But at the end, let's look at the top of the column here by that, you know, the same values were in play here.

57:46

I might have a driving force, let's say if I have 50 PPM of CO_2 left in the liquid phase at the top of the column.

57:55

Well, actually about $3/4$, maybe $2/3$ of that is still going to want to go into the liquid phase, All right.

58:03

So this allows us to see then that we're still maintaining, we're actually increasing the propensity of of the what's left to want to go into the liquid, but the absolute amount is much lower.

58:19

So once I have selected my point Y_B , I've nominated y_a based on the liquid I choose, I then have to think about, OK, I don't really know where this X_B is going to be yet because it's going to vary based on where Y_A ends up, right?

58:36

Those are the unknown balance in this equation.

58:40

So in the design process, the first thing I'm going to do is figure out what is my bounding condition, right?

58:47

Well, we already have one bounding condition and that's how much liquid I can put across.

58:52

So the liquid molar flow rate on entry $L_{\text{sub A}}$, which is functionally going to dictate the magnitude of L , right?

59:00

L is going to change a little bit.

59:02

It's going to increase if I'm moving molecules from my vapour to my liquid, but not by a lot.

59:07

So L at any point in the column is going to be a slight modification of $L_{\text{sub A}}$.

59:13

Well, I know from my flooding discussion that that is the upper limit to how much mass I can, I'm sorry, the upper limit to how much liquid I can inject in the column without violating the set up, right?

59:31

If I create a region in which I have a super high mass volume fraction of liquid, I'm flooding a localized region, or I can flood a large region, I'm making the column inefficient and the whole system goes out the window.

59:45

So I know my upper limit.

59:48

Sorry.

59:49

My upper limit to the amount of mass in liquid that can be injected is dictated by flooding.

59:57

OK.

59:57

And if we can't, like as I was shown in the previous slides, we can use a few pseudo empirical techniques to try to estimate what that point is.

1:00:05

Ultimately, for our column, it's something that we're going to need to do, trial and error to make sure we know exactly what that maximal flow rate is going to look like.

1:00:14

Conversely, I need to know the other bounding condition.

1:00:18

All right.

1:00:19

And to get there.

1:00:21

I'm going to first look at what we have drawn here is from YB.

1:00:24

I'm going to extend this dashed line so when I first start, I don't know where the point B is going to be.

1:00:31

So I'm going to draw this all the way over and find where does this bisect the equilibrium curve at that point?

1:00:39

That is the slope L / V of the minimum viable liquid to create a separation any low If the liquid flow rate L drops below that value, I do not produce an equilibrium separation, right?

1:00:57

I do not produce a mass transfer effect at the bottom of the column as the air first enters.

1:01:03

So in fact, the driving force, because point B prime is sitting specifically on this, the driving force for mass transfer is 0 at this point, but increases as I go from the bottom to the top of the column.

1:01:18

OK, So if I know that point, then I can say, ah, OK, I know Y or I know X of A because that's what I've commenced with in the system, right?

1:01:33

And because I've defined this, I'm going to start with the bounding condition and back up.

1:01:39

I found B prime, which means I know the amount of liquid the the concentration in my liquid phase at the Max at the end member, the maximal condition XB star.

1:01:49

So that's what would happen here if I drove the minimum viable liquid quantity across, meaning the liquid that exits here is completely and utterly saturated in in whatever component I'm using.

1:02:07

So if we're using the metaphors or the model of CO₂, then if I drive this all the way to the equilibrium curve XB star, that liquid cannot take a single additional molecule of CO₂.

1:02:20

And I'll come back to that.

1:02:22

So once I have that XB condition, well, now I can calculate Y sub AI know YB, I know XA and I know XB star.

1:02:31

I can calculate YA to that point right from my component mass balance.

1:02:37

I would use this terminal component mass balance here, but replacing XB star and appreciating this LB is going to be represent the minimum for LA and LB are going to be attuned to the minimum liquid flow rate.

1:02:54

OK, so the first design step is actually once I have my equilibrium curve and I chart out what are my points y_b and X_A , it's defined this minimum operating line first from A to B prime, and I use the equilibrium curve to do that.

1:03:10

And then I say to myself, OK, so now I want to back up a little bit and I want to figure out what if I want continuous separation across the column, All right?

1:03:22

Now, one of the reasons I've mentioned, we don't necessarily want our liquid to exit completely saturated in CO_2 for this example, right?

1:03:31

We don't want that.

1:03:32

And the reason that we don't want that is that we want every foot or every inch or every meter of that column to be transferring as much mass as possible.

1:03:45

If our column could not produce a vapor of sufficiently low CO_2 concentration, then we would take the decision to put two columns back-to-back and the outlet of the first column is the inlet to the second, right?

1:04:00

But we would not want to accept a condition in which we have spent all of this time and money and energy of materials to produce one inch of this column that is not produce, that is not actively transferring mass.

1:04:15

So we start with that end member condition and then we start to back up.

1:04:19

We say, OK, this is the minimum L liquid molar flow rate that we can deal with.

1:04:24

We have a ballpark estimate of the maximum liquid flow rate that we can deal with from that is the point at which we start flooding.

1:04:32

So in fact, the slope here, we have the minimum viable slope and we can determine the maximum viable slope from the flooding point.

1:04:41

And our actual operating line, right, is the one that we're going to choose.

1:04:46

If we're in a design sense, we would choose an operating line that's going to sit between those two points.

1:04:51

And ideally we would choose the one that when integrated is going to give us the maximal total amount of mass transfer.

1:05:00

So in the laboratory setup that we're going to be looking at now, this has already been done.

1:05:05

So the laboratory approaches it from a different angle and that is that the system is already in play.

1:05:12

And what you need to figure out is what is the operating line for that system based on the data we've collected, what is the equilibrium line based on our knowledge of thermodynamics.

1:05:22

If we were approaching it without ever having put a shovel in the ground, just as a pure design stage, then we would say, OK, let's figure out first the bounding condition for maximal liquid, the bounding condition for liquid, minimal liquid that we get from thermodynamics.

1:05:38

And it's between those two points that we're going to operate, OK.

1:05:47

So now if we had assumed that our operating line was going to be a line initially, then one of the points that we need to make is once we've taken the decision in a design sense of where this thing is going to operate, we need to appreciate it's no longer going to be a line.

1:06:05

Right?

1:06:05

At each point throughout this column, there is going to be a different rate or similar, but different rate of mass transfer.

1:06:12

And as a consequence of that, we're moving mass from one phase to another.

1:06:17

That means that one phase has a monotonically increasing molar flow rate and the other has a monotonically decreasing molar flow rate.

1:06:24

For this reason, we end up getting a curvature in our real operating line.

1:06:32

So on the note of absorption or absorption rate.

1:06:37

Now the convenient point here, and we're going to go more and more into this as we get through mass transfer in the coming lecture as well.

1:06:44

But remember that we're thinking about a liquid film that is coating all of my packing bed material.

1:06:52

I'm so I'm transferring mass from a vapour film through a liquid film and ideally we want the vapour film and the liquid film to be small and isotropic, meaning throughout the entire system.

1:07:06

I had the same film thicknesses in every direction.

1:07:11

So I don't have any bias upward or downward, right?

1:07:14

I have a homogeneous distribution of the film I can write.

1:07:20

So the the key message is that the rate of mass transfer of a molecule leaving one phase is equal to the rate of mass transfer of a molecule coming in to the other phase.

1:07:33

But I'm neither creating nor destroying mass.

1:07:37

Therefore I can write this absorption rate.

1:07:41

So the rate of mass transfer of the packed column in terms of I can write it in any of these four terms.

1:07:48

So using either a film mass transfer coefficient that's little case of Y, or a film liquid mass transfer coefficient, little case of X, or an overall mass transfer coefficient for the vapor or liquid phases, large case of Y or large case of X.

1:08:07

All of those rates are equal.

1:08:10

And the way I'm defining each of these is by comparing the operating in the equilibrium lines.

1:08:15

So the driving force $X^* - X$, the driving force in X phase is proportional to its overall mass transfer coefficient.

1:08:26

The driving force in Y space, that which I was just talking about is shown here and it's proportional to the overall gas mass transfer coefficient.

1:08:38

Now each of the overall mass transfer coefficients.

1:08:41

So we would we sum these in the same way we think about an overall heat transfer coefficient one on you.

1:08:48

But here we're approaching it either from the liquid or the vapor, right?

1:08:51

Whatever's going to feel more comfortable and whatever we have ultimately Sherwood correlations to power.

1:08:58

I can write that in terms in both in terms of the component liquid and vapor film resistances.

1:09:07

So this large case of X is a function of little case of X and little case of Y , OK.

1:09:15

And in both cases, M is the slope of the equilibrium curve at that point, the local slope of the equilibrium curve.

1:09:25

So if I've calculated the using a liquid or a liquid phase driving force and a liquid phase overall mass transfer coefficient, I'm looking horizontally across this space, right?

1:09:36

This is again why we want maximal separation between our operating and equilibrium lines.

1:09:41

In that case, I would take the local slope of the equilibrium line or curve here, whereas if I was following the approach I just showed where I'm looking vertically at the driving force and then I would represent that M as the slope here where it's taken.

1:09:57

OK, so the other interesting thing that I can extract out of this once I have a functional operating line.

1:10:07

So again, this is one of the reasons if we're not working on a highly sensitive or highly toxic operation, we can get a lot of information about mass transfer from running the column as an experiment before we either scale up or put it into practice for its engineering purpose.

1:10:25

Well, if I know right at any intermediate point that I'm able to say measure the composition.

1:10:31

So here at my point Y , I'm measuring the interface compositions $Y_{sub I}$ and $X_{sub I}$ the slope.

1:10:40

So the slope that's normal to the operating in equilibrium lines at that point at any point throughout the column, is going to be the ratio of the liquid film trans mass transfer coefficient on the vapour film mass transfer coefficient.

1:10:58

Critically, for our packed columns, this little $K_{sub X}$ is typically 3 to 20 times that of little $K_{sub Y}$.

1:11:09

So my mass transfer coefficient in a liquid is substantially larger, right, Typically 3 to 20 times larger than that for the liquid phase.

1:11:21

I'm sorry for the vapor phase.

1:11:24

OK.

1:11:25

So continuing down the track of thinking about column design and again this week we would approach design for a column that's not yet been built.

1:11:34

So we're approaching it from the outset saying we know we can find from a flooding perspective what is our maximal liquid velocity before we begin localized flooding.

1:11:45

We know from our well comparison of the operating in equilibrium lines, what is our minimal liquid flow rate condition, right.

1:11:53

This is the point at which we're getting any sort of transfer in one part of the column.

1:11:58

So once we have those bounding conditions, the next thing we need to figure out is well, what's the volume of transfer involved?

1:12:04

And, and the way that we'll break that down is to look at the cross-sectional area.

1:12:08

Now in this older nomenclature, we, we're going to use cross-sectional area S and that's just because we're talking about mass transfer for the moment.

1:12:16

So I'll try to make sure that that's always clarified.

1:12:18

And I'd encourage you if you're using this nomenclature, be sure that that's defined in your reports because S is not a common area or variable to use for cross-sectional area and the differential height through the column DZ , right.

1:12:32

So what we're relating here is the overall molar flow rate through the column.

1:12:36

So that V , the overall molar flow rate of the vapour phase case of Y , this is the overall or large case of Y is the overall mass transfer coefficients that's incorporating both the liquid and vapour film resistances.

1:12:50

Of course, the driving force across what that's applied $y - y^*$ we can see from the previous slides.

1:12:56

So this is the overall driving force for mass transfer through that column.

1:13:02

And this is then related to some differential height throughout.

1:13:05

So the further we go through the column cumulatively we get more and more transfer.

1:13:09

Now the thing that we want to tease out here is that we can rearrange this expression for the purpose of isolating our differential driving force dy .

1:13:18

So this is associated at any cross-sectional or cross section of the column relative to the overall driving force for mass transfer $y - y^*$.

1:13:29

And as we integrate that, we see a very useful form fall out that we're integrating from, say, point A to point B.

1:13:37

Now these can be across the whole column or across different portions of the column.

1:13:42

So we're just going to take the direct integral from A to B right now across the whole column.

1:13:47

And then we'll look at what this turns into in a moment.

1:13:50

So as we integrate, we can collect the integrated terms into two blocks.

1:13:57

And the reason we present it this way, it's a bit confusing from the purpose of absorption, a VS option perhaps because we don't necessarily need to take this step to do all of our design right.

1:14:07

But we're going this extra mile because we have to set ourselves up to look at what's going to happen in distillation columns where this framework will yield more value.

1:14:18

So as we perform the integral, we see the first collection of terms that drops out here.

1:14:23

This is the height of a given transfer unit.

1:14:26

So the height we're going to break the column into some number of transfer units N_{OY} .

1:14:32

And each transfer unit will have a consistent height H_{OY} .

1:14:37

So it's you can kind of think of it.

1:14:38

But if I have a column, for argument's sake, that's 10 meters tall, well, what I'd really like to do is think about how is that column delivering my mass transfer for the marginal, say, meter of height that I'm going to add to it, right?

1:14:53

If everything else is to remain constant.

1:14:55

And that's what the approach of number and height of mass transfer units or what we generally call transfer units as an approach, that's where its value is really embedded.

1:15:07

So we have our number and our height of mass transfer units in this case.

1:15:12

And if we go back for a minute and compare, well, if we're integrating from point A to point B, right, that's from the top of the column to the bottom of the column.

1:15:19

Now, if I take an ideal operation, right, that's one where I have a straight operating line.

1:15:24

So meaning I'm moving an infinitesimal amount of mass from one phase to the other, from the vapor to the liquid in this case.

1:15:32

So if I don't really have a change in molar flow rate of that vapor, what I'm going to get out is a straight operating line.

1:15:37

We'll call that an ideal condition.

1:15:39

So in that ideal limit of the operating line being straight and we integrate from point A to point, well, from B to point A, our number of transfer units N_{OY} is defined as $Y_{sub B}$.

1:15:54

So that's the mole fraction of my component in the vapour phase at the top of the column less that $Y_{sub A}$ at the bottom divided by $y - y^*$.

1:16:04

So that's the overall driving force for mass transfer, right?

1:16:07

So what that's if I think about that expression for a minute, what it's really giving me is how much mass transfer did I deliver relative to what I could.

1:16:19

Now if I have a non ideal operation and we've drawn this with a straight operating line, just for convenience, I can equivalently break this into small sections.

1:16:27

Or if I don't have a strong curvature to it, then the assumption of applying this for a straight operating line is not a bad one if I have a non ideal operation.

1:16:36

So these things are not no longer parallel, but I can see I'm going to have a different pitch in the operating line relative to the equilibrium line.

1:16:42

So this is more of the scenario that you've looked at for the column that we're working on in the laboratory.

1:16:48

Now I can still apply the same definition of N_{OY} .

1:16:53

So here's the mass transfer that actually took place $Y_d + y_a$.

1:16:58

But now all I need to do is correct the bottom, the denominator term to instead of having an overall driving force $y - y^*$, I put in a log mean driving force, right?

1:17:10

And we would see these log means coming up.

1:17:11

This is the same log mean definition that comes up in heat transfer.

1:17:15

So for those that might be a little bit uncomfortable, the reader chapter #5 that goes through the basics of heat transfer as a revision activity that also goes into detail about how the log mean driving forces, or in that case log mean radii are handled.

1:17:32

So the number of transfer units N_{OY} is then intimately related to the balance of the operating and equilibrium lines for my absorption column.

1:17:42

And the height of each transfer unit is set by the overall mass transfer coefficient and well, I should say by the mass transfer coefficient and the correlate corollary molar flow rate.

1:17:56

So if I'm applying this to a liquid mass transfer coefficient, I'm thinking about the liquid molar flow rate here.

1:18:03

And if I'm in a vapour mass transfer coefficient, I'm in the considering it relative to the vapour molar flow rate.

1:18:08

Now I can use either the gas film or liquid film, that's our little case, or I can use the overall liquid mass transfer coefficient.

1:18:16

So this is the purpose when we start going from this lecture into the next lecture.

1:18:20

And the reason these two things are coupled is that we first need to understand what's the role of our mass transfer coefficient in the absorption process.

1:18:30

And one of the things that we'll quickly see is that that transfer coefficient is effectively a combinatorial resistance for my mass transfer process.

1:18:41

Now we've not yet right gone through an explanation of how to get those.

1:18:45

We've seen a preview of using that porting our our thinking of nestled numbers over to Sherwood numbers.

1:18:51

So we can take a lot of those same correlations and apply them here.

1:18:55

And we'll go through that in the coming lecture.

1:18:57

But the whole purpose of that is to yield back to me what is this overall transfer coefficient.

1:19:02

Once I have that, then I can approach this and say, look, do I know my molar flow rate?

1:19:07

Do I know my cross-sectional area?

1:19:10

And can I get at the number of transfer units, for example, that I would determine through comparison of the operating and equilibrium lines.

1:19:18

When I have those, I can then calculate the overall height of the column $Z_{sub T}$, right?

1:19:26

And if I'm thinking about applying this approach to an existing column, then one of the key comparison points is going to be predicting or calculating what is the theoretical height of the column required to the height of the column that I'm working with.

1:19:40

So that's why we're setting it up in this structure so that you can look at, we're going to take our Nestle correlations, pour them to Sherwood correlations in the next lecture.

1:19:49

Once we can extract those back out, then we apply them into this framework for our absorption column using our transfer units.

1:19:57

Now in comparing the overall height of the column, there's a key consideration if you're comparing theory to reality.

1:20:04

If theory tells me that I have a or need a higher or a larger in magnitude column height then that which I have in my laboratory.

1:20:16

Or my pilot plant, or my process plant, then very clearly I've there's a mistake somewhere in the calculations, right?

1:20:24

Theory is going to return to me the smallest possible height for the operation I'm trying to deliver.

1:20:34

So if my real column is even smaller than that, there's a mistake either in how I've assessed the actual column or how I've completed the theoretical calculation.

1:20:45

Now a lot of this that we've talked about, we've mentioned that our equilibrium curve is governed, right?

1:20:51

It, it's a thermodynamic outcome.

1:20:53

So this is coming from a function of pressure, temperature and composition as we would expect.

1:20:58

And most of the time we will consider absorption columns that operate at either ambient pressure or very, very mild pressure, right?

1:21:08

And one of the reasons why we can think of if absorption was one of our earliest mass trans industrial mass transfer processes where we go back to the use of rock dumps and Ottawa sand as materials to create surface area between a vapour and a liquid phase.

1:21:25

Well, we're also not really able to deliver high pressure environments in that era.

1:21:29

So for that reason, a lot of the design of absorption columns tends to to be around at or just above ambient pressure.

1:21:39

But if we were to start thinking of using modern materials going to higher and higher pressures, then it's a very good question.

1:21:46

How should that affect the operation of the column?

1:21:49

Well, I can think thermodynamically.

1:21:51

I know that a change in pressure will absolutely affect the thermodynamic equilibrium point.

1:21:57

I absolutely know that it's one of my 3 core domains in driving forces.

1:22:01

So in the example that we're showing here, the equilibrium line, let's say P_1 is going to be atmospheric pressure.

1:22:08

So I can see the thermodynamic equilibrium line in atmospheric.

1:22:11

And if I increase the pressure to P_2 , I'm going to get a reduction in pitch of the operating or the equilibrium line, right further to the right of the diagram.

1:22:22

So the same, I'll end up getting a similar type of change in the operating line, but for different reasons, right.

1:22:32

So in either case, what I would end up doing is thinking through it higher pressures.

1:22:36

Well, what's going to happen?

1:22:38

I'm going to be compressing my vapour phase more.

1:22:41

As a consequence, my molar flow rates of the vapour being a highly compressible phase are going to change, they're going to increase.

1:22:49

And if the molar flow rate of the vapour increases, same volumetric flow rate but a higher molar flow rate because vapour is compressible, well, I'm going to have then a, a reduction in the minimum liquid rate.

1:23:02

So it's going to change the the relative pitch between the operating and equilibrium lines.

1:23:08

So in either case, when we went through the design basis of the column and said This is why we designed with a molar flow rate in line, right?

1:23:15

In that way, the design basis already allows us to easily account for pressure and the only direct change to our calculation is in what happens to the thermodynamic equilibrium line.

1:23:28

OK, So wrapping up here, the final few things we wanted to touch on.

1:23:34

Now we've been focusing on absorption, right?

1:23:37

So that's specifically taking a dilute material of interest in a vapour phase and transferring it preferentially transferring it to a liquid, right?

1:23:49

Our ideal absorption operation is when we're, we are able to select the liquid correctly, size the column correctly and capture virtually all right.

1:24:01

It's not always possible to capture exactly every molecule, but virtually all of our target material and to capture only that in some liquid phase.

1:24:10

And so this, you know, the example that we keep going back to is CO₂ absorption columns.

1:24:16

Very, very useful.

1:24:17

Either direct error capture as we're going to get to in class has limitations around size scaling, but and that's only because I have a very small thermodynamic driving force because I'm dealing with very dilute concentrations of CO₂.

1:24:30

I can apply this technology however to something like a flue gas, right, If I'm dealing with a post combustion process where I have an extremely concentrated CO₂ stream in the vapor.

1:24:42

In that case, absorption becomes a very tractable technology and it's certainly deployed to do this, to be able to pull that CO₂ into a liquid phase.

1:24:52

And then I need to do something with it.

1:24:55

So one of the ways that we can think about stripping columns is their absorption columns run in reverse.

1:25:01

So let's imagine I've applied my absorption to a CO₂ rich flue gas.

1:25:07

I obviously don't want to vent the CO₂ to the atmosphere.

1:25:09

I need to do something with it, but we also can't be.

1:25:13

If I'm going to store it in a reservoir, let's say a subterranean reservoir, I can't be injecting 300 PPM CO₂ material into a reservoir, right?

1:25:23

To make it economical, I need to be able to inject 99% or more pure CO₂.

1:25:29

So if I'm capturing 300 PPM or 400 PPM or more, how am I then going to transform that into a pure stream?

1:25:40

So the answer is we go to our stripping column.

1:25:43

Now if I take a stripping column where I'm going to say the inlet to that, let's say using direct error capture, is my CO₂ rich liquid phase.

1:25:52

And by rich I mean 3 to 400 PPM in the liquid phase.

1:25:56

OK, so now I need to be able to take that liquid and pull the CO₂ back off it to reconcentrate it in a vapor phase at such a high concentration that I can then inject it into a storage media or to use that in the further chemical refining process, maybe transforming the CO₂ into a different chemical material.

1:26:19

So stripping columns.

1:26:21

The convenience here is when I pair an absorption and a stripping column side by side.

1:26:27

If I'm not changing a process condition like pressure or temperature, then actually I can use the same equilibrium line or a very, very similar equilibrium line.

1:26:37

And so let's for the moment think about, let's keep the same equilibrium line that we had before.

1:26:42

But now instead of having my operating lines above the equilibrium line where I am absorbing material from my gas to my liquid, they are below my equilibrium line when I am stripping material from my liquid back into a vapor phase.

1:26:59

So the same math supply, right?

1:27:02

I can see here XB and XA, these are the boundaries of what we'll call a, a typical operating line.

1:27:09

And the only difference of where my minimum vapour flow rate, if this is minimum to effect transfer in the process.

1:27:16

The only difference between the stripping approach and the absorbing approach is that now I have the the potential to bisect the equilibrium line before right the edge or the end member conditions of the column.

1:27:32

So if I trace this second line for V_{min} , I can see well it's not at the end either end of the column where I'm going to bisect the equilibrium line.

1:27:41

I still have some distance between the two.

1:27:43

It's actually in the middle right?

1:27:45

So in the middle of the minimum vapour flow rate for this scenario and, and the same math could apply to to absorption.

1:27:53

It's just that the, the nature of the, the curvature tends to be that, that I don't see this type of this minimum condition.

1:28:02

So the minimum vapour flow rate is that at any point where that operating line is going to touch the equilibrium line.

1:28:08

And this same concept is going to carry with us through distillation.

1:28:12

So it's an important one to understand if in the example of my, let me just draw this out for a minute.

1:28:19

If in the example of my, this would be for absorption, right for AB, sorry ABS orption.

1:28:28

If it is actually this distance right between my, my absorption operating line and the equilibrium line, that's going to dictate the driving force for mass transfer.

1:28:38

Then we saw for the absorbing column, that's when this touches the equilibrium line, I get a point of no mass transfer.

1:28:45

And the reason we call that a minimum obviously is we don't want to be paying money for and using materials for a process that's not doing anything.

1:28:54

Now I can see that same concern emerge right here under a minimum vapour flow rate.

1:29:01

So in this region I have no separation between the equilibrium and operating lines.

1:29:06

That means I have no mass transfer taking place in the stripping column because those two are touching.

1:29:13

Now what we call this is a pinch point, and a pinch point is not specific to absorption.

1:29:19

It applies to any mass transfer process in which my driving force for mass transfer is 0.

1:29:26

Right, the name pinch point comes from I am pinching the operating and equilibrium lines together such that I have no distance between them.

1:29:35

If I have no distance, I have no driving force.

1:29:38

So as a consequence of that, I need to increase, in this case for a stripping column, the vapour molar flow rate.

1:29:46

So I'll remove these because it's the slides about stripping.

1:29:51

So this pinch point, this concept of a pinch point and what we looked at for absorption earlier, that also was a pinch point.

1:29:58

Now the column in that case was pinched at the top, meaning I have a section of the top in which there was no mass transfer taking place.

1:30:05

In this example, I have a pinch in the middle of the column and I can see actually the operating and equilibrium lines are bisecting for quite some distance, maybe $1/3$ of the length of the operating line.

1:30:17

So actually $1/3$ of my column is operating at a pinch point.

1:30:22

OK, so we're going to see the same phenomenon emerge when we go into distillation.

1:30:27

And this is an important concept.

1:30:30

We bound the operation when we by the pinch, when a pinch point is created.

1:30:36

So the the second example I wanted to raise was looking at something like a slightly soluble gas.

1:30:44

So this could be H_2S or again CO_2 .

1:30:49

What in reality is my combination of absorption and stripping going to look like?

1:30:55

Well, if I have the column side by side in the same flow process, so the materials are flowing out of one and into the other, they're in a connected system, then I can use the same equilibrium line for both of them.

1:31:08

And this would be an example of the operating line for the absorption column and the operating line for the desorption or stripping column.

1:31:16

And so I can see here I maintain some reasonable driving force at both end conditions of the column.

1:31:22

So I've stayed a decent clip away from any potential pinch points, X_B minus X_B star being the minimum driving force.

1:31:31

And I can see a a similar emergence here on the left.

1:31:34

And this process then gives me a really effective tool if I think about, well, heck, I can use a rock dump, I can use simple metallic or plastic rings, right?

1:31:45

And I just need a, a column vessel in which to hold these, where I flow mass from one to the other.

1:31:51

And I put these two columns side by side.

1:31:53

This is a really, really cheap and effective way to take some dilute concentration of material.

1:32:00

It doesn't have to be CO₂ or H₂S.

1:32:02

It can be anything as long as I've, if I've picked my liquid correctly and the OR thermodynamics allows me to operate at reasonable pressures and temperatures right where we don't want to be paying a lot of money for an absorption or stripping column relative to our other transfer methods.

1:32:21

Then in fact, with some very, very basic engineering, I can design a system to pull parts per million material from one phase, use a middle phase, in this case my liquid as an intermediate that on the back end allows me to concentrate what was, you know, 10s of PPM material into a very high mole fraction at the end of the process.

1:32:47

So it basically lets me take a complex gas and if I know, if I know thermodynamics and I've picked my liquid, I can say, ah, of that whole complex gas, I need to remove this one dilute component for whatever reason.

1:33:05

And this process for very little money allows me to do that and concentrate that one component into a different vapour phase that I can then either dispose of or react to form a safer or more useful product.

1:33:20

OK, so the very final note I wanted to end on is a thought of do we always have to use these dumped packing materials, right, The exemplar of our rock dump or ratchet rings or saddles?

1:33:34

Do I have to use this type of approach or is there anything else I can look at?

1:33:38

There is an alternative for absorption in stripping columns and that's structured packing.

1:33:43

So the way structured packing works, instead of filling the column with small objects that flow is directed around, and we saw that early on.

1:33:51

In fact, here I can see these two, they almost look like corrugated roofs, right?

1:33:55

If you've seen those older roofing materials that with the metallic corrugation in them.

1:34:00

Well, if I stack these at, say, 90° rotations of each other all the way through the column, and if I perforate holes to allow flow because I don't want to engender a huge pressure drop through the column, I can use a structured packing as a vehicle to create the same

kind of flow turbulence that all of my ultimately submerged particles or solids would have.

1:34:25

So we're not going to do any work with structured packing materials.

1:34:28

I just want to make you aware as you consider going into, you know, industry and where absorption or stripping columns might be useful.

1:34:35

It's not just the use of solid packing or dumped packing materials, but we have another alternative.

1:34:43

One point we do want to make is obviously the flow through structured packing is not as well defined, right.

1:34:50

This is a much more complex flow environment than if I fill a column with say spherical glass marbles, right, just as an end member condition.

1:35:00

So as soon as I put in the structured packing that the fluid dynamics get much, much more complex.

1:35:05

And so the ability to estimate something like, well, what is my, you know, minimum or maximum or sorry, what is my maximum liquid flow rate before I start getting flooding behavior.

1:35:15

That's not going to be something we can predict with the same degree of efficiency.

1:35:18

So it's probably going to require the engineer to go back and do a bit more experimental tuning at the rig before they know what are the optimal molar flow rates.

1:35:28

But one example where we would see structured packing is in natural gas dehydration.

1:35:33

So I'm trying to extract a dilute amount of dissolved water from natural gas.

1:35:38

This is one of the vehicles I can use to do it.

1:35:42

So as I mentioned, this lecture is tightly, tightly intertwined with Lecture 6, where we're going to unpack that practical mass transfer side of how do I get at these mass transfer coefficients.

1:35:53

We just need to go into a bit more depth to extract all of that content out.

1:35:57

But it's these two together that you can take to support you in the absorption app.

1:36:03

OK, wonderful, everyone.

1:36:03

I hope you've been having a good week and we will talk to you again soon.

1:36:07

Take care.

Lecture 06

0:11

OK, Welcome everyone to lecture number six.

0:13

So as a reminder, this lecture is coupled with lecture 5.

0:18

Both are presented to support absorption columns from both a theoretical design perspective, but also as we're working through the lab in in practical considerations.

0:28

The reason I've broken this into two is that we first need to set up the context of what is the operation.

0:33

We're actually looking at the thing we care about before we can understand why some of these more deeply embedded nuances in mass transfer are going to be required.

0:42

So in some ways, what I've done is to back up in this lecture and then go back to the fundamentals.

0:48

Now that we understand what we're applying those fundamentals into, one of the things I'm trying to tease out particularly in the first few slides as an appreciation for the difficulty of mass transfer relative to heat transfer.

1:02

So yes, we can draw analogues from things like our Nussle correlations and we'll look later on as to how we can do that, but in from Nussle to Sherwood correlations.

1:13

But in transforming the results of that back to something I can use right in the case of a Nussle correlation, it was my overall convective math, convective heat transfer coefficient, that transfer process in getting it.

1:27

Re extracting a useful term in mass transfer is a bit more complex because what I'm talking about requires more assumption.

1:35

And critically, we need to begin by reinforcing the different archetypes of mass transfer that can be in place.

1:44

So before we get there now, there is no additional reading planned for this week because last week we talked about chapters 8 and nine of the reader corresponding to chapters 17 and 18 of the required class textbook.

1:57

So again, chapter eight of the reader, this is my kind of short form revision for mass transfer.

2:02

For those that might have been uncomfortable with the first time and wanted a bit of a refresher.

2:07

Chapter 9 is really the meat of the section where we're getting into the the process of absorption relative to mass transfer.

2:15

So you're going to see content here that's coming from both of those reader chapters and corresponding McCabe chapters that we'll go through now.

2:25

So our two, let me grab my laser pointer.

2:27

So our two archetypes that we care about for mass transfer, and the reason we're approaching is we're going to base what we talk about on one or more of these archetypes.

2:39

So in the top case, we'll focus on this top case first.

2:42

We call this archetype equimolar counter diffusion.

2:48

Equimolar meaning an equal number of moles.

2:50

Counter diffusion.

2:52

I have one material diffusing one way, and it's being replaced or substituted by another material diffusing another way.

3:00

So equimolar counter diffusion.

3:03

Now in that scenario, and here I'm thinking about component A.

3:07

So diffusing from the left to the right, I can see from a high concentration to a low concentration, Component B from the right to the left going from a high concentration to a low concentration.

3:18

What makes this equimolar encounter the names that we're using is that I have a linear change between the two and a constant between the two.

3:29

So for everyone molecule of component A that flows to the right, it is replaced in its position by a molecule of component B flowing to the left.

3:39

So equimolar counter diffusion is our first archetype.

3:43

One thing I can use, I can consider a theoretical example if I take 2 stationary tanks.

3:51

So let's say I have like 2 fish tanks, right where I'm just a theory.

3:55

So I'm using A hypothetically.

3:58

But if I had these two fish tanks where I could theoretically put them back inside well end to end.

4:02

So there's one shared wall and the liquid in them.

4:06

I have component all component A in the first tank and all component B in the second tank.

4:12

And let's say they're soluble in one another, but there's no fluid motion.

4:16

And so if I removed the partition between the two tanks, then what I would end up seeing in its theoretical limit is this equal and opposite diffusional flux from component A and component B.

4:30

So I can write that flux out.

4:33

If I'm in a liquid system, then that mole or that molar flux for component A as written here is depending on the velocity times its concentration of component A in the system, less the diffusional contribution.

4:46

So the volumetric diffusivity and the concentration grade, I would take the same approach to apply it to a gas system except I'm correcting concentration or replacing concentration with mole fraction and instead of a concentration gradient here I have a mole fraction gradient and a molar density.

5:04

So effectively my thought here is to look at what is the molar flux of material from 1 component or from one side of the tank to the other.

5:15

Now if I had no velocity in that example, so I had just these two tanks and I removed the partition between them.

5:22

Then in the case of my liquid, because I'm using fish tanks, right?

5:25

So I have liquids in there.

5:26

Well, I don't have a background velocity.

5:28

So U naughty in this case would be if maybe both tanks were in flow and I'm looking at this interface while the whole system's in motion, then I have to consider something like U naughty.

5:39

Well, without that, if I have a purely static system, then in fact my molar flux is just the volumetric diffusivity and the concentration gradient on which it's supplied.

5:50

So critically, I can see there that to get the basics of a mass transfer operation correct, well, I really need to know this concentration profile as I move, you know, away from the interface in either directions of the interface between my two phases where I'm transferring this mass.

6:08

But I also volumetric diffusivity is critical to my ability to perform forward calculations.

6:14

So there are a few methods that I can use to calculate this diffusivity.

6:18

All right, if I have a gas phase, I can look at any of these three methods here.

6:25

So I now I can approximate this with theory using some estimate of the molecular velocity and the mean free paths of it, the tortuous path that a randomly diffusing molecule might take.

6:39

I can if I have a well defined, chemically well defined system.

6:43

So in this case something like a binary system where I know enough about the molecular or intermolecular interactions that I can capture those forces with a Leonard or well a potential field, right?

6:54

So if we go back to Thermo, you might have seen me talk about the Leonard Jones 612 potential as just one example.

7:01

So if I know something about the molecules well enough to use a potential model, then I can use that in the gas phase to get at molecular diffusivity.

7:10

And if I'm in porous media, I have to take whatever I would normally do in the bulk phase.

7:16

And I have to add another term to this to account for the fact that now my my gas molecules don't have free roam of atmosphere vapor to run in, right?

7:26

They don't have the whole atmosphere to flow around in.

7:29

They have a tiny little pore.

7:30

And so that acts as an additional constraint to the diffusion behavior.

7:35

So these are some of the approaches that we can use in the gas phase.

7:38

But I would caveat these by saying this is not anywhere near as well understood or well characterized a discipline as something like heat transfer.

7:50

So I wanted to tease this in the next few slides out because the degree of certainty we as engineers typically bring, the heat transfer problems, we need to be careful not to let that certainty also mirror how we look at mass transfer problems.

8:06

The discipline of mass transfer, because of the nature of what powers these diffusion curve or these volumetric diffusivities, what they depend on and what we don't know about, they depend on some things like the potential field, it becomes much more difficult to produce a prediction with certainty.

8:25

Now, this is further reflected when we go to considering the liquid phase.

8:29

So the Stokes Einstein correlation, you know, and this has gone into in some detail in the book.

8:35

I'm really not going to spend much time out of here.

8:36

This is a theoretical model that's really useful from a conceptual learning standpoint, but this is not practical for an engineer to use.

8:44

So functionally I have two methods for volumetric diffusivity that are useful to me in the liquid phase, the Wilk Chang correlation.

8:53

This is what I can apply for non or partially ionized systems.

8:56

So if I don't have a lot of electrolytes flowing around in the system, maybe I'm dealing with hydrocarbon dominant fluid liquid, then the Wilk chain correlation would be most useful.

9:06

But if I'm or if I only have a few electrolytes, if I'm in a pure non electrolyte system, so I'm in a pure hydrocarbon or have you know, 0 electrolytes flowing around, then I can take a simplification of that with or a simplification of the Wilfrank correlation that we'll look at in a minute.

9:27

So on the right hand side, I also wanted to tease out, well if our equimolar counter diffusion is one kind of bounding condition or archetype for mass transfer that we can use.

9:40

Well, what would happen if instead of having every molecule of component A flowing from from left to right being replaced perfectly in order by a molecule of component B, what would happen if component B was stagnant and component A was the only one diffusing?

9:58

So in that case I would get a curvature.

10:01

So if I only have diffusion in One Direction, I would end up getting a curvature in the concentration profile of both component A and component B.

10:10

So the central point of showing these two side by side like this is to highlight a difficulty in that or the the next level that makes mass transfer difficult.

10:20

When we think of the heat transfer analog, right?

10:24

A Joule is a Joule is a Joule and that you know, comes from thermodynamics.

10:28

So if I lose a Joule here or if I gain a Joule here, I've taken it from over there or it's transferred from over there.

10:34

The difficulty with mass transfer is that I need to think about a space or, or, or an isolated region, a control surface, and I need to hold that in my mind as I'm thinking about what's moving in or around it.

10:51

So if I have one component diffusing, I still have other molecules there and my thing or my, my overall term, something like the concentration is a sum of all of those things that are present, not just the thing in motion, right?

11:07

Whereas in heat transfer, we'll tend to talk about delta energy, energy moved or changed.

11:12

So for this reason, right when we start coming into mass transfer problems, we need to have a clear picture of all of the components that are present, and we need to be really aggressive about making sure our assumptions are listed.

11:27

If we're assuming equimolar counter diffusion, we must list it.

11:31

If we're assuming we have a stagnant second phase, we must list it when we're producing our predictions and report.

11:40

So if we were looking at something like a gas phase, and I'm not going to spend too much time on this because it's not a calculation I intend you to take, it's just something I want you to be a little bit comfortable with, right.

11:50

So where these these values actually come from and what do they depend on?

11:55

The Chapman and Skong equation is decent if I'm trying to produce calculations for binary diffusivity.

12:00

So instead of a single molecular diffusivity, this would be the binary of component A and component B together in the system.

12:07

So this is the type of semi empirical approach that we would get out where we have some empirical pre factor.

12:14

It's depending on temperature to the 1.5 power.

12:17

I then have a mean weighting of the molecular weights of components A&B raised to the point well square rooted or raised to the .5 power divided by pressure because again I'm operating in the gas phase.

12:29

And I'll then I have two terms I need to think about or or rather 22, well, two characteristic terms that are going to help me conceptualize why this binary diffusivity in general is a complex thing to look at.

12:45

So the first is the effective collision diameter that is going to represent.

12:50

If I have two, remember I'm in the gas phase.

12:52

So I have my binary system, I have molecules of A&B going in all directions at all points in time here, diffusing around when a molecule of component A and the molecule of component B collide, what is the overall diameter of that colliding system, right?

13:11

And the reason that I care is that the amount of energy in that process and the direction, the amount of energy that can be imparted in the motion of one of those components is related to the momentum of the molecule in motion, right?

13:25

So if I take, you know, 2 little toy cars and a crash versus 2 road transit crash, the size of the collision is critical to understanding the momentum at the molecular level.

13:36

So if I were to look in Appendix 19 of our textbook, we can see here, here's the collision integral and I'll come back to how we're going to get that in a minute.

13:45

But here's the collision integral for different types of molecules that I may or different types of conditions so that I can apply to different molecules.

13:55

All right.

13:56

If I come to the second table here for all of my different chemical compounds, I can see the far right hand side.

14:02

This is the collision diameter, the effective diameter for that molecule.

14:08

Now once I know the molecule's collision diameter and I've taken number average of the two, I then need my second term $\Omega_{D,2}$, which is the collision integral.

14:18

So once I know σ for both components A and B I say well for the same component A&B, what is this ϵ on K term, right?

14:28

Where I can look up for each of these and say OK for let's say acetone and end error, right?

14:34

I can see acetone has a value of 560.2 Kelvin and error of 78.6 Kelvin.

14:40

But that's not going to get me my actual Ω term that I'm going to need.

14:45

What I do is then multiply these by the temperature and then I can come over to this table and look at ϵ or KT on ϵ .

14:53

Sorry, I divide these by temperature or temperature divided by this right hand or this column rather gives me a value.

15:00

So I have KT on ϵ 1-2 and then I can read down in this table what is my $\Omega_{D,2}$ value, so the collision integral value for it.

15:11

And again, this is for a binary system.

15:14

So you'll notice in this side, I go from ϵ on K.

15:19

This is on the Boltzmann constant.

15:21

Well, to get this into an $\epsilon^{1/2}$, I need to take the square root of ϵ_a that I'd get out of this column and ϵ_B that I'd get out of this column.

15:32

OK, So again, we're not intending to go through the process of actually deploying these calculations in the lab.

15:39

But what I want to make you aware of is when we say something like the volumetric diffusivity, or in this case the binary diffusivity between two gas molecules.

15:49

To be able to predict something like that with even a moderate degree of empiricism, which we can see showing up in the Chapman and Scogg equation, I need to know something about the potential energy, the potential energy well between these two molecules or these two chemical compounds to say something like that.

16:11

Just like the origins of internal energy and driven dynamics.

16:14

It requires me to go back toward the foundations of chemical physics, in this case using say a Leonard Jones force potential to be able to get the right terms to then power that equation right.

16:29

So I'm ultimately This is why when we say we rely heavily on something like experimental data, right, it's peer reviewed studies or reference manuals that I can properly cite for volumetric diffusivity.

16:43

This is a really critical part of mass transfer for the practical engineer is knowing OK, if I'm going to do something in heat transfer, I can probably rely on theory and and historical empiricism to get me a long distance down the road when I approach mass transfer operations much, much sooner in the process, I need to have surveyed the literature to get a very clear understanding.

17:07

Are the volumetric diffusivities I need already there?

17:11

Have they been measured in a convenient enough or similar enough form that I can deploy them?

17:17

And if not, then step one in my process is actually to go out and find those or have those measured so that I can power the process because I really can't stretch too far in assumptions or similarity to previous approaches.

17:33

Now, if I'm in this special case of diffusing gas through a pore, diffusing fluid through a pore, then the main constraint to think about, you can imagine the pore in a rock.

17:44

And this if we went out into the garden and looked at any generic rock and put it under a huge microscope, we'd see that actually most of our rocks are made-up of these tiny little pores, which almost, if I were to zoom them up, look like a dry kitchen sponge, right?

17:59

So if you let a kitchen sponge dry and you can look at it, you can see all these little porous surrounding everywhere.

18:04

And the sponge, well, it's actually those that hold the liquid, the material of the kitchen sponge, if you go with one of those classic ones of yellow and green, that yellow material on the sponge, well that's not whole liquid is not dissolving into that.

18:19

But there were my kitchen sponge would dissolve when it got wet.

18:22

It's actually the little tiny gaps in throughout that entire yellow material of the kitchen sponge that can hold either liquid when the sponge is wet or when it dries out.

18:33

They're holding air.

18:34

So all these little pores that exist in in similarly in rocks and throughout the planet, I need to think about, well, what's the diameter and in many cases the diameter distribution of those pores throughout the rock material.

18:49

And these matter because if I'm trying to move material through those rock pores, I need to know firstly how big are the pores relative to the thing I'm trying to move through, right?

19:00

And the key example of this is if I look here between panels AB and C, Well, if I have really large pores, and let's say I have this as my binary diffusion equation of molecules A&B, well then the large pore is big enough for both molecules A&B to flow through.

19:17

And in fact, it's so large that for all intents and purposes now it needs to be a bit larger than this.

19:23

So I can fit, you know, multiple molecules in it side by side through it once.

19:28

But if it's sufficiently large, then in fact the molecules don't really know they're in a pore, right?

19:33

From their perspective.

19:34

If they they can only see the horizon immediately around them, then from their perspective actually either doing just fine and they think they're in a vapour phase.

19:44

Once the pore gets to an intermediate scale right where it's large enough to allow any of the molecules to pass through it, but it's going to constrict how easily it is for them to go at the same time.

19:56

Right now, the molecules are going to have to order up and they're going to have to take turns.

20:00

Because I can only fit one molecule through that pore at a time.

20:03

And if I go all the way down to the right hand scenario where I have a really tiny pore in this example, the pore would only be big enough to allow one of my, in this case, component A, to diffuse through instead of both components A and component B.

20:19

Now for our purposes here, because we're not going into a lot of the science of molecular diffusivity or the effect of porous media, but for our purposes, if we were using a porous material, which we are when we get to the lab of absorption, right?

20:37

So the 4th lab that we're going to do, if we were using a porous material, then the diffusivity through that pore is going to depend on the pore diameter or the pore radius, right?

20:48

So we tend to assume that pores are cylindrical and so they have a radius.

20:54

When we talk about a pore radius and correspond to that of a cylinder in the pore and here the nuts and diffuse diffusion.

21:02

So the nuts and diffusivity is some again an empirical pre factor times the radius of that pore times the square root of the temperature on the molecular weight of whatever species I'm trying to push through.

21:12

And if I had more than one species I would take an average molecular weight like we were looking at in the previous slide.

21:18

This would be entirely appropriate if the pore was small enough to restrict the free path, the mean free path of molecule.

21:28

So in that case I'd be looking at scenarios between the bounding scenarios of B&C here.

21:37

But if I'm in slightly larger pores, then what I can do is use a serious resistance approach to add these things up.

21:44

So one on the overall diffusivity through that large pore is then a one on the Knudsen diffusivity and one on the binary gas diffusivity, right.

21:55

So in that way, whatever one becomes larger is going to be the controlling factor that dominates the overall diffusivity.

22:02

So it's a clean approach to try to blend between those two end member conditions.

22:07

In this this prediction, R is in units of centimeters.

22:11

Again, because I have an imperial pre factor, I can't choose any units for R .

22:14

So this is in centimeters, obviously temperature in Kelvin and D sub K is then output with units of squared centimeters per second.

22:25

All right, So when we get into the liquid phase, and this is where we said, OK, we're going to have to rely much more heavily on empiricism now, the Stokes Einstein correlation.

22:35

And we're just showing you this to, to.

22:36

So we have an idea of where this might come from.

22:39

This would be assuming the molecule itself, right, is a perfect sphere.

22:44

So on the molecular level, my molecule is a perfect sphere.

22:48

And what it did was to think about the OR the relation of say, or what we looked at for drag coefficients around a perfect sphere.

22:56

Well, can we think about the ability for a spherical object, right, to migrate in a flow path?

23:04

What if we take that same approach and shrink it all the way down instead of a marble to the size of a molecule?

23:10

And that's where we end up seeing this Stokes Einstein equation from which uses the Boltzmann constant.

23:17

This is the viscosity of the diffusing material itself, it's average radius or the radius of the spherical molecule and its operating temperature.

23:29

So we would not use this in a practical engineering correlation if we were in the liquid phase.

23:34

There are a few approaches, and obviously these are going to depend heavily on where you can find evidence that the system you're trying to apply it to is appropriate, or better yet, if you have experimental data that you can substitute for your system.

23:50

But the Wilka Chang correlation is quite widely used.

23:54

If I have molecular weights below 400 right now, we would typically say we have 4:00 to 5:00 orders of magnitude smaller for volumetric diffusivity and liquid than that of the gas, right.

24:06

So these equations are going to produce really, really small numbers compared to what we might get if we were going through the exercise of having calculated gas volumetric diffusion.

24:16

But if I have a relatively small molecular weight, so below 400 here, I again have that molecular pre factor and I'll come back to size of B in a minute or so.

24:30

But we have our same molecular weight to the .5 power temperature now is to the one power instead of 1.5 MU in this case.

24:38

This is the viscosity of my material and $V_{sub A}$, this is my molar volume of solute as a liquid in its normal boiling point.

24:47

So my molar volume, my thermodynamic term, but if I had taken it to the its typical boiling point.

24:54

So we create a point of equilibration comparing across different materials.

24:59

Now $\Psi_{sub B}$, this is my association parameter.

25:04

This is in fact the direction that we go when we start talking about things like the cubic plus association equation and state from thermodynamics, right, that we showed, but we didn't really go into detail of how to use or to do it manually.

25:18

So this association parameter is going to account for the ionic association of dissolved material.

25:24

So if I take water and I start loading in different salts and maybe a bit of ammonia, right, I am increasing the amount of association of ionic association in that fluid as a consequence of that, right?

25:39

I'm going to have to account for the effect of that association parameter when I try to calculate things like how easy is it for stuff to move through that fluid?

25:47

So if we were to do a calculation like this, certainly I would give you each of these terms.

25:52

And so we're it would be a plug and chug type calculation.

25:56

But for all intents and purposes, again, we would be looking to literature to find volumetric diffusivity where possible in these complex systems.

26:06

Now if I don't have that association concern, I can take the same Wilko Chang correlation and I can drop out the size of B term and in fact I can simplify it a bit further.

26:16

So I end up with a different numerical pre factor.

26:19

Now MU said water, so this is now replaced with the viscosity of water instead of the viscosity of material that I have.

26:26

And VA is again that same molar volume solute when it's taken to its boiling point.

26:31

So just a simplification, if I don't know what else to try and I need some ballpark for a first order approximation of what my diffusivity might be, appreciating that this is a very, very approximate method to deploy.

26:50

OK.

26:51

So when we're now going into a discussion around mass transfer coefficients, right now, we can start to draw a clear distinction between molecular or volumetric diffusivity and the mass transfer coefficients.

27:04

And very simply, mass transfer coefficients are analogous to something like a convective heat transfer coefficient.

27:13

They are the actual description of what we're going to see, right?

27:18

However, doing this as we go away from laminar systems into ever more complex and turbulent systems becomes extremely difficult.

27:26

And so in that sense, what we end up doing is actually replacing mass or the molecular diffusivity with the use of a mass transfer coefficient that is then correlated to the system of interest.

27:40

So up to this point, what we've done is to introduce the concept of what is volumetric diffusivity.

27:45

And if we were to calculate it, how might we therefore go about doing that?

27:50

And we saw very quickly we got into not just having to know about, but having to exploit our understanding of something like a potential energy model, in this case the Leonard Jones 612 that we looked at on the previous slides.

28:05

But doing that in a turbulent system, particularly where we go beyond having just two components, which most of our practical systems are, becomes extremely hard to rationalize.

28:16

So these mass transfer coefficients, which will generically call little K sub C , these allow us to use a correlation to get to that same end.

28:25

And in fact, to go beyond that to be able to talk about transient or turbulent conditions, which is again where engineers often prefer to operate unless they have a very good constraint not to.

28:38

So our mass transfer coefficient then fundamentally is going to be, if we write this out for the again, the end member condition of equimolar counter diffusion, we'll take the form of a flux of component A divided by the difference in concentration.

28:54

So basically, what does that mean physically?

28:56

J sub A how much what is the the rate at which material is moving from high concentration to low concentration relative to the magnitude of concentration difference?

29:12

So in analogue, if we think about something like pressure, if I have a high pressure vessel and a low pressure vessel, how quickly is matter or material going to move between them when I open the gate, right?

29:24

That's the analog that we're looking at.

29:25

And our goal here is to use and deploy correlations to get at the heart of what is this little case of C.

29:33

Now fundamentally for equimolar counter diffusion, we've introduced this because our mass transfer coefficient reduces to a very convenient form and that is the volumetric diffusivity that we've just been looking at.

29:46

But divided by δ and δ is the film thickness in flow, right?

29:53

So in the same way that I have my hydrodynamic and thermal boundary layers, well,

that hydrodynamic boundary layer is going to engender a concentration profile if the concentration of material coming through is changing and diffusing.

30:08

So my hydrodynamic boundary layer then adapts to also represent this thickness δ .

30:15

But it goes a bit beyond that, right?

30:17

I have at some point I also have to consider at what point is my constant rather the momentum distribution of my system is affected.

30:28

Well, is the base effect.

30:29

If we go back to that very early slide, we had U not that's the overall velocity gradient in my system.

30:35

That's what gives rise to my hydrodynamic boundary layer.

30:38

OK.

30:39

But then I take a step beyond it because in this this metaphor of molecules in motion that gives rise to the hydrodynamic boundary layer, those molecules are both in a group motion of flow, but also individual motion.

30:54

The molecules still retain their individual degrees of freedom.

30:57

So it's kind of like you can imagine if you had a whole group of dogs that were running together through a park in a really tight configuration.

31:05

Well, they're still going to have the autonomy to to run and jump left, right and centre through the herd, but the overall motion of the herd's flow is still directing that background.

31:17

So we're having to think about both of these effects when we talk about little δ .

31:22

But the point being δ is effectively the film thickness that I'm applying the scenario to.

31:29

So when I have this little δ , or rather when I can calculate $K_{\text{sub } C}$, this is giving me a composite number.

31:38

So I can think of it as a how much stuff moved relative to the concentration profile and or I can think of it as the the actual volumetric diffusivity on the thickness of things.

31:51

It's or the thing it's trying to diffuse through, which is in this case the fluid film.

31:57

OK, so I can write this this out, this full definition.

32:01

I'm not going to expand it outward for either a vapor phase or a liquid phase or in the vapor.

32:06

I'm relating my vapor phase mass transfer coefficient case of Y to case of $C \cdot P$ on RT.

32:15

Similarly for liquid, I just, I'm obviously not using pressure here, so I'll multiply it by the density of that component of the liquid or the liquid phase and the average molecular weight.

32:25

So average, you know, as we've seen in previous slides.

32:29

And if I were to look at the other end member condition where I have only one way to fusion, then I can take the same approach to how I write this out, but I can simply substitute now little K sub Y here.

32:40

So I have an intermediate driving force divided by the potential driving force in the system.

32:48

OK.

32:49

So when we then take a step forward, one of the key points we've been driving at is that at the interface, right, I can approach the overall rate of mass transfer.

33:00

And this is when, again one of those really distinguishing characteristics between mass and heat transfer.

33:05

But the overall rate of mass transfer I can define from either the perspective of the liquid losing stuff, well, from phase A losing stuff or phase B gaining stuff, because I don't want to predetermine the directionality of the mass transfer, right?

33:23

So in that perspective, I can use that understanding to actually say a few powerful things.

33:31

First of those is that when I'm thinking about something like the overall mass transfer coefficient, and this is writing it for the gas phase.

33:40

In fact, that is the sum contributions of the gas inter or the gas film transfer coefficient and the liquid film transfer coefficient, where M here is the proportionality.

33:51

And in fact, this is the slope of the thermodynamic equilibrium curve or call it line, that it's really a curve as we come into the system.

34:00

OK.

34:01

Now there's one more point that we want to make here, and that's understanding what happens in this concentration gradient for two different systems.

34:09

So let's first focus on absorption.

34:12

And this will be a gas that is soluble in a liquid, meaning it's very easy to put the gas into the liquid.

34:19

And I can see here, if I'm at the interface now between a gas and a liquid, well, this whole interfacial region becomes a delta of interest right from my previous slide.

34:29

This is the delta that I care about if it's the two fluids that are in contact.

34:36

So on the gas side of this film of this dividing line, right here is my continuum gas phase.

34:44

So the main mole fraction of components in the gas phase.

34:48

And as it approaches the interface, I'll see a depletion in that component A because it's being transferred to the liquid, right?

34:55

So in the region of this interface and for relevance, this would be on the order of say 10s of microns at most, where I'm going to see this really strong curvature in the concentration profile.

35:07

And I'll come back to Y star in a minute.

35:09

So as the components in the the interracial region of the gas side are being depleted, well, they're being picked up by the liquid.

35:15

And in fact, the nature of diffusing across that fluid interface means that I have a excessive or an above, I shouldn't say above equilibrium, but it is it's a concentration greater than that of the equilibrium concentration of the component in the liquid phase in that same mirrored interfacial region.

35:36

Now technically this is at this is still an equilibrium profile, right?

35:42

So the nature of having a diffusion system in play or having an interface right because we don't have to be moving mass transfer when the transfer process is complete, we could still we would still have this concentration profile show up at the interface.

35:59

The interfacial region in this, you know, hundreds of angstroms through 10s of microns is not governed by volumetric thermodynamics.

36:07

So what we call equilibrium for a say cup of coffee, a large volume of molecules, the definition of equilibrium changes when I come into to very, very small systems like the interface between 2 fluids.

36:23

And so in this way, what thermodynamics actually predicts for me, and this is, you know, either an equilibrium prediction or if I were doing it in transfer would be looking at non equilibrium Thermo.

36:32

The whole nature of this is that actually in this interfacial region, thermodynamics dictates I will have a much higher concentration of this component A on the liquid side of the interface than if I go way out into the liquid bulk.

36:44

Right now in distillation, the process isn't exactly reversed because my goal here is to move material right from the liquid phase into the vapour phase.

36:54

And so I've just reflected these two.

36:57

So in the same walkthrough and the same process would apply.

37:00

Now critically, when we show this Y star here, so Y if we remember this is going to be my driving force.

37:08

The difference between $Y_{\text{sub A}}$ and $Y_{\text{sub A star}}$ is my thermodynamic driving force for mass transfer.

37:15

So the fact that this is higher than $Y_{\text{sub AI}}$ at the interface means I am not at equilibrium yet in the system.

37:24

This is a transfer system that's in play, right?

37:28

So it's trying to achieve AY star condition.

37:31

That's what the condition applied by thermodynamics that it's trying to satisfy and it's it's coming close to that, right?

37:40

OK.

37:40

So what we're now going to start looking at then is how we can see the the role of of our mass transfer coefficients.

37:47

And now we're going to start looking at, OK, in practical terms, if we understand what these are, these are convenient approximations for how things like diffusivity and film thickness are going to play out when we turn up to high velocity.

38:03

Transient turbulent systems are the practical systems that the engineer cares about.

38:08

So let's start looking at how we're going to relate these two things together, OK.

38:14

So the practical employment or consideration of these mass transfer coefficients, what we're looking at here are our definitions from the previous slide of our either vapor phase.

38:26

I've got my laser pointer here, either the vapor phase mass transfer coefficient or the liquid phase.

38:32

All right.

38:32

In either way, what we can do is relate these to the overall mass transfer coefficient $K_{sub C}$.

38:38

And within this we can see that each of these is related or defined by the flux of component.

38:45

So the mole flux $J_{sub A}$ of the component of interest relative to the difference in mole fraction of the from the interface to the bulk of the vapor phase or the interface to the bulk of the liquid phase.

39:00

So our goal is to say, well, for us to be able to predict how quickly stuff is moving.

39:06

And this is really important, right?

39:08

This $J_{sub A}$, this is a target that we're interested in how much, how many moles per square meter per second.

39:17

A mole flux J is the target that we're going after.

39:21

We need to be able to estimate, appropriately estimate this $K_{sub C}$ term so that we can get at $J_{sub A}$ for either the liquid or the vapor phase.

39:33

OK, So when we had introduced this in the previous lecture, just to let you know where we were going.

39:39

So our approach, all of those Nestle style correlations, right?

39:44

The purpose of those was to give us an indication of an overall effective convection when we have multiple things in play and that that's the analogue we're going to rely on when we start working on mass transfer problems.

40:02

But of course, the Nusselt number and the Prandtl number itself, will these have no relevance in the discussion of mass transfer?

40:10

These are characteristics of thermal versus hydrodynamic systems.

40:15

So instead I need to replace the Prandtl number.

40:19

With an appropriate mass transfer analogue and I need to replace the Nusselt number.

40:25

So for the Prandtl number, we are going to replace this with the Schmidt number.

40:30

So the Schmidt number is the ratio of momentum diffusivity on molecular diffusivity and it's shown here on the right hand side.

40:37

So here I have my viscosity, my volumetric diffusivity and the density of the system.

40:44

The Nusselt number is replaced by the Sherwood number, which is the ratio of the convective mass transfer on the diffusive mass transfer in the system and we show it here.

40:53

So I have considerations of or the Sherwood numbers defined by the mass transfer coefficient, the effective diameter in the system or the effective length scale in play of the flowing system and the volumetric diffusivity.

41:08

So in the same vein, these come together just like Nusselt correlations, right?

41:13

I have my originally I had a Nusselt number, some pre factor, some Reynolds number to a power and some Prandtl number to a power.

41:20

And I might have a few other things around that if I'm correcting for viscosity, but that was the general form that we look at.

41:27

Well, now I have a Sherwood number that itself contains my mass transfer coefficient.

41:33

I'm going to have some pre factor, some Reynolds to a power because I'm in a flow system.

41:37

But now I have some Schmidt number to a power as well.

41:42

So we're going to take a look now.

41:45

And I've not presented these over such a large number of slides as in heat transfer, but I've compressed them into just a few because we're now pretty comfortable and we're going to see correlations in fact that we've seen before just reapplied to this scenario.

42:00

So my Schmidt number, now if this is or momentum diffusivity on molecular diffusivity, again, I can either write that as a dynamic viscosity on density or with a kinematic viscosity.

42:12

But generally I would expect, and this is for the the component itself of interest or sorry for the the system itself, the volumetric diffusivity.

42:20

So I would typically expect it for gases, my Schmidt number is going to be somewhere between .5 and two, but for liquids it'll be much, much larger.

42:28

So on the order of 10 to the two to 10 to the five, but many of my muscle correlations that we were using were actually going to bring them over directly as a mass transfer analogue.

42:40

So here I'm defining my Sherwood number and I'm just like we did with muscle.

42:46

I'm spelling it out the first few times, but I won't thereafter.

42:49

Just reminding this, the correlation is the Sherwood number equals this right hand side.

42:55

But we can put our definition in there to remind ourselves that our target is case of C.

43:00

That Sherwood number is .664.

43:02

That's my pre factor and it's first.

43:04

And we'll remember, we'll see that pre factor before.

43:07

As we've seen, we're raising the Schmidt number to the one third power and the Reynolds number to the one half power of the square root.

43:13

And the third root is how we wrote that before.

43:16

And I'm writing B here just to indicate this is the Reynolds number across a flat plate.

43:21

So the characteristic length of that plate is B.

43:24

When we were talking about heat transfer, our analog was the distance from the leading edge, and we used Reynolds number sub X.

43:31

So when we're going from a flat plate, but we're still in a laminar flow and looking at a pipe, well, again, here's our definition of the Sherwood number.

43:39

And now I can see I have again the pre factor.

43:42

And now I'm taking the cube root of both the Schmidt and the Reynolds number.

43:45

And I have one flow term that's going to show up here, again taken to the third root.

43:51

So I'm writing it in a slightly different style as we've seen, but it's actually the same equation and the same approach, which also conveniently right if we go back to to heat transfer obeys the same limiting value of 3.66.

44:07

So when I'm in laminar flow through a pipe, both my Sherwood and Nusselt numbers together in these correlations obey a limiting value.

44:17

Or sorry, the Sherwood number and Nusselt numbers together obey limiting value 3.66.

44:21

And I can use correlations for either one if I'm trying to get into the nuance of the heat or mass transfer.

44:30

OK, So if we're going to go to more more complex and turbulent flow systems, here is my adaptation and the Cedar Tate correlation.

44:38

So this is again in cylinder pipe flow, but I'm going to turbulent conditions pre factor Reynolds to the .8, Schmidt to the one third.

44:47

And I again have the exact same viscosity correction that we had before.

44:52

An alternative approach in turbulent pipe flow, a cylindrical pipe flow, we can, if we don't have those viscosity corrections, we can modify the power on the Reynolds and Schmidt numbers.

45:03

Although I would tend to use the Cedar Tate correlation if I didn't have additional knowledge around it or around the scenario I'm applying it to.

45:13

If I seen and we would have seen in heat transfer, there are those conditions where I have extremely high Crandall numbers and those start to get into really unique scenarios.

45:24

So if similarly in mass transfer, if I have a high Schmidt number, so this is above say 430 but all the way to 100,000, I can employ this correlation for turbulent pipe flow.

45:35

And then on the bottom, I'm looking at two correlations for flow.

45:39

So normal to a cylinder or normal to a bundle of cylinders, right.

45:43

These would be the same analogue that we looked at flow across an external air cooled heat exchanger containing cylindrical pipes.

45:51

So for a single pipe, my pre factor is .61, it's the root of the Reynolds number and the cube root of the Schmidt number across this Reynolds number range.

45:59

So consistent with what I might expect for external flow of air or liquid and a natural convection or very, very mildly forced convection.

46:09

And if I flow normal to a tube bundle, then it becomes a bit more approximate, right?

46:13

For the same reasons that we talked about.

46:16

Then I might have, you know, local buoyancy effects start if I'm denuding.

46:20

So denuding means to selectively remove one or more components to denude a phase in components.

46:26

So just like I can heat my phase across a an external tube bundle and I'm going to have a local pockets of less or more dense external fluid.

46:35

Well if I'm denuding that fluid through a mass transfer process or alternatively picking up components through mass transfer, then I'm going to have local variations in density that make it a little more approximate when I apply it to A2 bundle.

46:47

So I see the same pre factor show up or not the same different pre factor, but the same approach of Schmidt to the one third power we would have seen before and Reynolds to the .4.

47:01

And then finally we have a few more conditions for external mass transfer coefficients.

47:05

And these are not something we're going to go into in too much detail here until we get to add add a DS orption.

47:12

But we can imagine that, you know, we've talked a lot about submerged objects and you know, many submerged objects can lead to a bed and then that bed can go into a.

47:22

So engineers, chemical engineers really like to talk about packed materials for to accelerate our mass transfer processes or our transfer processes.

47:33

But what if we're actually considering the mass transfer between a flowing fluid and a material itself, like a submerged, say, sphere in the simplest of the cases.

47:46

So if I'm flowing past an isolated sphere, but I have a mass transfer process between the fluid and the physical solid sphere itself, right?

47:55

Maybe that sphere's purpose is to selectively grab a hold of one really toxic, really dilute component in my fluid, and this is a very common application of this approach.

48:10

Then I need to be able to calculate that effective mass transfer rate so I know how much toxin I can remove from this fluid as I float past a bed.

48:20

So in this case, we have again, and this is the similar to the latter third of the heat transfer correlations.

48:27

But here we're going to break the Sherwood correlation in half.

48:30

So we have a standalone pre factor and then plus my multiplicative pre factor, the square root of the Reynolds number and the cube root of the Schmidt number.

48:41

If I go from laminar flow to turbulent flow, the form stays the same, except I now have a square root across the whole the whole form.

48:52

But I modify the power on the Reynolds and Schmidt numbers internally.

48:56

I'm sorry, I modified the power on the Schmidt number internally a little bit.

49:01

And then if I'm flowing through a packed bed, so this could be instead of a single sphere of flow from laminar to turbulent, now I have many of these spheres or very spherical objects.

49:12

So cylinders being reasonably spherical, if they're not too long or or high sphericity, if they're short cylinders, then I can similarly employ employ this correlation.

49:24

I have my pre factor of 1.17 Reynolds to the .585 and the same cube root of the Schmidt number.

49:31

There are conditions on this that I can't have a bed that has too high or too low of a void material.

49:37

So this is its limitation to spheres and cylinders that will tend to give me that 40 to 50% packing.

49:43

And then finally, if I have something like rising bubbles or falling droplets, then I can use a adaptation of that.

49:50

So again, as now the square root of both the Reynolds and the Schmidt numbers to the pre factor of 1.13 where rising bubbles or falling droplets might be really important.

50:00

As if you think about something like the Deepwater Horizon blow out.

50:04

So deepwater oil and gas blow out where we had a whole swarm of oil droplets that are rising to the surface of the ocean over some three to 10 hour period depending on what week we were talking about and what operations are being done.

50:20

Well, each of these droplets as they first come into the ocean water obviously has a very, very different chemical profile to the ocean water itself.

50:29

And so there is a natural proclivity towards some mass transfer of the components that can be in equilibrium with water that are soluble in water driven by their the equilibrium difference.

50:42

And so in that case, I can imagine each of those rising and we call it here bubbles, but it's really a rising fluid in another fluid of the variable density.

50:52

So each of these rising fluid particles is going to have a mass transfer process for each of its components.

51:00

Now, the very, very heavy hydrocarbons are going to have an infinitesimally slow mass transfer, right?

51:06

Because those do not want to be in water, right?

51:08

So they have almost at equilibrium.

51:10

There's almost no, the equilibrium solubility is so terribly low in water that the transfer process is effectively 0.

51:19

But something like methane, right?

51:21

If I look at crude oil when it's saturated with methane at high pressure, about 20 to 30 mole percent of that oil is going to be methane.

51:30

Well, methane is actually you can put a lot of methane in the in a water phase under reasonable pressures, right?

51:37

Not 20 to 30 mole percent, but I can definitely dissolve a few mole percent of methane in water.

51:42

Absolutely.

51:43

And so they, the lighter hydrocarbons in that scenario, the Deepwater Horizon absolutely have a propensity to, to transfer, to dissolve across that rising droplet interface to the ocean water.

51:56

And one of the key questions in fact, is we're looking back across that exercise was to predict from a risk standpoint, well, how much, what is the transfer rate of methane into this water?

52:08

Because that's going to dictate things like biogenic food sources, right, for different species, ecological species in the water column as a function of height.

52:20

And one interesting side effect is if you look at the Gulf of Mexico from 2011, so a year after the deep water rises through about 2013, 2014, you see a really different profile of ecology throughout the water column, much of which in those upper, not the first layer, but the intermediate layers of the water column.

52:38

So 100 meters ish and down, we actually see quite an increase in the amount of of ecological activity of the things that can eat methane.

52:48

So the naturally occurring microbes and that that can eat methane had a heyday because all of a sudden the water column had 1000 times the food source that they're naturally used to.

52:58

And all of that, the prediction of all of that is driven by an understanding of this transfer process across an individual rising droplet of fluid in another fluid.

53:09

Now the exact same thing happens in reverse for falling droplets, right?

53:13

We can envision we're just turning gravity upside down, but the same transfer process is going to be in play, OK?

53:22

So hopefully we've gotten to a point where we're able to use these correlations, right?

53:28

The point of each of these correlations we've gone through, we know how to calculate the Reynolds number.

53:33

We know how to get at our Schmidt numbers in the same way we can calculate our Prandtl number, the combination of the two.

53:40

And I would definitely, definitely make sure that we've each of you had time to sit down and go through the reader chapters 8:00 and 9:00 specifically 8 on how we can weaponize the Schmidt and Sherwood numbers for our purposes in mass transfer.

53:54

But just like the Nusselt number, the point of these two is that we are going to calculate the Reynolds and Schmidt number.

54:02

We get those, we can find the right correlation for our application and we calculate the Sherwood number.

54:08

Once we know the Sherwood number, we are one step away from being able to get at the mass transfer coefficient for our system, given that we know the definition of the Sherwood number incorporates the mass transfer coefficient.

54:25

So once we have the mass transfer coefficient is our Holy Grail of the process that we've gone through in this lecture.

54:31

That's the thing we're trying to get AT.

54:34

And the point we've made is that we have to use, it's a reductivist Holy Grail, but it's the best thing we've got at present.

54:40

So once we can get that, then we can go back to our absorb, sorry AB absorption design process and say, ah, OK, now that I have that mass transfer coefficient, now I can start to do some calculations around the size and the scaling of the column.

55:00

So I can either compare my absorption predictions to reality, or if I'm designing from the ground up, I can start with the bounding conditions and work toward where I want to recommend the optimal point to be.

55:13

OK, I know that mass transfers tends to be a bit of a difficult topic.

55:17

I hope that I haven't added to the confusion.

55:20

But please, especially as we come into this module and the next, please be sure that you're making use of the team's chat to raise questions and clarifications around any of the content.

55:30

The more we all discuss it together, the easier time we'll all have to get through it.

55:35

OK?

55:35

Take care everyone, and we'll see you in the next lecture.

55:37

Bye.

Lecture 07

0:10

OK, welcome to lecture #7 So this is beginning our second module in mass transfer, our third module overall.

0:18

So now we're going to start talking about distillation columns.

0:22

This we don't have a foundational or revision chapter in our reader.

0:27

Now we're going to go straight into distillation, which is chapter #10 I would also encourage you to make sure that if the distillation reader chapter isn't making perfect sense, make sure that you had at least a look and a glance at McCabe's chapters 21 and 22.

0:46

Before I get into the meat of this lecture and the chapters it corresponds to, I really want to make the point.

0:52

Distillation, right?

0:53

As we would have seen with absorption, the process itself, right?

0:58

We can get really fancy with the chemical physics, with the mathematics and their

applications, but at the end of the day, the actual operation we're doing is pretty simple, right?

1:08

Simple enough that we're able to do it in the 19th century without too much fuss.

1:13

And that is we have a column, we fill it up with some solid inert material.

1:17

We have a gas and a liquid.

1:18

If we bring them in contact, we're going to move some finite amount of stuff from one to the other.

1:24

The previous 120 years have been more around optimizing that and as we get more insight to chemical physics, being able to predict how to improve it.

1:31

And there will be huge predictions or sorry, huge improvements to take at moving forward.

1:37

But the basis of it is not that hard.

1:40

And the reason I say it that way is that other engineering disciplines, if they need to, can make an attempt to talk about or design or work on an absorption column.

1:51

There's not a whole lot of really unique disciplinary knowledge required to improve or optimize an absorption column that we would get from chemical engineering.

2:02

Like, we're obviously the best suited of the disciplines, but it's something our colleagues can join us on.

2:08

Not so for distillation.

2:10

Distillation is one of the few things that chemical engineers do that no other discipline in the world can do.

2:18

No one has taught how to design them, how to optimize them or operate them, how to diagnose problems in them, or how to take an existing column, as you'll learn, are very expensive and port them into new applications.

2:31

So distillation is where I really want us to make sure we've had a chance to go through the reader.

2:38

Definitely sit down and go through the textbook.

2:42

The more comfortable you are with distillation, the more value you can offer to the market as a chemical engineer because it's one of these really, really unique skill sets.

2:52

OK, so in this lecture we're going to be introducing the concepts of distillation.

2:58

What is it and what's the basic flow of how we go through the design.

3:02

In fact, the next lecture on practical distillation design is more around working through examples, right?

3:08

We're actually, I'm trying to capture most of the need of distillation in this lecture so we can see it from front to back all at once.

3:15

And then we'll go back and revise a few of the concepts in the next lecture.

3:20

OK, so to begin talking about distillation, we need to start by thinking about our going actually back to what we talked about with thermodynamics.

3:31

So in when we ended our curriculum in thermodynamics, we were thinking about this flash operation.

3:40

All right.

3:40

At the very end we went to vapor liquid equilibrium and the point thereafter was to talk about flash systems.

3:47

So a flash meant that I was going to take a whole chunk of material.

3:51

Right now I don't want to presuppose its phases up front, whole chunk of material at some known composition because I have to know that dynamics, but known composition and known pressure and temperature.

4:03

So pressure, temperature composition is that side and I'm going to expose it instantly to some different pressure and temperature.

4:12

Pressure and or temperature typically will vary pressure because it's the easiest thing to put across a check valve.

4:20

So I take it from 1 thermodynamic environment to another.

4:24

What happens to the thermodynamics?

4:25

Well, it says equilibrium is going to change if I go from one environment to the other.

4:30

If equilibrium changes, then the distribution of components between however many phases are present also change.

4:38

It's the nature of equilibrium.

4:40

So my simplest flash was a single stage with a binary mixture, right?

4:46

That's and that's we were insinuating toward the end of thermodynamics, but we didn't call it a single stage flash, but we were calling using a binary mixture because chemically it was the easiest thing for us to think through.

4:59

OK, So what we were doing there was what we'll now call a single stage flash.

5:05

And in this diagram here on the right hand side, you can see an example of what this might look like in a very early 20th century application.

5:13

I have some feed of stuff presumably in the liquid phase because especially back in the day we did not like carrying things around.

5:20

In the vapor phase, it comes into a vessel where it's going to flow through some pipe network and back out.

5:27

Now, what's being sprayed in here classically would be steam, steam to warm it up, right?

5:34

Again, 100 years ago, very difficult to create pressure.

5:38

So if I'm going to want to increase the pressure of the system, I'm probably going to have to increase its temperature to my Jewel Thompson effect.

5:45

So if I as I spray steam in here, but I can equivalently in the bottom of this really simple heat transfer heat exchanger, I can equivalently have a fire burning or coal burning 100 years ago, right?

5:59

So I'm introducing a heat source on the bottom as this very crude heat exchanger is going to operate effectively allowing me to heat the species up from whatever its feedstock, presumably atmospheric and ambient conditions.

6:12

So once it becomes heated naturally, like all species, its pressure is going to rise.

6:17

And as it comes into this vessel, if I've chosen the initial conditions and I set this valve to drop pressure across this at the right valve closure, then as it comes into this environment, I'm going to go from something like a pure liquid phase.

6:31

I'm going to heat it under high pressure to keep it liquid under higher and higher pressure.

6:37

And then as it comes across that valve C, it's going to drop.

6:40

So that valve C would be an exemplar of why we'd use something like an orifice valve or an orifice choke, right?

6:48

So I'm going to instantly drop pressure.

6:50

Well, when I drop pressure now I can get into a two phase region.

6:55

And in that two phase region, I'm going to have a split of my components.

6:58

So the composition, the concentration effectively of stuff in the liquid is no longer, well is not equal to the concentration or the mole fraction of stuff in the vapo.

7:08

So I'm splitting my components between these two phases, right?

7:13

And this is what we were looking at in thermodynamics as the VLE application.

7:17

So we would remember in that scenario well the effectiveness of the split.

7:22

If I want to figure out well what components maybe I have, if I have a binary, then I have to be operating that vessel at a pressure and temperature inside the large vessel at which .1 component, right has a preferential volatility and one doesn't, right.

7:40

Meaning I have a relative volatility.

7:42

I can look at is that I can diagnose from the outcome the mole fraction of A in the vapor and on mole fraction of A in the liquid over mole fraction of B in the vapor on B of the liquid.

7:54

This is the relative volatility of A&B together.

7:58

So if I was in a scenario where I had say not enough A going into the vapor phase, then

I would decrease the pressure in this vessel, which would mean I'd turn the choke harder.

8:10

So I apply a harder choke, I drop more pressure, meaning I'm at a lower pressure in the vessel, meaning it's easier for stuff to go up.

8:18

So I get more relative volatility or more volatility of component A.

8:23

Now, I could calculate the relative volatility if I've measured the mole fractions at the top and bottom that I need here.

8:30

But if I didn't know beforehand and this is where we ended the Thermo, I could predict that behavior through something like.

8:36

And you'll remember this is Ron's law for kids, right?

8:38

Because I'm not using activity or fugacity coefficients.

8:42

I'm not correcting for non ideality in the liquid or vapor phase, right?

8:46

YIYIP is XIPI SAT, so I can rearrange that to get Y on X and then replace those with in the definition of relative volatility with PA sat on PVSAT.

9:01

OK, so this was our single stage flash vessel.

9:05

Now we what happens in this thing is dictated by Roun's law.

9:10

Roun's law is the thing that's governing the core equation or the core law behind this.

9:15

We're sure we might start by thinking of a an ideal liquid and vapor phase, but ultimately we want to progress this into a real liquid and real vapor phase.

9:28

So I can write out a component mass balance across this and this would be my single stage flash vessel.

9:35

I can run a component mass balance across that and I can also rewrite that or resolve that, rearrange that as a function to represent Y as a function of my relative volatility and X.

9:50

So in this way, I can rearrange this for a single stage flash into the basis of Y equals stuff times X for that stuff is a is a property of my governing law.

10:05

So in this case wraps law.

10:08

Now it's important to note that in this flash I'm also balancing enthalpy.

10:12

So the, you know, not once I cross Point C, the inlet to the flash vessel, the enthalpy of this composite stream will be equal to the enthalpy combination of components in the vapor stream in the liquid stream.

10:26

So if I'm knowing if I know something about the composition, I can also use this fact that the flash vessel if I assume it's adiabatic is not exchanging energy and therefore I can apply an energy balance to give me another pathway to characterize the system.

10:42

OK.

10:42

So this is just the setup.

10:44

This is the basic frame.

10:46

When we ended thermodynamics, the last thing we looked at in a little bit more detail here, I can see this is my traditional PXY curve.

10:54

So I have my bubble on the top, dew on the bottom.

10:56

If I were to nominate the pressure in that vessel, as we were just talking about, well, if fluid's going to come in at, let's say, an equimolar binary composition, well, the 2nd, if I'm operating that at the correct pressure, not too high, not too low.

11:10

So in this case, maybe about 40 kpa right as it splits, I'm going to have my gas phase composition.

11:21

So if I trace, if I put my marker here first at the bisection of my operating my flash vessel pressure 40 kpa and my feed composition.

11:31

So we'll call it ecomolar to begin with.

11:33

Well, as I trace to the right, I'm going to bisect and imagine these are straight lines I'm drawing.

11:38

I'm going to bisect the vapor curve, the do curve, and so this composition that it drops out with gives me the gas phase composition.

11:47

This is Yi and I can do the same with the left to get what's the liquid phase composition.

11:53

So if I started with something that were equimolar by taking it into that single stage flash vessel, what I'm functionally doing is exploiting the gap between my bubble and dew point curves such that the vapor composition is now enriched in component 1, right.

12:13

I can see here I'm getting out about 60 between 60 and 70% on this diagram at these conditions and the liquid phase is denuded in component one.

12:24

I can see it's exiting with call that 20 to 30 mole percent on this diagram.

12:30

So we had spent so much time in thermodynamics on Route's law $PXYTXY$ because it's the nature of being able to correctly predict the gap between bubble and dew point curves.

12:45

This is the property I can exploit to separate material on a molecular level, right?

12:52

And here we've done that just in a single flash vessel.

12:55

So it'd be a tank, maybe the size of a car, traditionally turned on in right, a run material in.

13:00

I'm exploiting my thermodynamic choke valve or my orifice at Point C to induce a pressure drop.

13:09

When I do, I get flash vaporization, a preferential vaporization, or a flash of some material.

13:17

And it's in fact my routes law and my thermodynamics that tells me the degree to which I'm going to enrich the gas phase and denude the liquid phase.

13:28

All right.

13:28

So when we go into a distillation column, what the core concept from thermodynamics to or thermodynamics single stage flash vessel to a distillation column is that we are now taking individual flash vessels and we're simply stacking them side by side by side by side where the outlet to one is the inlet to the next and the outlet of that next and it's liquid is the inlet to the first.

13:54

But instead of having them arranged horizontally, what we're doing is arranging them vertically.

14:00

So this what is labeled A in this graphic, This is our quote distillation column itself.

14:07

So the components of the column, we can imagine in one portion of the column, wherever we nominate the feed is going to be, and we'll come back to that a little bit later on.

14:17

But wherever we position the feed, let's imagine we begin with our binary mixture just for simplicity.

14:24

So in the binary mixture, I've selected just like I would do with my single stage flash vessel.

14:31

I need to ensure that I have selected on that entry stage where the feed is first injected, that I have a pressure in temperature such that the lighter of the two components, meaning that which has a higher relative volatility is going to be preferentially vaporized.

14:49

So the gas phase leaving that stage of the column is going to be enriched in that that lighter component.

14:56

So here's my first stage of the column and the liquid leaving that because the liquid that's been injected is losing it is being denuded of that lighter component.

15:07

Subsequently, in a binary system, we know it will be heavier in the rich component, meaning that the component of lower volatility or lesser volatility.

15:17

So in my feed stages, I first inject here.

15:20

I can see this and we'll take a look later on at what these column stages look like.

15:25

But as I inject this fluid or this this liquid, I'm probably going to have a valve here.

15:30

So as it comes into the column, right, sorry, not a valve here, but as it comes into the column, I'm going to usually begin with a liquid mixture.

15:37

Now distillation columns, unlike the single stage flash we just looked at, we can choose whether we want a pure liquid, a pure vapor or some combination of the two.

15:46

And that dictates or rather that's a dictated parameter from the design process.

15:52

But as the enriching vapor flows upward into the next stage, we can imagine, well, I have less hydrostatic pressure.

16:03

So we know if this is a fluid column, whether it's liquid or gas, as I go from the middle to the top of the column, I'm going to be decreasing the operating pressure.

16:11

And as I go from the middle to the bottom where we're picturing a large amount of liquid here on the bottom, the hydrostatic pressure from both the liquid and the gas is going to mean the bottom of the column is now operating at a higher pressure.

16:24

OK.

16:24

So naturally I have this pressure distribution within the column.

16:28

And if we think about that, the natural gap between my bubble and dew point curves.

16:33

And again, we can use the binary system as a starting point to think about because I can maintain that gap between the bubble and dew point curves at a variety of operating pressures.

16:44

My goal as the engineer is to ensure that say in the PXY space for my bubble and dew point curves, that each tray of this column as I go from the top to the bottom is sitting within the two phase region.

17:00

So meaning there is a gap between the bubble and the dew point curves where the pressure corresponds to each stage of the column.

17:10

We'll be looking at this in more detail in the design process.

17:13

So in the above, the feed stage where I have an enrichment in this lighter component, that which has a higher vapour pressure and as a consequence the higher volatility.

17:25

We call this the rectifying section.

17:28

So it is rectifying the purity of my light component and in the below this feed stage where I am preferentially enriching my liquid phase in the heavier component or components, we call this the stripping section.

17:46

Effectively, we are stripping out any lighter components because they're going to continue flowing upward.

17:55

So let's follow an example here of material through this column so we can get a sense of what's going on.

18:02

Now my feed we're initially going to start out with and we'll come back to with this

additional heat exchanger here as it's basically an optimization that allows me to capture some excess heat and make the column a bit more efficient.

18:14

But the feed that's coming in right, I nominate it will come in at some temperature and pressure.

18:20

The extent to which I do a Preheat exchange allows me to potentially warm it up and precondition it for the column.

18:26

I as the engineer, I'm going to select in the design process whether again I have a subcooled liquid, saturated liquid, combination of vapor, liquid saturated vapor or a super heated vapor.

18:39

I get to pick what the in.

18:40

Well, in the design process, I pick what the inlet conditions are going to be.

18:44

So let's say for argument's sake, this is going to enter as a two phase mixture.

18:48

So it's already beginning to, or it's already at an equilibrium condition dictated by the pressure and temperature at this point, as it enters this first stage, let's initially follow what happens to the vapor.

19:00

So the vapor on this first stage, let's say it begins in an equimolar mixture for a binary, so 50% component A, 50% component B.

19:09

Well, my component A preferentially wants to vaporize.

19:14

So as I the vapor bubbles that flow upward to the second stage, these will perhaps be at 55 percent of component A.

19:22

And as the vapour flows upward, I'm losing more and more of my heavy components or enriching my light components.

19:28

So I may have 60% of component A in the second stage and so on and so forth such that the vapour bubbles that finally leave the very top of the rectifying section at the top of the column.

19:41

This is now at a maximal point of concentration or mole fraction in my lighter component, so it has been denuded of the heavier components in the system.

19:53

Now this vapour that flows upward we can imagine, as we tend to not like low pressure vapour streams in engineering, right?

20:02

They don't carry enough momentum.

20:04

We don't have a compressor right here, so I don't have enough momentum of that flow.

20:07

I'd much rather turn that enriched vapour back into a liquid so I can store it or transport it more easily.

20:14

So here what we're looking at is a condenser.

20:17

Right.

20:17

So we take that vapor and we put it across the condenser.

20:20

Now I can use something like a cold water, just a tap water because this is a heat exchanger.

20:25

So we're not mixing mass between the two here.

20:28

What we're showing is a two stage condenser, but I've put this through a heat exchanger using cold water or another fluid such that 100% liquid drops out.

20:38

So I've taken that vapor enriched in component A and went through a heat exchange process, condensed it into a liquid.

20:46

Now from this liquid accumulation tank, I have two options.

20:52

And this is part of the the we're going to look at in the design phase of the column, but also the operating strategy of a column.

20:59

So as I come out of that liquid accumulator, I first am going to be able to direct and decide how much liquid do I want to return.

21:08

This is liquid rich in the lighter components.

21:11

How much of that do I want to return to the top of the column?

21:15

And I get to choose that as the engineer by setting the flow rate of this reflux pump effectively.

21:23

So I get to choose how much of that pure or enriched liquid is going to be reinjected into the column.

21:31

Noting that what I don't reinject into the column, I'm going to take as we call an overhead product.

21:37

So this is the product at the top of the column enriched in those lighter components or lighter components for a binary.

21:46

And so this L / D , meaning the molar flow rate that I returned to the column divided by the molar flow rate that I take as a product, we call the reflux ratio.

21:55

And that's, we define here as R sub D .

21:58

So the reflux ratio, this is a key parameter both in the design of the column because they're at steady state.

22:05

We don't want material accumulating at any point in the column, right?

22:08

It has to continuously be at steady state.

22:12

So the accumulator height, the molar flow rates through this top section of the column would be not changing with time if we're matching our design expectations.

22:22

OK, Now the reflex, we consider reflex ratio from 2 conditions.

22:27

The 1st is how we design the column to operate its steady state, but the second is appreciating how we manage the reflex ratio and change it during the process of starting up a column.

22:38

So we're going to come back to that later on because the operating is another layer of complexity.

22:45

So let's say for argument's sake that we have a reflex ratio of one that's going to mean one mole of per second of fluid is or liquid is re entering the column and one mole per second of product is taken, right.

22:59

So we have an equity in the molar flow rates.

23:02

So this enriched liquid falls back down through the column, right, where it's going to start picking up heavier components, but it's meaning that lighter vapor.

23:11

So what it effectively does is allows the engineer to enforce a high purity condition at this very top stage of the physical column when I have a very high reflux ratio, right?

23:22

I establish that purity loop as I go from the top of the column vapor product, through the condensation and back in.

23:30

This should all be sitting at pretty much a consistent product quality before I'm going to start thinking about in an operating sense, taking a product from the column.

23:41

So the liquid that is initially injected in the feed, as this flows downward through the column, it is going to be stripped of those lighter components.

23:50

Or another way to say that is it's being enriched in the heavier components.

23:54

So the same process that takes place on the top, I get on the bottom, but mirrored right.

23:59

So I get an enrichment circuit through the bottom.

24:03

So if I look at the liquid outlet, this is going to be the point of maximal concentration of my heavier component or components.

24:10

Now of course, we wouldn't do a cooling process here because this is already quite cool liquid that's coming off.

24:17

And so my purpose, sorry, it's already a liquid phase, so I have no purpose of cooling it down to liquify it.

24:23

But instead what I'm going to do is put it through a reboiler.

24:26

This is simply a shell and tube heat exchanger that we would have looked at earlier but for the the design of it operates as a boiling unit or a re boiling unit.

24:36

So you remember that we had those internal heat exchangers by overflow.

24:40

We're here and it's the vapor product above that overflow that we take and reinject into the column is now vapor that is enriched in that heavier component.

24:50

Now traditionally most distillation columns will take a bottoms product.

24:55

We call this the bottoms product.

24:57

So in the same way we'd pull off a bit of our heavier, sorry, our lighter overhead product is stream D.

25:03

We would typically pull off a bit of the bottoms product or the intentions to pull off the bottoms product that we would call or sorry that we call the bottoms product here that is heavily enriched in those heavier components.

25:17

When we do so critically now we when we are taking a portion of the product from both the overhead stream and the bottom stream as we're showing here, we would consider that both of these stages are additional equilibrium stages.

25:33

So going back to our original point, if each of these little horizontal lines indicates what would otherwise be a separate single stage flash vessel from thermodynamics right here I can see I have some number of flash vessels side by side.

25:48

I'm just stacking them vertically.

25:50

When I have a design where I am both or taking a partial product both from the top and the bottom of the system, then both of these unit operation flows act as though they're additional 2 stages, right?

26:09

Two more flash vessels, two more equilibrium stages.

26:13

If I don't take a bottoms product, meaning I pull liquid out here, I vaporize everything and return it to the column, this is no longer an equilibrium stage.

26:22

All it is, is a heat exchanger with the purpose of changing phase.

26:26

So it's an equilibrium stage when I'm splitting the product and taking a portion of it and the same thing would apply to the top.

26:33

So in many, well in simpler distillation columns you will typically see, and this is the case for the laboratory set up, we are not using the bottoms product.

26:45

Well, we're not using the re boiling system as a bottoms product.

26:49

So whatever liquid comes out the bottom, we're vaporizing everything and re injecting it into the column.

26:54

However, in the laboratory set, if we are taking an overhead product, so we would consider in the lab that this overhead, this condensation system is going to act as an equilibrium stage.

27:06

But if we have a complete reboiler, meaning we vaporize everything, this does not act as an equilibrium stage.

27:13

Now we're going to be going through this diagram and different versions of it and learning how to design it.

27:18

But the key point I want to begin with, what are the things that the engineer gets to decide?

27:24

So the 1st and most important, the number of plates were also called equilibrium stages in the column.

27:30

This is a key design parameter of the engineer.

27:33

And in fact, this is what we're going to use the method of McCabe, the McCabe Thiele method to determine.

27:41

And this McCabe Thiele method, right, is where we end up using the Caves textbook from because this is the origin story of that method and it is used to design virtually every modern distillation column there are.

27:54

We can methods to automate it now, but the method itself is an adaptation of what we were looking at previously with the operating and equilibrium lines in our absorption columns.

28:08

So this number of plates and stages, this is what the equal or the McCabe Thiele method is going to deliver and we'll learn how to do that.

28:16

The feed location and the feed rate.

28:17

So where does this enter and how much is going in?

28:21

Now, the real consideration for the engineer is the location, the feed rate, the molar flow rate of input product or input to this column is ultimately dictated by the overall mass balance, right?

28:34

If I'm operating this steady state, I better darn well make sure I don't have an accumulation of mass anywhere in the system.

28:40

So what at a very high level, if I drew a control surface all the way around this, what I need to ensure is that the molar flow rate of what comes in is equal to the molar flow rate of what comes out of the top versus what plus what comes out of the bottom.

28:55

Those three things must be equal.

28:57

So that place is a pretty clear constraint on the feed rate, but the feed location is up to the engineer to the side.

29:03

And in fact, the McCabe Thiele method tells us how the reboiler duty, meaning the heat flow into the reboiler.

29:10

Here we're using steam.

29:11

So that duty would come from the type of steam and the flow rate of it.

29:15

Or if I'm operating with something, I have variable temperature, maybe on molten salt or I'm using an electric type reboiler kettle that I can determine how much energy am I transferring into this to, to vaporize this liquid?

29:28

Now traditionally I wouldn't want to take that past a saturated vapor.

29:33

But if I wanted to start getting into more and more energy duty, right, this is going to affect my design.

29:39

And then similarly the condenser duty.

29:42

So here I'm showing cold water coming in.

29:44

If if we don't have a choice of what temperature, then our choice of duty, meaning heat flow is going to come from the flow rate of that cold water through the system.

29:54

So here we're taking a look at a slightly more graphically designed distillation column.

30:00

And I show this because I always find it difficult to look at a static black and white sketch and try to visualize where are things flowing and why.

30:09

So in this, let's take a look at what's actually going on here.

30:14

And I'll come back to the inset examples or the industrial example here in a minute.

30:19

In this particular column, we have 7 trays or equilibrium stages within the column, as it's shown.

30:26

So our feed, right, is on the 4th tray from the top.

30:29

So tray #4 and we can see here, the suggestion is that we're feeding 100% liquid.

30:36

Now we don't know whether that's a subcooled or a saturated liquid, but we'll assume it's saturated for this purpose.

30:44

So here we have our liquid feed that's going to pour into this into these trays.

30:48

Now the design of this is such that when we originally looked on the previous slide and it was just a solid black line here.

30:56

Well, in reality, we actually see the tray is structured and if we look at the inset that we have an individual set of trays that hold these little areas for liquid accumulation.

31:07

And at the end of that tray, so across from the feed will be this Weir that allows additional liquid that might be flowing atop each of these active tray spaces to spill over effectively.

31:18

So we call this the down Comer area in the sense that the additional liquid that's going to be falling down will be coming through this right hand as it's pictured side of the tray.

31:30

Now an interspersed throughout this active tray area, you'll see these little T shaped designs.

31:35

So this is what's known as a bubble cap.

31:38

Now, the idea here is that if I'm also, if I have warmer fluid, fluid, meaning liquid and gas beneath this particular tray, then the vapor is going to be what's rising, right?

31:48

It's less dense and it's warmer, so it wants to migrate up.

31:51

So this vapor will pack inside of each of these little T shaped units or these bubble caps.

31:57

And as the local pressure becomes ever so slightly higher than the pressure beneath it, these bubble caps will open.

32:03

As they open, the gas is allowed to escape.

32:06

And critically, you can see that there's a contact area between the edge of the bubble cap and the liquid that's beneath it.

32:11

So the gas, if I follow imagine one pocket of gas is going to flow through this bubble cap.

32:17

And as the pressure here, it's high enough, the bubble cap will open, allowing this gas to flow into and the bubble cap might rise a bit, allowing this gas to flow into the liquid.

32:28

Now, I can also have a static system here where it simply allows the pressure to build and it's going to directly bubble it without any motion on the tray.

32:35

So we'll come back to a little bit later.

32:37

There are variations in these tray designs and the bubble cap designs.

32:41

These are part of the IP of buying different types of distillation columns, right?

32:47

And different designs around them.

32:49

But the essential thought is that or the design premise is that I have these gas bubbles that are going to come up and they're going to bubble into the liquid.

32:57

So at this point you imagine I have the intimate contact of a gas bubble and a liquid.

33:03

And those two phases have a slightly different composition, right?

33:09

The and that's because the liquid is coming from this equilibrium tray above, it's falling through the down Kerber area, so over this Weir.

33:17

So the equilibrium established at this pressure and temperature is different than the equilibrium established at this pressure and temperature.

33:25

Therefore the liquid at coming into this intermediate tray is different in composition than it is than is the gas, or rather I should say different in chemical potential, right?

33:37

Because that's our driving force for mass transfer.

33:39

So as this bubble rises from the the tray beneath and contacts the liquid that's fallen from the tray above, I now have a chemical potential driving force for that little bubble as it contacts the liquid.

33:53

And what do we know from thermodynamics about when we have a chemical potential driving force?

33:58

This is what allows us to transfer mass from one phase to another.

34:03

So in this way we would call this intermediate trade.

34:06

This is 1 equilibrium stage because it's not happening as one, you know, flash vessel, but rather you can visualize in this stage I have actually 100,000 tiny little flash vessels.

34:19

Every time a bubble's going to contact liquid, I'm able to re establish a new equilibrium.

34:25

Right now, as that equilibrium is established between this in each of these pockets, between the gas and the bubbles and the liquid, the resultant bubble that then flows upward and out has been denuded in some way.

34:39

Meaning it's lost one or more, well, a fraction of one or more components to that liquid phase.

34:46

And it's now in equilibrium with the liquid as it exits.

34:49

So the gas in this bottom space that's flowing upward has a different composition to the gas in this middle tray after it's contacted that liquid.

34:58

Now if I go back to the main diagram for a minute, I can see when I insert my feed here, this is going to establish equilibrium on this intermediate tray.

35:06

But here now I have three additional equilibrium stages above that here I can see my reflux line.

35:12

So that's the the liquefied distillate return, right?

35:17

So I've taken that gas vapour return, put it through a condenser, a total condenser.

35:22

So I've put all of it back into the liquid phase and I'm returning we don't know how much in this diagram, but some portion of it into the top of the column.

35:30

So the, well, actually, if I'm using a total condenser, then the meaning I've condensed 100% of the vapor, then actually the composition of this vapor is identical on a molar basis to the composition of this reflux because I'm not taking it through another equilibrium stage.

35:46

If I'm condensing all of it.

35:49

Similarly as I come to the bottom, I'm going to be continually.

35:54

And then we're using the color of the liquid phase here as a kind of a proxy to indicate compositions.

35:59

You're able to see a nice gradient in terms of the bottoms composition, as we call this liquid is going to be much richer in our heavier components, leading to the darker color than the tops.

36:11

Composition is another name for it where it's going to be depleted in those heavy components and much richer in the light components, hence the lighter color.

36:19

So this is what's happening on each of these stages.

36:21

Now critically, if I were to take an example here, these are the size scale of distillation columns that you might find in industry where just one of these columns would be represented by the diagram of what's going on here.

36:35

And so in this picture I can see there are looks like 4 distillation columns connected together.

36:42

Now good rule of thumb like why do engineers or chemical engineers care so much about distillation columns?

36:48

Well when we go to build these for industry, a really good heuristic or rule of thumb for the cost to know how much are these going to cost is every tray tends to cost about a standard luxury car or Mercedes-Benz is the old heuristic.

37:05

So for every tray of a distillation column, the engineer needs to account for about 1 Mercedes-Benz in cost right Now, we're not saying like the best or the cheapest Mercedes, but kind of an average luxury car.

37:16

So, and that's a good heuristic because it scales to different locations on the planet, right?

37:20

It's much more expensive to import a high end luxury car maybe to a really, really remote region without a car dealership than it is to buy it right next to the factory.

37:29

So as we start to try to think about where do we place distillation columns?

37:34

How do I construct them in different environments?

37:37

If I have to think about maybe building them in a really harsh environmental climate, I have to go to ever more expensive materials.

37:46

And if we imagine in Perth, maybe a Mercedes-Benz costs something on the order of

\$150,000, then something that's going to have 10 trays in it will be a \$1.5 million column.

37:59

Now that doesn't account for the cost of my condenser, my reboiler, any of the pipe network, any instrumentation.

38:05

That's just the column itself.

38:08

And so when we drive by and you can see, you know, there are examples of this, I think Kwinana has quite a few as you drive by facilities that have these numbers of distillation columns put together.

38:20

It's actually quite, quite remarkable to look at and say, wow, you know, from an engineering and a process landscape, that is a phenomenal amount of money that's been spent to create this distillation system.

38:31

Now, something that we'll come back to a little later, but why would I tend to see multiple columns put together?

38:36

Well, right, the distillation column itself is designed to target a much more complex operation than AB absorption.

38:47

In absorption, I'm really targeting 1 component, right?

38:51

Maybe I can get lucky, and if I pick the right liquid phase, that can collect two toxic or two target components for my liquid or for my vapor phase, maybe I can get two in one if I'm really lucky.

39:04

But the power of a distillation column is that it can take in a feedstock built of any number of components.

39:10

And when I say any, I'm talking above 10,000.

39:14

So I can take an incredibly diverse chemical mixture, feed it into a distillation column, and based on the design process I go through and how I decide to run the column, I can split that chemistry in half.

39:29

I basically get to pick a point, right?

39:32

If I imagine I line up all of let's take 10,000 components, maybe we're taking a heavily pressurized biofuel of some sort.

39:41

So I've refined this, I've biodegraded it in a high pressure environment and what I get out of that is a 10,000 component distribution.

39:50

So if I were to take all 10,000 of those components and line those up in terms of their vapour pressure, so I'm giving myself an indication of the relative volatility.

40:00

Of course I need to go back to thermodynamics, my activity and fugacity coefficients, to get an ever more refined definition of that relative volatility, but vapor pressure is a good first approximation.

40:13

So if I took my 10,000 components and lined them up from 1 to 10,000 in terms of their intrinsic pure component vapor pressures, what I'm effectively doing in a distillation column as the engineer is creatively deciding OK.

40:27

I'm going to cut this line of 10,000 in half and I get to pick where I cut that.

40:34

So if I were to think about something like a biofuel, well, if I have a heavily diversified biofuel, I can probably fractionate that to maybe a, a very light portion of the fuel can be used as like a bio gas or a, you know, a bio butane kind of an intermediate gas liquid form.

40:55

Depending on the pressure of the storage, maybe a intermediate cut can be used as a bio diesel to power a passenger car.

41:04

A slightly heavier cut as I go to maybe 10 or 11 carbons on forward is going to be a bio kerosene that could be used for something like synthetic or low emissions jet fuel.

41:15

And as I go further and further down the line, I can find all of these chemical uses.

41:21

So if I look at distillation columns, I say, ah, OK, if I take these 10,000 components that are lined up in vapor pressure, the first column is going to cut the thing in half.

41:31

So now I have 5000 components and 5000 components.

41:34

The first are the lighter 5000 and the second are the heavier 5000.

41:38

But if I choose to cut it right in the middle, well, if I bring in two more distillation columns now, one for the light 5001, for the heavy 5000, and for argument's sake, let's say I cut those in half again right in the middle.

41:52

Now I have the top quartile of the lightest 25% or 2500, the intermediate or the 2nd and 3rd quartiles right each that are being split out from distillate from these three distillation columns.

42:05

And I can keep going through this process.

42:08

So in this way, if I know that I'm going to be taking in a constant feedstock of this, say a bio fuel for A50 year lifespan, right, I have 50 years on the project I can operate, then it's absolutely in my best interest to say how many chemical precursors, how many chemical feedstocks can I create from this bio fuel, some of which are this bio?

42:30

Yeah, call it a bio fuel as a distribution.

42:34

And so that's why when we start to look at these industrial distillation columns, you'll end up seeing quite a few columns put back-to-back to back in the industrial process.

42:44

Because as long as the engineer has confidence that we'll be able to produce and use these for the cost of 1 Mercedes-Benz per tray, right?

42:52

So huge capital investment up front.

42:55

Then we can turn around and say, well, as long as we have a constant feedstock, we can produce $N + 1$ refined chemical outputs, where N is the number of columns in play.

43:09

So the first column creates 2 and then from that I split forward.

43:14

So these industrial columns then tend to be very large.

43:18

If you're going to create a system like that where you're going to take a really complex feed and split it and you're going to bring in multiple successive columns to continue splitting and refining outward, then you really want to operate at the largest possible scale to exploit economies of scale, right?

43:37

So you want the largest possible columns to bring to bear.

43:40

And that's why these tend to be, I think just for, for an example of scale, this might be something like 200 meters in height, right?

43:48

So really big columns when you go to the large scale industrial processes here again, we see just as a reminder, the upper portion of the column where I have a, a bias toward my lighter components, I'm enriching in those lighter components called a rectification section.

44:06

And the bottom part of the column I call the stripping section.

44:09

Now these names matter because when we start talking about our operating line, right, remember that, that in the absorption column, I only had one operating line.

44:19

Well, the novelty of the distillation column.

44:23

If I'm being able or if I'm choosing to cut something in half, this large distribution in half.

44:29

Now I have two operating lines, one for the rectification side and one for the stripping side.

44:37

Now if we were to say, move the feed location from this middle tray down to the very bottom tray, that would be perfectly fine.

44:46

All it means is that my stripping section is only one equilibrium stage, and in that case my rectification section would be 6 equilibrium stages.

44:56

Conversely, if I fed this on the very top across from the reflux, I would have one rectification stage and six stripping stages.

45:05

So the engineer gets to choose when I talked about at the beginning, the choice of where do I feed this thing is one of the critical choices that the engineer is going to make.

45:15

And in fact, that's the key outcome of the McCabe Thiele method and design or design method and diagram is to help you understand where you feed it and then allow you to introduce things like uncertainty parameter variations and decide am I always, is this feed location robust enough to account for the variations that I might get in the industrial process?

45:40

OK.

45:41

So we're going to come back here and look at this in more detail.

45:48

But in the upper right hand corner, this is an example or this is the first portion I should say of an example of how we're going to look at distillation in the XY plane.

45:59

So if you recall in AB, AB absorption, we had our equilibrium line and we had our either straight or slightly curved depending on the amount that the flux of mass transfer going on operating line.

46:13

And we were looking at those two positions where the distance between these was my driving force for separation.

46:19

And if you recall, in fact, the further I was away from or the further these two lines were separated, the larger the driving force.

46:28

Now I could look at that right, either as the $Y - y^*$ or the $X - x^*$.

46:34

So I can visualize that driving force either in the X-plane or the Y plane.

46:40

Now we're going to come back and talk about this more in a few slides, but this is the central insight of the McCabe Thiele method is that when I'm diagramming this in the XY plane, what I really can do is say, well, each of these driving forces in the, if I look combinatorially at the X and the Y, the sum of these two represents the global driving force across that system or across that particular equilibrium stage, bearing in mind the absorption column was one equilibrium stage.

47:15

So in this instance, what we're able to see is we can relate each of these column positions to a different set of X's and Y's.

47:25

And I don't want to go too far on this because we're going to come back and look at it in much greater detail.

47:31

And on the bottom, this is a very simple diagram that that we'll find in, in the McCabe unit operations text that's basically illustrating a, a much simpler type of column where I'm going to feed it into the reboiler.

47:44

So I have one heating source in the reboiler.

47:46

I can imagine, you know, I'm going to have a liquid pool sitting above this heat exchanger.

47:51

We haven't shown it, but this would be the Weir for the overflow and a recycle loop beneath it.

47:55

And then it's the vapor that's going to start coming up through this column where I'm taking a complete vapour outlet, condensing all of it.

48:04

Again, we're not diagramming how that's done, but I have a condenser operating and then I'm splitting through some valve, the portion that I'm taking as a reflux and an overhead product.

48:14

So well, we can represent a distillation column with a very simple type diagram like here.

48:20

In fact, this is the degree of messiness that's happening inside of the column.

48:24

And if our whole purpose in getting into mass transfer and delving into absorption first was to look at how can we both maximize or controllably maximize this.

48:36

The contact area between my phases for mass transfer, the distillation column adds one layer of detail or one layer of capacity above that.

48:47

And that's how can I maximize that area whilst taking each fluid through a range of pressure and temperature conditions.

48:59

So we're going to come back in a few slides and look at how we can diagrammatically or how we're going to deploy the McCabe Thiele method diagrammatically to help solve these.

49:10

So before we go too far, just a quick note on what we'll now call is a multi stage flash.

49:18

Basically when I bring each of these equilibrium stages, they're akin to a thermodynamic single stage flash that we did at the very end of thermodynamics.

49:27

Now we're just bringing an N number of those flashes together.

49:31

So the nomenclature that we're going to use, we can we're going to use the term plates or stages interchangeably.

49:38

They just come from different subdomains of chemical engineering.

49:42

But in this case, if we're looking at the plate itself, the NTH plate, because we can start working on the column without knowing how many plates are going to be involved.

49:49

Our nomenclature will be that for that NTH plate, the liquid and vapor that are in equilibrium will be Y_{N+1} & X_N flowing at molar flow rates respectively of V_{N+1} & L_N .

50:05

And those are being contacted by two incoming streams that have different subscripts.

50:11

So the liquid coming into contact being presented to the stage is L_n at flow rate L_{n-1} .

50:19

It has a mole fraction X_{n-1} , whereas the vapor coming into contact has molar flow rate V_{n+1} , so coming from the stage beneath it with its molar composition or molar mole fraction Y_{n+1} .

50:34

So on any given stage, right, I have two phase or two flow streams leaving and two flow streams entering that are actually uniting an equilibrium point of three what the the contacts of three different stages.

50:52

Now here I'm showing an example.

50:54

This is a type of distillation column you're probably likely to find in a brewery or a distillery where it has a pretty singular purpose of making ethanol, right?

51:05

So I'm not particularly as concerned about splitting say 10,000 components, but maybe I'm trying to purify away some of the components that could be harmful.

51:14

So perhaps I'm, if I am getting rid of methanol, then I'd be taking my ethanol as a bottoms product and pulling methanol off the top of the column.

51:24

Now here what our approach is going to be is to talk about continuous distillation.

51:30

And when I say reflex, I just mean that that return line from the very top of column shown up here running back through a condenser and back into the the top stage of the column, that's my reflex.

51:41

So if I'm operating with reflex, it means that top stage is establishing equilibrium or acting as an equilibrium stage.

51:49

And and we will typically operate our our distillation columns with reflex.

51:54

Now continuous distillation, and I want to talk about this for just a moment.

51:57

The reason we say continuous is that once I bring this this distillation column to steady state and if I'm thinking about a pilot or an industry scale column, that's probably going to take on the order of weeks, right.

52:10

Well from when I first start operating the column to when it established a steady state will be a weeks long process where it is operating 24 hours a day and we'll get into it to why that's the case.

52:22

But in that process we would call that continuous distillation effectively because the column never stops, right.

52:28

So it's, it's operating with a steady state flow rate in steady state flow rate out ultimately in continuous distillation.

52:36

And this is comparable to batch distillation.

52:39

So in batch distillation there I only have one block of feed.

52:45

So I have one unit of feed, whether that's a, you know, 100 liters of liquid or, or whatnot.

52:51

I have one defined volume of feedstock that I'm going to distill into two different things.

52:57

So in in batch distillation, we can use the same column to do it, but it just means we're not going to operate it indefinitely.

53:04

And in fact, the math for batch distillation gets much, much easier.

53:10

And, and we can look at an example I think in next in the next lecture just to illustrate where batch distillation can be useful.

53:17

The key tenant though is that I tend not to want to use a distillation column for something like a batch distillation because of the cost, right, If each one of these staged.

53:29

Now obviously not in our little distillery here, but at the industrial scale, if each stage costs a Mercedes-Benz, that's a pretty expensive engineering operation.

53:38

And so realistically, I'm going to want that column operating as frequently as possible with the ideal limit being that of, of continuous distillation.

53:50

OK, so I've left some of my diagramming on here just to connect to what we were just talking about.

53:56

So if I'm using this nomenclature, plate N, so this is my NTH plate in the system and the one above it is the $n - 1$ plate $n - 2$ and so forth, and plus one below and so forth.

54:08

Then I can also associate the pressures and temperatures at each plate.

54:15

So the temperature of this NTH plate is $T_{\text{sub } N}$, the pressure is $P_{\text{sub } N}$, so on and so forth.

54:22

So if I were to take, in this case we're using a TXY diagram, again, temperature and pressure are both varying across the stages of the column.

54:30

That's what's allowing me to exploit my knowledge of thermodynamics to change equilibrium across each stage, or to exploit different equilibrium conditions at each place or each stage.

54:41

Then I can in TXY space look at my bubble and do curves.

54:45

So when I plot these two out, you can see here I have the dew curve on the top and the bubble curve on the bottom.

54:51

And if you remember, let's look at the NTH stage from thermodynamics, we learned right that it's the gap, and I've reinforced this a bit, but it's the gap between these two curves.

55:02

This tells me the potential that I can use thermodynamic equilibrium and phase equilibrium VLE to split components across 2 phases.

55:14

So quite naturally, when I start thinking about a column where I'm going to have multiple stages involved, I can say, ah, what I really want to do is position these stages across the entire width of this, in this case, the TXY diagram.

55:32

So if I go from the TN minus or sorry, the T or the NTH stage, so operating at temperature T_{NI} can see my liquid is going to leave that stage flowing downward with a composition X_N where the gas is flowing upward with a composition Y_N .

55:48

And in this case, N would be my lighter component, right?

55:52

So this, this TXY, we would typically we've drawn it for a binary system, which is entirely fine to use in a distillation column.

55:59

I just point out earlier the 10,000 components because column distillation columns can flex from separating a binary all the way up through separating a 10,000 component mixture.

56:10

They, they do not, it's not quite as simple as that, but generally they are capable of crossing this.

56:16

When I get into really complex multi component systems, I have a few more things I have to account for, but the process remains generally the same.

56:24

So if I go to the stage below or above that right, play $n - 1$, right, I'm going to be at a lower temperature.

56:34

So you remember as I go toward, as I go up, I'm going toward the condenser.

56:39

Well, the condenser is cold.

56:40

It's a cold heat exchanger that's condensing vapor into liquid.

56:44

So in txy space, I'm going to a lower temperature, which is why we've drawn it in blue here.

56:51

So as I go to that next stage up, now the liquid that's going to come off that stage and flow down to my NTH stage has a mole fraction $X_N - 1$.

57:02

And I've drawn this here to illustrate that.

57:04

You know, if I was looking maybe this is my equimolar position, so perhaps I'm going to start on that.

57:11

Or I have on the $n - 1$ column a liquid that has maybe 55 or 60 mole percent of component one.

57:18

As I come to the NTH stage, now the liquid flowing out of that is no longer 55 or 60.

57:25

Now it looks to be about 45 or 50 mole percent.

57:29

So as I'm going through this column, each stage for this particular TXY diagram, it looks as long as I'm in the widest part of the gap between the bubble and dew curves that I'm able to every stage change both the liquid, the outflowing liquid and vapor mole fractions of component 1 by somewhere in the neighborhood of five to 10%.

57:53

Now as I go toward the edges of the TXY space here, I can see the gap is starting to be narrow.

57:59

This means I have a much smaller separation potential between the vapour and liquid phases.

58:06

But again, as long as there is a gap, I have a positive separation potential, right?

58:11

And if I were to build stages that took it all the way from this upper point and all the way to the lower point, then I could actually take maybe starting with an equimolar mixture fed in the middle.

58:22

And I can take this and separate it all the way out to say 99.9 mole percent of component one in the vapor phase or in the distillate product and 99.9% component 2 in the bottoms product, right?

58:40

If I'm taking the bottoms product, which I probably do in a situation like this.

58:45

So that type of separation efficiency, if we think back to the effectiveness of our absorption systems, that degree of separation efficiency, right, going from equimolar, so 50/50 to 99.9% as long as I have a gap in the the TXYPXY space, I can exploit it.

59:06

That's a really extreme separation efficiency for a single operation, right?

59:12

And if you think from a kind of just a 30,000 foot view abstractly for a minute, if someone handed you a glass of water and said, well technically this contains 50% ethanol and 50% water and I would like you to separate out on a molecular level.

59:29

I want 2 glasses, one containing the water to say 99% purity and one containing the ethanol.

59:36

Can you separate those two components out of the original glass you had?

59:40

Well, we've only come up with a few ways as engineers to figure out how to do that, and this is one of our most powerful.

59:49

It exploits a lot of principles of chemical engineering and brings them together in a single operation.

59:56

So the McCabe Thiele method.

59:59

So I'm introducing it here.

1:00:01

I'm going to talk more on the next slide as to how these or some of the parameters here and how they connect together.

1:00:07

And we're going to come back in the next lecture and go even deeper into examples of how to deploy this.

1:00:12

If I can highlight one thing that I hope you leave this class with, it is an appreciation for how to use and understand the McCabe Thiele method.

1:00:23

This is a really powerful tool.

1:00:26

So in the method, we are again working in XY space, right?

1:00:32

And we're going to go through what each of these lines mean.

1:00:36

But first let's look.

1:00:37

We're going to draw our XY diagram.

1:00:41

And the first thing I do in the McCabe Thiele method is I draw a solid line connecting the two edges of the diagram.

1:00:48

So going from 00 to Infinity or one one.

1:00:52

Now, I prefer to do this in a square diagram just helps me visually to look at and it can help prevent the eye from obscuring.

1:01:03

However, it is valid if you want to stretch and move this diagram around, you can deploy it in different configurations.

1:01:08

The key aspect is that I need to connect the points 00 and 11 as a solid straight line.

1:01:16

So once I do, and this is kind of the platform that we're going to work off of, then the second thing I'm going to need is my equilibrium line, which we're or equilibrium curve, which we're going to show here in green, right?

1:01:28

This is the same curve, the same equilibrium that we've talked about with absorption, right?

1:01:34

So what I would do is take the totality of the chemical mixture that I have and figure out, well, if I, let's say a binary system for simplicity here, well, if I start with say one mole percent of component one, then I can go to a tool like multflash and quickly establish what is the equilibrium split of OK, so we'll, we'll come back in the next lecture and look at some examples of how I can deploy equilibrium data.

1:02:01

Roughly the the two primary sources I would look at are either the peer reviewed literature, so you can get there through Google Scholar and Paris Chemical Engineering Handbook is always a terrific resource.

1:02:13

Or potentially the the NIST Chemical Web book might give you some good leads and links to follow out.

1:02:18

But you want to make sure if you are using data, which is of course the gold standard, you're using a reputable source of data.

1:02:23

So something like Engineering Toolbox is going to be a terrible idea if you want equilibrium curves.

1:02:30

But as a backup if there isn't been experimental data on it, then you can always use an equation of state, ideally deployed through a refined industrial product like multi flash or Hisis to be able to estimate for you what that curve is.

1:02:44

Appreciating that there will be some uncertainty if this hasn't been reported in the literature and you're working on a rather novel system.

1:02:52

So here I have in green, my equilibrium curve from thermodynamics in black is the solid line that I've just drawn connecting 00 and one one.

1:03:01

And I can see these kind of form an envelope of sorts, right?

1:03:05

If I ignore everything else from it, the green and the black, I have this envelope.

1:03:10

Now, the equilibrium data is not always going to fall out to look like a perfect parabola like this.

1:03:14

It can have different curvature.

1:03:16

It can have humps toward the upper end or the lower end of the diagram or biases in that direction, but we're just showing it here.

1:03:22

Is that what we'd hope is an ideal kind of parabolic nature to the curve?

1:03:28

OK, so the first thing I'm going to do, the McCabe tailing method, the equilibrium data I get from Thermo and the 0011 line.

1:03:37

So the $Y = X$ line, I'm going to just draw manually.

1:03:41

So once those are in place, then effectively I have my five step McCabe tailing method.

1:03:49

The 1st step in this is that I need to figure out where is my feed line going to be.

1:03:55

So in purple, this is the McCabe Thiele feed line.

1:03:58

Now this line, I know its position, right?

1:04:04

So if I know the mole fraction in X of what's flowing inward, then I know where this is going to begin on the $Y = X$ line.

1:04:15

All right, So this, if I drew a straight line down, this would be the mole fraction of component one in my feed.

1:04:24

What I don't know yet, and we're going to come back to and look at on the next slide, is the pitch of this line.

1:04:29

So here I've drawn it perfectly perpendicular or probably an oxymoron.

1:04:34

I've drawn it perpendicular normal to the $Y = X$ line.

1:04:39

All right, which I have a square diagram I'll call a 45° line, but $y = X$ is a bit easier.

1:04:44

So I know the position of where the feed line starts based on the feed composition.

1:04:50

How much of component one do I have?

1:04:54

It's pitch, and it can go anywhere from this pitch right through a horizontal pitch through a highly vertical pitch.

1:05:01

If I'm drawing it normal here, this is going to indicate that I have a saturated feed.

1:05:08

So once my feed line is established, so I can kind of visualize before I draw everything else on.

1:05:14

But I have this the $Y = X$ line, my equilibrium green curve from thermal.

1:05:19

And this feed line is kind of like holding up almost the the parabola of my equilibrium curve or the arc of my equilibrium curve.

1:05:28

So now we need to think about, well, how am I going to to lay in the information of the column?

1:05:37

So the first thing I'm going to do once I've drawn this feed line and all I need is the feed composition.

1:05:43

And so the quality is in pure liquid, pure vapour, somewhere in between.

1:05:48

So the second thing to begin laying in the specifics of the column to this diagram, I need to think about I'm going to 1st focus on the rectifying lines.

1:05:55

If we recall, we had those two portions of the column that the bit that was above the feed tray.

1:06:01

So from the feed tray up to the point of the vapour exit, we call the rectifying section.

1:06:07

So I have one operating line to govern the rectifying section and the 2nd to govern the stripping section below the feed stage.

1:06:15

So if I'm going to focus on this rectifying line first, well to draw the rectifying line, the first thing I need to do is figure out where is my distillate composition going to be.

1:06:25

So this is if I go to the very top of the column and I take that distillate product stream, right?

1:06:31

And this doesn't say anything about the reflux ratio yet, but it's just if I take the composition at that point of my component one, what is it going to be?

1:06:41

And again, because these columns are designed to create very high purities, I can clearly see I'm able to separate, right, all the way up to the edge of the diagram.

1:06:51

So this might indicate something like a 90 to 95% pure distillate stream.

1:06:58

So I find this intercept, right?

1:07:00

That's all I'm going to do.

1:07:01

And I'm going to plot this as x_D or y_D because remember that vapor that's leaving is the same composition as the distillate product.

1:07:11

I'm condensing 100% of it and I'm going to so calculate this Y intercept and I plot this and then I'm going to take this, sorry.

1:07:23

I'm going to plot it from this point, x_D through the Y intercept.

1:07:29

So where do I find the Y intercept?

1:07:31

It is defined as x_D on the reflux ratio plus one.

1:07:37

So the second step, the first fit is that I need to know my distillate composition.

1:07:43

The second step is I bring in my reflux ratio and the composition.

1:07:48

So if my distillate composition was .9 for argument's sake, and my reflux ratio was one, then I would have $.9 / 2$ or .45, probably a bit above that, but that's not a bad guess.

1:08:02

So if I know my distillate composition and I've set my reflux ratio, or at least I've guesstimated what I'm going to start with because I can take this in an iterative design process.

1:08:13

Now I have the two points that define the strip or the rectifying line in blue.

1:08:19

So I draw this point, I draw the upper point, and I connect the two.

1:08:22

So don't worry about the stair steps quite yet, but we're going to connect these two points.

1:08:28

OK, so now I'm almost done.

1:08:31

Now I have my equilibrium data from Thermo in green.

1:08:34

I've drawn my feed line in purple.

1:08:37

And there I need to only know quality and composition.

1:08:41

And I've just drawn my rectifying line based on only two pieces of information, the distillate composition and the reflux ratio.

1:08:49

Now the stripping line, I start again by my position on the $Y = X$ line, knowing the bottoms composition.

1:08:56

So if I'm taking a bottoms product, this should be heavily depleted or denuded in that the lighter component or alternatively, I can say it's very enriched in the heavier components.

1:09:08

So I would expect if this X is my light component from zero to 100% mole percent, that my bottoms composition should be very much to the left hand side, the severely to the left hand side of this diagram.

1:09:21

So if I set that bottoms composition first, and this is my design spec now I initially start on the $Y = X$ line.

1:09:29

Now the question is going to be how do I where do I draw this up to right?

1:09:34

I don't know from the outset, I don't know the, I don't know the pitch that this is going to take this red curve that I've drawn.

1:09:43

Well, in fact, the solution, and This is why I think McCabe Thiele is such a fun method, is that the 2nd bounding is that this red line must bisect the feed line and the rectifying line.

1:09:57

And there is one unique solution for that.

1:09:59

And to the point that my laser pointer is here.

1:10:04

So as the engineer, if I note my feed is what I've been given, right?

1:10:09

What's its composition and in what condition is it?

1:10:12

Now if the condition is not ideal for me, yes, I can do some pre work to change the condition, meaning I can take it from a liquid to a vapor or some combination.

1:10:20

And that's going to change the pitch of the purple line.

1:10:24

So these things are really connected in the center there.

1:10:26

I can imagine if I change the pitch of the purple feed line, then I'm moving the rectifying or the tripartite intersection.

1:10:35

So where these three lines come together, I can shift that to the right or to the left based on the pitch.

1:10:40

So that's always a good, you know, certainly good to look at in the design process.

1:10:45

But if you're working on an existing column and trying to optimize it, that pre feed or the feed conditioning is a really good opportunity for the engineer to explore.

1:10:57

So if I know what I'm starting with and whether or not I'm going to precondition it, the only three things I need to construct the McCabe Thiele diagram are my distillate and bottoms compositions, MY2 product compositions.

1:11:13

And let's imagine that nine times out of 10, those are our constraints, right?

1:11:17

We're building, we're operating a column to deliver something.

1:11:20

So what we deliver is usually out of our or out of our choice.

1:11:24

It's what we've been told we need to deliver.

1:11:27

So the X_D , the distal composition and the X_B bottoms composition, that more or less is what we've been directed to do.

1:11:37

And then around that, I need to know the equilibrium curve and I make my one decision on the reflux ratio, and that's going to fully define each of these lines and curves.

1:11:51

So once I've drawn these things out, this little stair stepping here, this is how the McCabe Thiele method is deployed.

1:12:01

So I start at the intersection of XD on the $Y = X$ line.

1:12:06

So my distal composition and I go horizontal until I hit the equilibrium curve, perfectly vertical until I hit the rectifying line again.

1:12:14

Horizontal to equilibrium, vertical to rectifying again.

1:12:18

Another stair step.

1:12:19

Another stair step and I'll stop here for a moment.

1:12:23

So so far I've traced 4 different stair steps, and these must be perfectly horizontal and perfectly vertical.

1:12:32

I've traced 4 different stair steps in the rectifying side of the column so far.

1:12:38

The mind blowing revelation of the McCabe Thiele method is these represent the 1st 4 stages of the column or the first four plates.

1:12:49

So this is my top equilibrium plate, my second in each plate.

1:12:54

This has bubble caps, but more bubble caps, right?

1:12:56

This is these are the physical plates that we were looking at.

1:12:59

So it's going to take me 4 plates or stages, right?

1:13:05

Just to get here now, I've paused here because now I'm about to bisect the feed line.

1:13:14

Now I don't keep taking this downward between the rectifying.

1:13:18

Once I bisect the feed, I don't care about the rectifying line anymore.

1:13:23

I've just drawn these outwards so you can see how they cross.

1:13:26

And obviously I need to know the Y intercept to be able to draw them once I cross the feed stage.

1:13:31

And this in this case would be the fifth stage.

1:13:34

Now.

1:13:34

So I go horizontal from the rectifying to the equilibrium and again imagine these are perfect.

1:13:39

Doing it by hand on the tablet is not quite perfectly horizontal and vertical.

1:13:44

Once I cross that feed stage, now what I go down to is no longer the rectifying line but the stripping line and I go horizontal to equilibrium.

1:13:53

Now down again I pass through rectifying and go to the stripping line for the next stage.

1:13:58

This would be the 6th and again for the seventh stage.

1:14:02

And then I'm going to pause.

1:14:03

So I can see there's clearly 8 stages in this column, right?

1:14:06

Because I'm going to need another stage.

1:14:09

So now at this point, the engineer can say to themselves, OK, if I go horizontal and as soon as I turn vertical, I'm going to move past the point of $X_{sub B}$ right?

1:14:23

As this drops vertically down to the $Y = X$ line, I don't have any more stripping line left.

1:14:29

There's no more runway left to the stripping line that I can decrease vertically too.

1:14:34

That's OK.

1:14:35

That's part of the method, right?

1:14:37

So what this is indicating, let's just say we're, you know, 20% overshoot here, what we intended to be, That's OK because it indicates to the engineer, hey, you can look at this in one of two ways.

1:14:49

Either we can start playing with some of the design parameters.

1:14:53

If I haven't built the column yet, clearly I can start playing with the design parameters to bring all of these into a perfect kind of celestial alignment.

1:15:02

Meaning first thing I'll change is the the reflex ratio, right?

1:15:06

It's a very easy change to make.

1:15:08

It's going to pitch.

1:15:09

I, I can imagine if I increase $R_{sub D}$, it's going to decrease.

1:15:14

It's going to pull that rectifying line downward, which is going to push this inward.

1:15:23

So it's going to pull this outward, which means I'm going to potentially be able to get away with only seven stages if I can pull the reflex ratio high enough to pull this point downward far enough.

1:15:34

Alternatively, I could choose to increase the reflex ratio and push this upward a little bit, which is going to pull the end of this eighth stage in alignment with the expectation for $X_{sub V}$.

1:15:47

So if I'm working at an existing column, I can look at those really simple tweaks, well, design or existing those really simple tweaks to the reflex ratio or more elaborately, the feed quality.

1:15:58

So how much vapor do I have to ensure that I have alignment at the top and the bottom of the from my expectations?

1:16:06

Alternatively, the engineer can say to themselves, ah, if I over, if I overshoot this by 20%, well, is this distillation column going to feed another unit operation?

1:16:21

And from the examples we just looked at, maybe that is another distillation column.

1:16:26

And if the answer to that question is yes, then perhaps it's not a bad thing to have a little bit of margin, right?

1:16:35

If I've spent one Mercedes-Benz for each one of, in this case, 8 trays plus all of the accouter Moss around it, right?

1:16:43

My condenser, my reboiler, my valves, my piping, my instrumentation, my data acquisitions, Maybe having a little bit of margin built into the system because I can't go and easily add another stage to the column is not a bad choice.

1:17:01

OK, so the only thing that we've not covered here is how to well, and we're going to come, as I said, we're going to take an example of how I can start to get or use equilibrium data.

1:17:10

But the only thing I've not talked about in the method itself is what do I do with this feed line?

1:17:15

So the feed line itself, I can imagine I fundamentally if I'm taking a vapor liquid system, I can have only one of five feed conditions.

1:17:25

Either it's a cold feed, meaning a subcooled liquid.

1:17:29

So cold feed pure liquid would be a older nomenclature, but it's a subcooled liquid.

1:17:34

So beyond the point of the two phase region, that left hand side where I'm at saturated liquid.

1:17:40

If I go to the left of that I have a cold feed or a subcooled liquid, I can next have a saturated liquid meaning I have no vapour.

1:17:51

But I have a liquid saturation condition.

1:17:54

So the left hand side of the two phase region and Thermo, perhaps it's partially vaporized.

1:17:59

So portion is somewhere in the middle of the two phase region.

1:18:02

And remember in in a say a pH diagram, I can use my lever rule to determine what's my fraction of vapor and liquid based on where I'm at linearly in the two phase region.

1:18:16

Or it's a saturated vapor, meaning I'm on the right hand side of the two phase region.

1:18:19

Or if I've gone beyond the right hand side of the two phase region, I have a super heated vapor.

1:18:24

So I can only have one of these five feed conditions in each case.

1:18:30

What the thing I need to calculate is the quality.

1:18:32

So in 99% of the scenarios that we're going to talk about, look at, I'm only going to bound this as between saturated liquid and saturated vapour.

1:18:43

Those are the conditions that I really care about.

1:18:46

I'm not going to go to the extent of having more exotic conditions in the laboratory.

1:18:51

So my quality is quite literally our thermodynamic definition of quality.

1:18:55

If I have a saturated liquid, it's 100%.

1:18:58

If I have a saturated vapor, it's 0 percent or zero.

1:19:01

And if I'm in the middle of the two phase region, it's somewhere between those two points.

1:19:05

And I would use the enthalpy of the mixed feed to tell me what to calculate what is that quality?

1:19:13

Once I know the quality, this is the equation.

1:19:17

So the Y equals MX plus B , quite literally Y .

1:19:21

Here's my slope of the feed line M dependent only on the quality Q_X plus B , the Y intercept of the feed line.

1:19:30

So it's the composition of the feed on one minus the quality, right?

1:19:35

So here what I'm looking at is the nature of what happens as I start to change the quality of the feed line, right?

1:19:46

In fact, let me get rid of that little arrow so we can see it more clearly.

1:19:52

So the point that I want to make is that here we're not changing.

1:19:56

So if I highlight in purple, so we're not changing in this diagram, the rectifying line for the system.

1:20:06

All we're looking at is what's going to happen if I change the quality of the feed.

1:20:12

So I go from curve A.

1:20:14

So let's say curve C change colors here.

1:20:20

So if I'm maintaining the same bottoms composition in each case, then the first point of bisection, right?

1:20:33

Terrible.

1:20:34

Today with the drawing, the first point of bisection for my stripping line will be here.

1:20:41

So if I'm, you know, merrily and I call this stair stepping, it's just my nomenclature.

1:20:46

But if I'm merely stair stepping my way right, I can see that that position is going to be critical to determine where that feed stage is going to be AT and the number of stages in the column.

1:20:57

Conversely, if I, and I'll draw this in green if I had Point C now here is the bisection of my stripping the three phase or the three curves and the stripping line.

1:21:12

So in this case, right what I have done in changing the quality of the feed is also to change the the well Tri section really of my operating stripping and feed lines.

1:21:24

And as a consequence change the the way that each of these trays is going to interact between my operating sections and the equilibrium curve.

1:21:34

So the number of stages and the optimal stage for the feed, OK, Now if I wanted to calculate the something like the flow, so the flow in the stripping section and we'll come back to this and look at it again in more detail in the next lecture.

1:21:53

But my flow in the stripping section is basically going to be related to the.

1:21:59

So the liquid molar flow rate is equal to the average liquid molar flow rate less the portion of the feed that's going to be vaporized times that feed molar flow rate F , right.

1:22:12

And conversely, I have one minus that effect for the flow in the rectifying section.

1:22:16

So from the feed point on I, I'm basically doing a total mass balance around the column to write each of these stripping and rectifying flow equations.

1:22:26

OK, so I'll, I'll stop this here.

1:22:29

I know it's been a relatively long lecture.

1:22:31

This is one of the most important concepts I think in my opinion, for most of the chemical or throughout chemical engineering and operations.

1:22:39

And the way that we're teaching it here is a little bit different.

1:22:42

It's it's an older method to that of what we can use in a computer.

1:22:46

But the power of it is that it's visual.

1:22:48

So we're actually using our ability to to take thermodynamics and plot everything out, but then in that to visualize the performance of a unit operation in one of our thermodynamic spaces, in this case, the XY plane, which I think is just really, really cool when we spend so much time looking at the thermoplanes as as these conceptual models for what's going on.

1:23:12

Here's an exemplar of where a thermoplane is actually representing a physical model in the world.

1:23:18

OK, So we'll come back in the next lecture with again, a more detailed run through through the McCabe Thiele methods.

1:23:27

We can continue unpacking this together and cleaning up a bit of the detail around what might happen when I start to bring the column into operation for the for the shutdown period or if I'm thinking of operating it in a batch code.

1:23:41

OK, I hope you enjoy everyone.

1:23:42

As a reminder, and again, I I would really encourage course this.

1:23:47

This corresponds to Chapter 10 in the the Reader.

1:23:52

But again, this is the McCabe Tilly method and this is McCabe's textbook, right?

1:23:58

So or originally authored by McCabe.

1:24:00

So chapters 21 and 22 in our class required class textbook.

1:24:06

I'd really, really recommend reading these, right, if if you're enjoying chemical engineering and mass transfer and this is something you want to do in your career.

1:24:13

Being able to read these words from the individual who first came up with it, who invented it out of, well, not out of thin air, clearly, but who first originated this idea that has come to define modern chemical industry.

1:24:30

I think it's a really cool opportunity to read that person's words and to hear how they framed and conceptualized the argument.

1:24:38

OK, take care everyone, and we will see you in the next lecture.

1:24:41

Bye.

Lecture 08

0:10

OK, and welcome to lecture #8 So here's a continuation of our discussion on distillation.

0:15

As a reminder, this corresponds to Chapter 10 in the Reader.

0:19

And again, quite critically, again, this is McCabe tailing method and this is originally McCabe's own textbook, now joined by co-authors.

0:27

So very much worth a read to hear that his own words as to how this method was designed and the kind of intellect, creative engineering intellect that came up with it.

0:37

This would be chapters 21 and 22 of the current edition.

0:42

So today what we're going to do is unpack a bit more about the detail of how we design and understand both the bounding and operating conditions of distillation columns.

0:52

But before we begin, I wanted to take just a moment and talk about this equilibrium curve.

0:56

So one of the things that we would have seen in the previous lecture, we need very little information to use the McCabe Thiele method.

1:06

And This is why the method has persisted for so long, right?

1:10

To get, and this is just for this example, but to get my feed line, I very simply need to know only the quality of the feed.

1:18

So bounded between zero and one.

1:20

If it's going from a saturated liquid to a saturated vapor in my two phase region, right?

1:25

So my quality from zero to one.

1:27

Or if in the rare case I'm dealing with a sub cooled or super heated vapor, then we have those equations in the last lecture that modify the quality to account for that.

1:35

So I can still use the same approach and the composition, right?

1:39

It's going to dictate where this feed line sits.

1:42

Those are the first two pieces of information.

1:45

The 2nd 2, which I don't almost club as one, but we'll call them two.

1:49

Here are the bottoms and distillate composition.

1:52

Now I would call these one functional piece of information because they tend to be the spec that I'm designing the system to.

2:00

These are my products.

2:01

And so very much I need to know what those are to choose distillation as the right method in the 1st place.

2:08

And then the final point is the reflux ratio, right?

2:10

And that's going to dictate effectively the slope of this rectification line or also called the rectifying operating line.

2:19

The slope of this is defined as the let me get my laser pointer as the reflux ratio on the reflux ratio plus one.

2:27

And this slope gives it the property that at the Y intercept is defined as the distillate quality or the tops or sorry, the distillate composition or tops composition X_D on the reflux ratio plus one.

2:41

But we also need to say something about the equilibrium line.

2:44

All right?

2:45

So this is in Y or XY space, meaning that I have a constant temperature and a constant pressure in thermodynamically to draw this system together.

2:57

Now the way that I'll take that, let's say if I have 10 stages in the column or 10 trays, I'll find or estimate what I think the temperature is on each tray and I'll take an average across all 10A number average.

3:08

Same thing for the pressures.

3:10

Once I have my average pressure and temperature in the column to get or average temperature and pressure my operation, I'm going to go to my knowledge of thermodynamics to get the equilibrium line.

3:22

And very simply the way that I'm going to do that is first by going to let's say the peer reviewed literature.

3:30

So I can go to Paris Chemical Engineering Handbook.

3:32

I can search Google Scholar if I'm looking at peer reviewed sources, I can potentially look at tools like NIST chemical web book to find some useful links and studies to go to and you'll actually find that for common operations, things like ethanol distillation, right how we make vodka and others.

3:52

This is a very well studied problem.

3:54

So you can go to literature and find exemplary data sources that have physical experiment and data sitting behind them.

4:01

If I'm dealing with a system and will still stay in a binary system for now, we'll toward the end of the lecture we'll look at what happens in multi components.

4:09

But in my binary system, if I'm doing something that's never been done, well then the only other source I have at my disposal are thermodynamic predictions.

4:18

So these are equations of state predictions for vapor liquid equilibrium VLE.

4:22

This is why we spent so much time on VLE and thermodynamics as opposed to the other polyphasic equilibrium like solid liquid equilibrium or liquid liquid equilibrium, SLE and LLE respectively.

4:39

So for VLE, we can use our cubic equation the same and we're going to deploy that.

4:45

And let's say a tool like multiflash is for simplicity.

4:49

So if I load up multiflash, and again I'm working in a binary system for now, I enter what are my MY2 components?

4:57

I nominate my average temperature and pressure in the system and I'm going to select the right equation and state for these.

5:04

So we've talked about SRK advanced, Peng Robinson Advanced, and CPA Info Chem.

5:10

These are my kind of flagships for different purposes.

5:13

CPA for associating meaning fluids of a lot of ion activity.

5:18

Peng Robinson if I'm dealing in a heavy or a hydrocarbon system with really minimal aqueous contributions or SRK if I'm kind of in a general mix of between these two points.

5:31

So SRK is kind of the stock standard cubic of the 20th century.

5:34

And in multiflash, I'd use the SRK advanced implementation as kind of a general baseline.

5:40

So I enter my components, nominate my average temperature and pressure, and select my equation state, my standard.

5:46

Three things to do with a flash calculation in multiflash.

5:50

So to get the equilibrium curve, I do one more thing and that is I'm going to start by giving multiflash a global composition of my component one because again, this is X of component one and Y of component 1.

6:08

So I give it a global composition of component one of let's say 5%.

6:13

Right now in multi flash I take everything on a mole basis on a mole fraction.

6:17

So I might do .05 component one and .95 component 2.

6:22

Therefore, using A1 mole basis, if I put .05 of component one in and then .95 of component 2, I've already entered my temperature and pressure.

6:31

I've nominated my equation of state.

6:33

So I hit the little PT button to do a PT flash.

6:36

On the other side of that, if I've selected the right pressure and temperature and I'm in a two phase region, multflash will say here is the compositions of both your vapor and liquid phases.

6:46

So when I look at component one, well the vapor phase will be enriched in it because component one is more volatile.

6:52

So instead of .05, I'll probably have .07 or could have .07.

6:59

And in the liquid phase will be depleted in component 1A little bit.

7:02

So from .05 will might go down to .03.

7:05

So if I trace up here to .07 and across to .03, and I'll delete that here and just draw the actual point in, this would be the first point on my equilibrium curve.

7:19

Now I could do this again instead of .05, maybe I do .1.

7:24

So now the vapor is going to be enriched to say .15 and the liquid still depleted to say point O 7.

7:31

So I might draw a second point here and so on and so forth.

7:35

I'm going to take this all the way up the equilibrium curve and I'm going to flapper calculate individual points.

7:41

And then I'm going to draw a curve by not by hand, but I'm going to draw a curve that cleanly connects all of these points.

7:48

All right.

7:50

If you went back to pre computational methods, you would use what's called a French curve.

7:55

It's a drawing, actually, a drawing implement that's kind of like a piece of really stiff, silly putting wrapped in plastic, right?

8:06

So it's something that you can bend and manipulate to be able to align it on all these points.

8:11

And then you can take your pen or your pencil and trace one time to draw the curve that connects all these points.

8:17

Today we might use a computational method that is effectively doing the same thing.

8:22

So I can either get this data if there are sources appropriate to my problem, or I can go to multi flash or Hisis or any other trustworthy Geo dynamic tool and extract them based on some number of points.

8:34

Right now to the inevitable question.

8:37

I wouldn't draw a curve like this with only five points.

8:41

I wouldn't do 50 points.

8:43

I think something on the order of 15 to 20 is a good start in place.

8:47

Certainly if you were doing this for a large scale industrial operation where you have zero room for uncertainty or error, my inclination would be to probably use 20 or 30 points to fully define the curve.

8:58

Make sure that you've not missed any strange behavior between any two points and potentially to take another step and not just use one implementation of your equation of state, but to think through a few of them.

9:10

So if I were to look at Multi Flash, then I have more than just one implementation of CPA.

9:16

Perhaps I'm going to try all of them and report the ensemble average of all.

9:21

So I'm going to end up doing 80 or 100 calculations, right?

9:25

For the mindset of the professional engineer, an hour of that engineer's time is always going to be worth it if they can reduce the uncertain or reduce the risk, the probability of a mistake, right?

9:38

Because mistakes on this scale are 10s of millions of dollars, they can reduce the probability of a mistake by even 1%.

9:47

Then the extra hour of their time is always going to be worth it.

9:50

And that that will be how the industry looks at professional engineers and how most engineers look at themselves.

9:57

So what what we'll do in this lab and the way that we're looking at it, I think one appropriate equation state is certainly enough.

10:04

I wouldn't want people going out and doing hundreds of flash calculations.

10:07

I don't think that's where the value in the activity is, but to make you aware of, you know, never refuse the opportunity to do some additional calculations when they're that accessible to you.

10:19

And it allows you to say something about the uncertainty where that operating or the equilibrium curve might actually sit.

10:26

OK.

10:27

So with that curve in place and with an understanding of only needing functionally what I'd call 4 pieces of information, reflux ratio, feed quality, feed composition and the product composition composed both the bottoms and tops sort of distillate and bottoms products.

10:46

Now I can I fully define this, this McCabe tieling curve or this McCabe tieling method.

10:53

So now we'll think about how we're going to start operating this column.

10:59

So let's imagine we've shut the column down.

11:01

It's sitting there at with no flow and critically no energy running through the condenser or the Royal as I go to start the column up.

11:13

So this start up condition, well, the first thing I'm going to do is start a column up.

11:17

Obviously, I don't start with mass flow, right?

11:20

As long as we have a decent amount of mass in our reboiler because we don't want to be super heating gas if we've drained the system.

11:27

So as long as that the bottom half of the column has a decent amount of liquid in it, then

the first thing I'll do is slowly power up the reboiler little by little and slowly start the condensing system.

11:40

Usually something like cold water flow to to the primary condenser, the total condenser.

11:48

But you know, again, until I start vaporizing a lot of stuff, what goes through that, I'm not going to have material flow through that condenser.

11:54

So it's really the re boiler that I'm going to start with.

11:56

And we would power that up relatively slowly, right?

12:00

In the same way that that with our tea kettle or our stove, we're used to boiling things with a constant heat flux coming in.

12:08

We don't want to take step changes in heat flux.

12:11

So we like that kind of constant heating condition to allow the fluids to homogenize as they're being heated.

12:17

So as I start heating it up and bearing in mind I do not start a column up with feed flow, I start it up from the reboiler and no feed flow.

12:27

So as that reboiler starts warming up and eventually I go through those stages of boiling, just like we talked about in the lectures around heat exchange or design, then what I'm going to, I can look visually and interrogate.

12:41

I can actually see the boiling in the laboratory reboiler.

12:45

So I can see the type of boiling.

12:47

And in fact, when we look at that pilot system in the lab, the thing I'm looking for are those stages of boiling that I can observe the same thing on the stove top with a pot of water.

12:57

I'm looking for those characteristic types of boiling, right?

13:01

Where are my bubbles forming?

13:03

How quickly am I getting a nice film boiling?

13:06

What does the noise sound like?

13:07

Is it noisy like a kettle?

13:09

Because that's going to tell me I'm somewhere in the intermediate band of nuclear boiling.

13:12

Or do I see these massive jets like the kettle when it's finally done and I have that nice sound of bubbling, then I'm into to jet boiling and I can see those nice jets of gas that are coming up to the top.

13:24

So I'm visually interrogating the boiler to look at what's the nature of the boiling process.

13:30

So once I see that boiling in play, if I had sight glasses in my column, in fact, I would start to see vapor matriculating upward toward the upper end of the column.

13:41

And of course, now we need our condenser operating, so this could be a cold water flow through it so that when material comes through into the condenser, it will be fully liquefied.

13:52

Now, of course, we're not collecting material at the top of the column.

13:56

So I always, always, always shut down and start up a column under a total reflux condition.

14:03

So the very last reflux, well, the very last reflux ratio, and I'll get to this in a minute that the column will experience before full shutdown and the very first it experiences on start up is an infinite reflux ratio, meaning 100% of my condensed material is being returned to the column.

14:27

And we get the name infinite reflux ratio.

14:30

Because if I imagine the definition of that is the molar flow rate of the reflux, the amount of material molecular rate going to the column divided by the molar flow rate that I'm extracting as a tops product.

14:43

Well, if I'm dividing by zero, not taking a tops product at the shutdown or startup at the very end of shutdown or the beginning of startup, rather than I'm dividing by zero.

14:54

Hence my reflux ratio goes to Infinity.

14:58

So I begin that process.

15:01

My initial boiling material is moving through all these column stages, but I when it first hits that condenser and condenses to liquid, 100% of it's going to go back to the column and I'm actually going to let that infinite reflux condition or total reflex condition persist for a while.

15:20

I'm going to use the reflux as the initial source of down flowing liquid in the column.

15:26

So the boiler's heating it up, the condenser's driving it down, and I'm taking neither a tops nor bottoms product.

15:36

That's critical and I'll get to why in a minute.

15:39

So the first thing I do is I adjust the duty in the system, the thermal duty going to the reboiler and the condenser to bring the system into Thermo.

15:51

Sorry, a thermal steady state, meaning the temperature of my individual stages is not changing over time.

16:00

And often times at the industry scale, we obviously don't have sight glasses on columns, so we'll usually get the indicators for these points based on measurements.

16:08

So I'll have temperature measurements at all of my stages and I'm looking for those to reach a steady state before I ever think about turning on mass flow into the column.

16:19

So once I see that steady state profile emerge and noting that I'm at total reflex during the start up process, there is a key insight here.

16:29

So this is really important to know.

16:33

If I begin turning on the feed, the moles per second that I increase the feed to must be equal to the moles per second that I open up to pull product out from the distillate and the bottoms.

16:53

So if the column is designed to produce a distillate product and a bottoms product, all right, let's say for argument's sake I turn my feed from zero.

17:02

I turn it initially to one mole per hour.

17:06

I'm turning it on to a really super low flow rate, 1 mole per hour.

17:13

I need to take one mole per hour of content out of the column through either one of the product streams.

17:22

Now ideally, if I plan to take an equal amount of tops and bottoms product, then I'd open them up at about the same ratio, right?

17:31

If I was biased in my design to have 80% tops product, 20% bottoms product by mole flow rate, then I would open it up at about that ratio as well.

17:41

But the key aspect is I'm turning the reflux ratio from Infinity down.

17:46

So I'm because I'm taking a distillate product, a tops product, the amount of Topps product I take needs to balance the mass that I'm putting into the column in time.

17:59

So in theory the startup condition is that, and this is the punch line that I need to maintain a relatively consistent mass in the column at all times.

18:11

Now I say relatively consistent because it's not possible for us to manage this at a perfect consistency, but I need to keep it as close to perfect as humanly possible.

18:24

Now we obviously don't take a massive step change in feed to go from zero to all of the feed.

18:31

I can, I'm going to step that up as well.

18:34

So I take a little step, increase the feed by little step, increase the product flow rate by little step, meaning I decrease the reflex ratio by little step, wait for that to come to equilibrium.

18:47

So I'm or steady state.

18:48

So I'm looking at the temperature sensors again.

18:51

Once that equilibrates out, turn the feed up a little bit more and turn the reflux ratio down a little bit more.

18:58

Wait for steady state in the profile of the column and again up and up and up until my feed flow rate equals the design constraint.

19:08

And at that point my reflux ratio and my distillate, my product flow rates from the distillate and or the bottoms will equal or distillate.

19:17

And if I'm using it bottoms rather will equal my design constraint from the McCabe or my design basis from the McCabe Thiele diagram.

19:29

So the reason that this matters so much is that when I look at these columns, I am

dealing with a simultaneous heat and well, dual heat transfer process and a multi stage mass transfer process.

19:43

So if I introduce an upset, let's say I accidentally trip over the cord and I turn the reboiler off for 5 minutes in the middle of my startup process in the lab, I've made a mistake.

19:56

I realize that mistake and I real quick check everything safe and I'll reactivate the reboiler and turn it back on.

20:05

So it's only lost 5 minutes of thermal load.

20:08

What is going to happen?

20:11

Because it's a combined heat and mass transfer process, that step change, which mathematically we would have called a heavy side function, meaning I have a discontinuity that that step change or that discontinuity is going to propagate from wherever it was started.

20:28

In the my example, the reboiler, it's going to propagate up every one of these stages in the column all the way up to the top into the condenser.

20:39

So maybe an hour later I'll see a step change in the condenser profile, meaning it's temperature, pressure, and composition.

20:49

Not pressure, sorry, temperature and composition.

20:52

But then because the condenser is returning stuff to the top of the column, it keeps going and I get that step change propagating from the top of the column now back down to the reboiler.

21:06

And so it's kind of like a game of ping pong, right?

21:08

Instead of bouncing once on each side of the table, it's going to bounce the number of stages I have in my column.

21:14

So I can imagine a really strange game of ping pong with a long table.

21:18

If I have 10 stages in the column, if the introducing a step changes like hitting the ball where it's going to bounce has to bounce through each one of these stages, it's going to hit the other wall and be bounced back to me or hit the other players paddle and be bounced back.

21:33

All 10 stages to me.

21:36

Right now, each stage that that step change propagates through and again can be thermal or can be mass.

21:45

So I can do a step change in flow rate, or a step change in thermal load or thermal duty.

21:52

Every time that step change moves from 1:00 equilibrium stage to the next, I might lose 1% of that driving force.

22:01

So the step change decreases in magnitude from one stage to the next.

22:05

That works in my favor.

22:07

But if it's only 1%, it means it's going to propagate and bounce like a ping pong ball from the bottom to the top to the bottom to the top to the bottom of the column through every stage until I've effectively reduced 1% every time and reduce that step change functionally to 0.

22:26

So a simple act like having accidentally tripped a heater for only 5 minutes could propagate up and down and up and down this column for the better part of an hour or two hours.

22:41

And this would be for the lab column, where it takes usually only about 20 minutes to bring it to steady state.

22:46

So for that reason, we really, really, really care about start up.

22:51

It's the most critical thing that a chemical engineer can contribute to the process because we must ensure that we do not introduce a step change ever in the startup process or during continuous operation, whatever we do.

23:07

With these columns, you can kind of envision like if you had to maybe move a grand piano through a house and you were only by yourself, Well, you're definitely not going to push at 1 angle with everything you got for fear that you might tip it over right or crack a leg and it'll fall.

23:22

You're going to take it inch by inch and get on all sides of it and push ever so slightly to push it through the house, treating it very preciously.

23:31

That's the kind of metaphor for a distillation column, a really extensive, heavy, large, precious thing that can move only ever so slowly through phase space.

23:42

So when we start up these columns, we begin with this infinite reflex or total reflex condition where I have an infinite reflex ratio for that very good reason, right?

23:53

And, and in fact, if we were shutting it down, we would do the exact same thing in reverse.

23:58

We would start at our steady state, whatever our design system was, we would pull the feed flow rate down and reduce the product flow rates out.

24:06

So we maintain that thermal map or that sorry that we maintain the total mass through the column.

24:12

They were in the column until I've reduced it down to zero.

24:16

I'm probably going to have to drop the reboiler duty a little bit as I go.

24:19

And the very last thing I'll do is to bring that reboiler duty down to 0.

24:24

And so this way when we go to restart it up, we begin with a consistent mass distribution in the column.

24:31

So this condition of total reflux, this is critical as I think about a column during a dynamic or a transient operation.

24:40

And this does represent one of our bounding conditions in the system.

24:45

Now during operation, the idea behind total reflux is such that I can also plot this on the McCabe Thiele diagram, right?

24:56

But if my under reflux or total reflux, if I'm not taking a distillate product, then I can envision in this definition of the slope of the rectifying operating line defined as the reflux ratio on the reflux ratio plus one.

25:11

Well I have Infinity divided by Infinity plus one.

25:16

So in fact in total reflux I use the $Y = X$ line as the rectifying operating line.

25:23

So if I'm stair stepping in total reflux, I'm using that operating line to do it until I crossover to my stripping line.

25:33

Now I can also if I'm, if I'm looking then of what is the minimum number of plates that would be a so and I can see under total reflux condition, right?

25:40

Because I go from having it's a rectifying line that I'm, I'm bouncing between or stair stepping between because that goes all the way down to the $Y = X$ line.

25:51

I have much bigger compositional coverage across each equilibrium stage, so as a consequence, the number of stages in the system is going to decrease quite substantially in the rectifying section.

26:04

So I can use the McCabe Tilley diagram to get AT for a total reflux condition.

26:10

How many stages am I going to have or do I need rather?

26:14

And that is very much going to be the minimum number of stages for my design.

26:21

Now if I neglect, when I say ideal mixtures, I mean thermodynamically ideal.

26:27

So when I'm neglecting fugacity and activity coefficients, the Fenske equation is basically a merger of the the route of routes law into my component material balance.

26:40

And so I can define the number of stages I require as a function of the distillate and bottoms product compositions.

26:47

Again, these are usually my design specs and critically the relative volatility of my binary AB components here.

26:53

Or when I say ideal, I mean these are defined only as the ratio of the vapor pressures.

26:58

So this, the Fenske equation can be a useful starting point and say, well, if I only have 5 minutes in the back of the envelope calculation, how many stages should I be thinking about as a minimum?

27:10

And then I'll go into the McCabe Thiele process from there.

27:15

Now this, this bounding condition of minimum reflux.

27:18

So as I go away from that minimum reflux point where I'm able to use this $y = X$ line as the the rectifying operating line, as I turn the reflux ratio down from Infinity, meaning I'm taking ever more product, I'm going to increase the number of stages required theoretically to obtain the same separation at the bottom.

27:42

So the minimum reflux ratio that I can have.

27:47

If I think about what's the lowest, I can draw the reflux ratio now.

27:51

So as I go from an infinite reflux ratio that sits on, let me draw this out with a pen here.

27:59

So at a condition of infinite reflux, imagine that's straight, and here's my infinite reflux ratio.

28:07

As I turn the reflux ratio down from Infinity, I'm at some point going to hit a condition where I have the minimum possible reflux ratio, right?

28:20

So maybe from Infinity, I initially turn it down to 100 and then ten and then five.

28:25

And this, my rectifying operating line is going to pitch upward as I turn the reflux ratio down.

28:32

And I keep saying the verb turn because it's physically a valve that we're turning that's directing the flow balance between my reflux line and my distillate product line or my tops product line.

28:45

So now at some point I've decreased the reflux ratio sufficiently that my rectifying operating line.

28:54

And again, imagine that straight is now going to bisect the equilibrium curve and this is at point D.

29:03

Now again at that point, and I'm going to delete what I've just drawn so we can look at it in more detail here.

29:09

At that point, what I can see is my operating line and my equilibrium line have no distance between one another.

29:18

This is why I spent some time during our AB absorption lecture talking about the pinch point where I'm connecting my operating in equilibrium lines because at that point, if you remember, we have no chemical potential driving force for separation.

29:38

Now, we didn't like that in our absorption column because it meant that we were, you know, spending money on a portion of a column that was effectively doing nothing.

29:47

And we don't like doing that.

29:48

We don't like spending money for no outcome.

29:51

Now if an absorption column is one of the cheapest mass transfer processes known to

chemical engineers, what do you reckon we think about a pinch point in distillation columns?

30:01

We hate them.

30:02

We hate, hate hate distillation point pinch points in distillation columns because these are one of our most elaborate and complex, meaning extensive and emissions intense systems.

30:13

The more I hit a pinch point, if I think about what will happen to my stair stepping through this point, well, OK, I and I won't draw all of these, but let's envision right here, I'm going merrily along stair stepping.

30:25

And then eventually I reach a point where I have to zoom in here, right?

30:30

I'm going to have to zoom into this to see do I have any distance between the two?

30:35

And if it's a proper pinch point, I'm going to be zoomed in so much I'm looking at individual pixels trying to stair step between them.

30:42

What does that mean, right?

30:44

If I zoom back out to 30,000 feet, what does it functionally mean?

30:47

My pinch point.

30:49

When I have a pinch point, I require an infinite number of plates or stages to achieve separation.

30:59

So critically, at the minimum reflux ratio I need an infinite number of plates in my column.

31:06

And remember, the heuristic for distillation columns is each of those plates cost the Mercedes-Benz.

31:11

So for this reason, we always avoid pinch points.

31:16

However, we do like the minimum.

31:18

We, we need to go through this calculation to know that when we're designing or operating a column, we know because again, that reflux ratio is a valve.

31:26

So on that valve must be enforced.

31:29

The condition on it that it cannot be turned past the point of the minimum reflux ratio.

31:35

And quite practically, the minimum reflux ratio plus a small boundary, right?

31:40

Knowing that if we're slowly migrating this column to lower and lower reflux ratios, we cannot bring it to the point of the minimum.

31:48

We need to stay some distance away from that, OK.

31:54

And so our actual columns, we will operate between these two points and, and so these are something that will be really useful for, you know, whether you're diagnosing an existing column like we're doing in the lab exercise or designing a column, it's critical that the engineer takes a few moments to look at and we can do it visually with the KDT, but look at what are these two bounding reflux ratios.

32:20

So if we talked about the minimum and maximum reflux ratios, maximum obviously being Infinity, how do we know what the optimum is?

32:28

So for practicing engineers, right, we don't think just about the thing we're charged with doing.

32:33

We have to think about all the things that it requires.

32:36

So it's not just the process that creates something, it's the money, the emissions, the people, the land, the impact, it's everything around that and the technical contribution that we're looking at.

32:49

So quite critically, we can we would bound the optimum reflex ratio with cost, right, simply because we're assuming here if we're either building or operating within an industrial plant environment that things like safety environment, land, these have been built into the industrial process.

33:12

So for modifying a column or installing a new column, of course we always go through each of the safety steps and has OPS and everything.

33:20

But our design decision for optimization is going to come down to product, product or production of our the satisfaction of our constraint in this case, tops and bottoms product and the money required to do it.

33:36

So for the cost, I can think of what's driving this cost as two contributions, right?

33:41

And I really like this diagram because here we're looking at and this is a theoretical framework, but this first curve is the fixed cost.

33:50

So as I go to a higher and higher reflux ratio, my fixed cost, meaning the and and fixed costs is an older parlance that would also now be updated to say emissions costs, steel emissions money, right?

34:04

If I had to ask for more proper or you know, corrosion resistant steel to be made, shaped, installed, yeah, that's money.

34:13

But that's also emissions.

34:15

So that's a fixed cost to get the steel in the ground.

34:19

But then as I go to higher and higher reflux ratios, I'm going to need a higher cost or I'm going to engender a higher cost of heating and cooling, right?

34:27

I'm putting more load on the top or more duty is required at the top and the bottom of the column to balance out that higher reflux ratio.

34:36

Now these are not one to one.

34:39

We just draw them this way in theory.

34:41

So we'll look at the practice in a minute, but they go in opposite directions.

34:46

So as my reflux ratio goes down or goes up, sorry to the right hand side of my theory, my fixed costs are going to drop, My operating costs are going to increase by some margin.

34:56

And so the over the sum of these two, my total costs are going to be optimized at some intermediate reflux ratio, right.

35:07

If I look at the practical scenario here, we can see this is the drop in fixed costs for and this is an example from the 7th edition if you want to go through in detail.

35:17

But this is the cost drop of a fixed or capital expenditures now called CapEx.

35:23

And this is the increasing cost of steam and water as I go to higher reflux ratios.

35:28

So we can see again these are not the the one to one crossover that we show in theory, but in fact this is more of a linear edition.

35:35

So our sum total of these two curves is actually shown here.

35:39

The combination of the two.

35:41

So I can identify from this example, the optimal reflux ratio would be 1.2, where my theory, the McCabe Thiele theory would show me the minimum reflux ratio would be something like 1.181.16.

35:55

And my maximum reflux ratio is Infinity.

36:00

So this, this balance of CapEx, OpEx and in the context of McCabe Thiele is a really useful tool as the engineer is trying to think about what is the best scenario for my system.

36:14

So now when we think about the practical columns, once we've we've thought about how we're going to operate in terms of the optimal reflex, well, we have one more constraint that we need to consider and that is that nothing in reality, especially for engineering systems is going to operate at an ideal limit.

36:35

So in a compressor or a pump or a turbine, we talk about efficiency and we typically characterize that efficiency for the entirety of the operation.

36:45

So in something like a liquid pump, we can very well have an inefficiency coming from 100 different locations, right?

36:53

And in thermodynamics, the way we would characterize that efficiency is by thinking of the total energy relative to that energy which is distributed into the fluid, the loss of which constitutes my porer or decrease in efficiency.

37:07

And functionally a distillation column is going to operate the same way.

37:11

But what we have to appreciate is that in the context of the distillation column, it is these individual distribution points.

37:20

So this is a bubble cap, right?

37:21

Where I can see the caps going to drop up, the bubble flows out and contacts through this region with its liquid there.

37:27

By establishing equilibrium, this is the individual mechanism that can be inefficient.

37:33

But I don't have just one of these to consider.

37:35

I can have 100,000 in a massive column, right?

37:39

Probably a bit much, but 10,000 points in a mass.

37:42

So a lot of points of small inefficiency, but they're usually all of the same design.

37:49

And so the way that we handle this, we take the same thermodynamic approach of thinking about a global efficiency and applying it to the system.

37:55

But we are doing it with the insight that this is happening on the, you know, micro to mezzo meaning small to medium length scale of the individual bubble column or bubble tray itself or individual bubble cap.

38:11

So the way that we're going to handle this and instead of thinking about an overall efficiency, which we certainly can use, again, difficult to estimate for those reasons, the Murphy efficiency is basically a composite efficiency for what all of these individual bubble caps are going to do in unison.

38:30

And because they're all of the same design and they're all operating with the same mechanism, I'm going to get a global contribution from them.

38:38

So this Murphy efficiency is what accounts for that.

38:40

And very simply, the Murphy efficiency, if I think I'm this denominator, $Y^* - Y$, and this is for any N tray in the column, right?

38:50

So Y^* is always going to represent what's that point of contact at the equilibrium curve?

38:56

So here I have my vertical driving force and that which is an equilibrium or the equilibrium point with my position.

39:03

And X is Y^* .

39:05

So that's my denominator.

39:06

How much thermodynamic driving force or chemical potentials driving force to be specific, could I possibly have or what is the theoretical the maximum driving force and thermodynamics, The Murphy efficiency is related to the actual driving force that I experience, right?

39:25

Where this Y_{n-1} , Y_1 , I'm basically I constrain the driving force.

39:31

So if I have a Murphy efficiency of 50%, it means my chemical potential driving force is half that which I could access in theory.

39:42

So my system has constrained half of my chemical potential driving force.

39:47

Now the way this is drawn, if I look at this bottom diagram here, I can see this is my $y = x$ line.

39:52

Here's my stripping operating line, my rectifying operating line, and the solid black outer curve is the.

40:00

Equilibrium curve.

40:02

What I can see when I apply this Murphy efficiency, what it's effectively doing, let me grab my pen here, is it's pushing inward the equilibrium curve uniformly, but by a percent.

40:17

So it's pulling this equilibrium or pushing the equilibrium curve toward the $Y = X$ line by some percent.

40:25

And the net effect if I grab a green pen, is that my actual, my operating equilibrium curve or that which I'm going to use in the calculations in the McCabe Thiele process is outlined in green.

40:38

And it's this dashed line here.

40:41

So the degree to which is my Murphy efficiency goes from zero to say 50 or 60%, it's going to push or pull that equilibrium curve toward the $Y = X$.

40:53

And because my operating and stripping lines are not moving or my rectifying and stripping lines are not moving, it means I need more trays, right?

41:01

I have a smaller space between both operating lines and the Murphy efficiency based equilibrium curve.

41:10

So in this example, we would have drawn something that's say 90% efficient, but I could do, right, any number of these.

41:17

Now in reality, and this is a really important point for the lab, when you think about, well, no column, no process is actually 100% efficient.

41:27

So the equilibrium curve you have and thinking through, well, how did we get that?

41:31

What might be the uncertainty of that?

41:33

If it's data, could I compare it to theory and go back to my lessons of thermodynamics to talk about how much confidence do I have?

41:41

What uncertainty would I apply to that equilibrium curve, right?

41:44

Maybe when I look at those measurements, there's some scatter in the experimental points.

41:48

So I, if I used a, a French curve or I had a, a computational method, I might say, well, there could be a three to 5% variance in this actual equilibrium curve.

42:00

So that's one source of uncertainty.

42:02

But if I find that actually I need a heck of a lot more plates in practice than I was supposed to need in theory using that theoretical equilibrium curve in the McCabe Thiele diagram, well, the difference between the two, the tray efficiency is one of those major things that I can chalk that up to right now.

42:22

That doesn't mean I don't have to account for any efficiencies in both heat exchangers, perhaps fouling in the pipe network around that or the feed network.

42:31

Those are all additional contributions to consider.

42:34

But in the column itself, the Murphy efficiency or the Tray efficiency is going to play a really big or plays a primary governing role to tell me why does my theory deviate from the actual practice?

42:50

OK, So in this, so far what we've gone through in the previous lecture is in totality the McCabe Thiele method.

42:56

And now we've looked at in this lecture the bounding points of the minimum and maximal operating conditions, the optimal, which means we've brought in an additional constraining parameter in this case money slash emissions.

43:07

So it's a combinatorial CapEx, OpEx consideration.

43:10

And if I'm diagnosing an existing column, the source in which I'm likely to find a lot of that deviation from reality.

43:19

And this is all to do with continuous distillation.

43:22

So the last couple points that I'd like to go into, where do we go from here?

43:27

What are the different flavors of distillation that I can look at?

43:31

And one point I'd like to make is what happens in a batch distillation.

43:35

Now you would have seen in the previous lecture I talked a bit about why we tend not to use batch distillation, right?

43:42

We're typically operating at a point where these are so expensive to build that we would not want to have this system not operating at 24 hours a day, right?

43:56

But there are certainly those cases where a batch distillation is going to be appropriate.

44:02

Typically we're talking really small plants and in particular, this would be useful for, you know, something where I have either a really remote facility and I'm going to use a batch distillation column, which itself is a bit simpler than a continuous distillation column.

44:18

Maybe I'm going to use that batch distillation on a number of processes and so I can buy one unit and then deploy it for, you know, 345 different small plant needs.

44:30

That's one good example.

44:33

But most of the time, right, this is a really niche application of distillation to do batch.

44:38

And very, very simply, it means here's my inlet, right?

44:42

So my inlet is, I have a little tap here and I fill this thing up with stuff, whatever stuff I have that I need to distill, knowing that I'm not going to distill all of it out.

44:51

I'm going to get some fraction of it as a product.

44:54

I'm going to use a heating source.

44:55

Now this is shown as steam could well be any heating source you can imagine and this is one of the reasons batch distillation is useful for remote applications because I can use a variety of heating sources for this.

45:06

I don't need to have, you know, constant access to steam at constant conditions.

45:13

So much like our discussions on re boilers, we would expect we're going to fill our whatever heat exchange system we have, we're going to submerge that in liquid at a minimum, perhaps a bit of an overflow.

45:25

We're not sorry, not an overflow we're in here because we're not continually injecting.

45:30

So we're going to fill this up at a minimum with liquid.

45:32

We don't want these kind of steam pipes or any heating pipes exposed to air.

45:35

They need to be in a constant environment.

45:37

So I probably would overlay the pipe, the heating pipe network at the very bottom of the batch, still fill this up with our liquid of interest.

45:44

As this comes to a boil, I have my vapor exiting very simply and it's going to come up here to some condenser here we're using cooling water again, could use anything, could use an air cooled heat exchanger if the process is in under really severe conditions.

45:59

And the outcome, it's going to fully condense that vapor phase and the outcome is a product.

46:06

So in this case, I'm basically doing a single stage flash, right?

46:12

However, that single stage flash is changing in time.

46:16

So the one thing that separates this a single stage flash vessel is a continuous throughput with a continuous output, and I'm exploiting only one gap at one point between the bubble and dew point curves.

46:30

Well, here the situation's a bit different.

46:34

I have a single volume, but it's changing in time.

46:39

So the point of the curves that I'm exploiting are themselves changing in time.

46:44

So the first, if I have 100 moles for argument's sake in my batch, still the 1st 10 moles that come off this again are going to be enriched in those lighter components, newted in the heavier components.

46:57

Which means the composition of my batch still after the 1st 10 moles leave will be richer in my heavier components.

47:05

So the place in the XY diagram that this or sorry, the TXY or pxy diagrams that the batch still is operating after the 1st 10 moles leave will change, all right?

47:19

And this will continue going until either I can't pump enough energy in to vaporize more light components, meaning I'm now just sitting with heavy components and I have a very, very low vapor flow rate, or I have filled up my product receiver.

47:37

I need to empty the system.

47:39

So the, you know, one of the reasons we don't like batch distillation top everything else is that at the end of the process, I'm still left with a rich liquor, we would call it here in the batch still it's it's enriched in the heavier components.

47:52

Now, if the process was to get rid of the light components and we go back to continuous distillation, I can design these systems that go up to say 99% separation efficiency between at a molecular level between the components.

48:05

Well, I'm going to have a really, really hard time driving that kind of process through a batch, right?

48:12

I'm very unlikely to get that kind of separation.

48:14

That's so it's an inefficient application.

48:18

But if you're working in a remote environment where you do not have access to things like a continuous heating source of constant flux, the same for cooling, and you don't have access to a continuous feedstock and critically a need for the continuous product.

48:35

So if this is not plugged into a whole industrial network that's going to always be demanding and pushing and pulling mass and energy from that, then a batch still can be or a batch distillation can be a useful application.

48:49

We can incorporate a bit of reflux if we want to.

48:52

So we could tap this reflux line and put it back into the batch still this can.

48:57

So you can imagine a valve here with a portion of feed and a directional valve to control how much dumped back into the bat.

49:04

Still, we'd probably want to put some small mixing element here to prevent stratification if it's not a turbulent boiling or a rigorous boiling system, and we could still deploy the McCabe Thiele solution.

49:16

But here, because we're only rectifying, we're only in the upper half of the column, we only have our rectifying lines.

49:23

So we don't have a feed, we simply have our equilibrium curve, the $Y = X$ line and the rectifying operating line, right?

49:31

Where this is going to ultimately dictate how far my bottoms product can be purified.

49:38

Now we're not going to do examples of executing this.

49:41

I just, I want you to be aware that of the role of batch distillation.

49:45

And if you've done calculations and design and continuous distillation, then picking up and solving on the fly how to do a batch is pretty easy.

49:55

So the the second kind of direction I'd like to go, and this is I think the much more important one is what happens when we go beyond binary compositions.

50:05

Very, very rarely, if ever will the practicing engineer come across a binary system just doesn't happen.

50:12

We are always dealing with impurities even in the parts per million or parts per billion that we have to account for.

50:20

So the way that we're going to do that and this, this goes back to that example of lining up the 10,000 components.

50:28

And this could come from a, a crude oil, a biofuel, any source, right?

50:32

If I have a naturally occurring source of chemistry, I'm going to usually have a wide distribution and diversity in the chemical components.

50:41

So to handle these, the way that I can go about this is involving what's called the K factor characterization.

50:49

If that's applied to a hydrocarbon characterization, we call it a Watson K factor.

50:54

So what this means for each of my K factors, and you'll remember from early days we talked about Y on X to get our relative volatilities.

51:03

All the K factors says is look, instead of calculating α_{AB} for a binary, I want to take Y on X , right, which we'll see in a minute.

51:12

We or we see from thermodynamics our ideal systems, we can relate to the vapour pressure on the operating pressure and we're going to calculate this K factor for every one of my components.

51:25

So if I'm the, the requirement to do multi component distillation is very simple.

51:30

I must know how many components I have, that's it.

51:37

So for each of these, sorry, well, I must know how many components and how much of each component.

51:42

So I I need to know the feed composition to do any or to to begin the multi component distillation process.

51:48

Once I do, I can very, very simply calculate K factors based on the vapor pressure.

51:55

Now this is assuming ideality, but we've gone through intermodynamics.

51:58

If I wanted to incorporate either vapor phase or liquid phase non ideality, it's very simple.

52:05

All right, I'm going to go from relating this through Roun's law for kids, right?

52:11

Yip is $X_i P$.

52:12

I sat to incorporating the fugacity coefficients $\gamma_i \phi_i^L$ equals $X_i \gamma_i^L \phi_i^L$ sat with the activity coefficient built in and so in that way my K factors are going to go.

52:28

If I incorporate for non ideal systems, K_i is going to be or I'm going to have my liquid phase correction γ_i^L for the activity coefficient multiplying vapor pressure and the system pressure multiplying the fugacity coefficient.

52:47

It's still going to be the definition of Y_i on X_i and so the fundamental nature.

52:53

Because I'm using and manipulating Rout's law to get at this solution, I can exploit the same summative relationship I had in Rout's law such that the sum of all Y_i equals one or the sum of all $K_i X_i$ equal 1.

53:07

Because the K_i is simply clubbing the vapor pressure and pressure at a minimum and potentially the activity in fugacity coefficients.

53:16

So from these K factors I can exploit the same definition of the bubble point relationship and the dew point relationship where the sum of all X_i is one or similarly the sum of all Y_i on K_i equal 1.

53:31

So in doing this once I you know I can ensure that my K factor is sum to unity.

53:38

That meaning that I have the correct vague pressures and compositions in the system.

53:42

I can then quite critically write a relationship for Y_i equaling a function of the K factors in X_i or X_i as a function of Y_i and the K factors.

53:54

So what do we do with this when we bring these K factors together?

54:00

And we'll look at this just in the concept of a flash, but this is effectively we do one single stage flash.

54:07

We know how to do all of the single stage flash, right?

54:10

Where my distillation column is just a single stage flash connected to a single stage flash and so on and so forth.

54:17

So once I've figured out what those K factors are going to be, I can write by this solution of writing Y as a function of F .

54:26

And this is again for incorporating now an overall material balance on a single stage flash vessel.

54:34

So that would be this vessel as outlined on the right.

54:38

I can now write this X sum of all X equal 1 and put that in terms of well, the remaining K factors, the percentage of the feed that is vaporized or the mole fraction of the feed, sorry, the mole fraction of the feed that is vaporized, it's not a percent.

54:57

And in each of the X_{sub} is in this feed.

55:01

So this what's highlighted in blue here 1 equals for the sum of all components the mole fraction of component i in my feed that's $X_{sub} f_i$ on one plus the moles of the mole fraction of the feed that's vaporized from zero to one times the K factor i -, 1.

55:24

So for each of my component i 's if I have say for argument 10 components in my multi

component system, when I expand this term I'm simply going to write it 10×1 plus the second plus the third plus the 4th.

55:38

In each case I'm varying X_{FI} and K_I right they relate to each component.

55:44

So for components one through 10, I have X of component one in the feed and K of component 1 + X of component 2 IN the feed plus F , but they all share the same F the the mole fraction of the feed vaporized.

55:58

And that's the the insight of the Ratchford Rice equation.

56:01

I now have a $1 = A$ for A10 component system.

56:06

Again $1 = a$ ten term summation where there is only one unknown shared in every term and that's this little F .

56:18

So to solve the Ratchford Rice equation, what do you reckon we do?

56:23

Well, we're going to solve it numerically, right?

56:26

So there is no way that I'm going to rearrange this to write $F =$ a function of stuff because the denominator in this expansion is too complex.

56:35

So I in old school, now being in the 80s and 90s, we would use a calculator, like a visual calculator, put it in guess and check, refine, guess and check over and over and over.

56:46

It might take 30 minutes.

56:48

Now we would go to Excel, and when I solve these in Excel, what I like to actually do is say, subtract 1 from both sides.

56:56

So I set it equal to 0.

56:58

That's just the kind of math person in me that likes to do that.

57:02

But whether you set the form equal to 0 or one, you're simply going to iterate.

57:09

And so you can plot this out and look for what's the value of F That gives me either a value, in this case a value of one, or if I've subtracted one from both sides, a value of 0.

57:19

So I can do it visually, or I can use a tool like Solver in Excel to get that.

57:26

Now, a note on that.

57:27

So we're not going to go too deep into this now, but this is a setup because advanced thermodynamics is going to go further down this road.

57:34

But if I'm a practicing engineer, right, yes, you can use goal seek to get things like F.

57:41

That's usually going to be reasonable.

57:43

However, if you are turning in a report that you know, for a very expensive operation for a client who has a very high risk operation, I wouldn't personally just go to goal seek and say, hey, this is the 32nd outcome of goal seek.

58:01

I'm like, sure, that's a good first approximation, but I would always personally take the step of plotting that equation out for all potential F.

58:13

So you can visually say I have confirmed there is only one real solution to this equation and this is the value of F.

58:21

So it takes 10 minutes versus 30 seconds, but is a very important check on your own work before you were to turn the solution back.

58:30

So once we have this F in the Ratchford Rice equation, the whole purpose is to get F.

58:36

Well then I can go back to the definition of my K factors where I have one on F and I can calculate out, well, what's the bottoms composition?

58:46

Because now the only thing I don't know in this expression is X_{bi} , right?

58:52

And as soon as I know X_{bi} , I can use my definition to get Y_{di} .

58:58

So the bottoms composition of component I and the tops composition of component I.

59:03

And I repeat that process for every one of my components.

59:06

And This is why it would be helpful to set something like this up in Excel so that if you change your value of F, you instantly get the refined solution for the bottoms and tops composition.

59:18

OK.

59:18

And of course, then the final sanity check when you're done with everything would be ensuring that all of your tops so $Y_{sub I}$ is on the top sum to 1 as your $X_{sub BS}$ sum to one, just to make sure that you have consistency across the solution.

59:35

OK.

59:35

All right.

59:36

So this will bring us to the end of our module on distillation.

59:40

This should be pretty tightly correlated with the reader.

59:44

And again, if you've enjoyed this distillation as one of the favorite topics that I ever get to talk about in terms of practical engineering, I think it is such a fantastic operation.

59:54

And in particular, the McCabe Thiele method is just a combination of gorgeous art and science together.

1:00:02

If you've also found this quite inspiring, I would really encourage if you can take a couple hours at some point in the semester or even after the semester, to sit down with the textbook and read chapters 21 and 22 because they or sorry, yeah, 21 and 22 because they are written by the original engineering creative intellect that came up with it.

1:00:23

And there's something I find really profound in being able to read it and see it through that person's eyes, and it helps us become more creative and outward thinking as we go forward in our own careers.

1:00:33

So just my two cents, but I hope you've enjoyed in the next two lectures.

1:00:38

We're then going to turn to our final unit Operation on Mass Transfer, and that is add adsorption.

1:00:46

So we will see you in lecture #10.

Lecture 09

0:10

OK, and welcome to lecture #9 on Absorption columns.

0:15

So before we get into the detail here, the reader corresponding to this module now will be Chapter 11, and this will take us for the next two weeks.

0:25

It's actually a relatively short chapter by comparison, and today we'll get into why.

0:31

And this would correspond to chapters 25 and 26 of the 7th edition of the Caves textbook.

0:36

So again, I would strongly encourage, you know, if you're having a bit of adsorption is not going to be hard mathematically, but it can be a bit difficult conceptually.

0:48

And so if you find that the way I've done the lecture or written the reader, if the words I'm using are not really clicking, Please ensure that you can use the required unit textbook as a resource because McCabe and Co workers present this from a slightly different perspective.

1:04

They'll use a little bit different language and hopefully that will click.

1:09

So before we get too far along, I just wanted to back up for a moment and talk a little bit about or visualize our flow from early work in gas absorption, right.

1:20

And what we saw there is we effectively have one, one mass transfer process that's exploiting one gap in our PXYTXY so that the bubble point or the bubble curve do curve.

1:33

We're exploiting one gap in that one point of a gap in that for the purpose of separating mass between two phases, vapor and liquid, we can do the same kind of approach in a single flash vessel.

1:48

That's again, you know, we still have a constant flow of material through this steady state, but we're exploiting 1.1 point of a gap between the bubble and dew point or curves.

2:01

And when we extend that concept, which are really two ways to attack the same problem, if we want to improve that and take it to a much more extreme output, really the the mental insight is that we're just putting multiple vessels together, but instead of lining them up left to right, we're stacking them on top of each other top to bottom.

2:25

And conceptually you can think of these single flash vessels or basically drilling holes between each of the vessels stacked from top to bottom.

2:33

And this LED us to the multi stage or continuous distillation process that we focused on for the past two class weeks.

2:39

So the reason I frame this like this is that the mass transfer operations covered today are continuous operations, right?

2:48

Meaning they are designed to operate at steady state, meaning nothing is changing in time.

2:57

The reason that adsorption, and adsorption comes last is that this is our mass transfer operation where stuff is changing in time.

3:07

So we now have to think about a time derivative and that makes it a little bit more complex.

3:14

So before we get into adsorption processes, and again throughout this lecture, I'm always referring to adsorption.

3:23

Occasionally I might fumble and slip and say absorption.

3:26

So please neglect that we're here to talk only about adsorption for this lecture.

3:32

The nature of mass transfer and absorption is something we're visualizing here on the bottom left.

3:39

We're still going to be working with a column, right?

3:42

So we're still thinking of a columnar design.

3:44

But instead of filling this with a material that is giving me surface area.

3:50

Now whether that material is a ring or a bubble cap makes no difference.

3:53

Those are intended only to create surface area.

3:57

Now it is my solid itself in the bed that is doing the work.

4:03

So in an adsorption column I am moving mass from a fluid phase, could be liquid, could be gas from a fluid phase to a solid phase.

4:15

And the process that is being exploited is the process of molecular adsorption.

4:25

So what this is happening, I can again use a liquid or a gas.

4:29

The feed that I flow through is going to be contacting some porous solid now in the column.

4:34

So instead of having a clean solid material like steel now I'm going to choose a porous material like rock.

4:41

This, if you recall back, we talked a little bit about flow through porous media when we brought up nuts and diffusion.

4:47

And as a modification on volumetric diffusivity or molecular diffusivity in this context, I now need to think about, well, if I have a solid like a rock.

4:59

And remember we used that metaphor of the kitchen sponge, the little classic green and yellow kitchen sponge.

5:06

Well, when that thing is dry, all that means is it's pore matrix is filled with air.

5:11

When it's wet, it's pore matrix is filled with water or soapy water.

5:16

So when it's dry, you can hold it up to the light and actually visualize the pore matrix through that sponge.

5:23

And if I were to zoom all the way down to it's not molecular, but say a 10s of microns length scale on a normal rock outside the house, I would see a really similar phenomena, similar look.

5:36

And so we need to think about how do we, excuse me, move material through that porous matrix.

5:43

So in pushing material through my porous solid, I'm able to exploit the nature of the porous solid of having a porous material if the porous material is something that wants to hold one or more components out of my fluid.

6:01

So the more surface area, meaning the more pores and the smaller the pores I have, the greater the surface area, the more surface area I have, the more potential that I can put stuff on the surface.

6:12

And that process that we're going to talk about when I take a single component, a single molecule out of the vapor or liquid phase.

6:21

So maybe up here I have 1000 flowing components, but only one of these likes the surface as I flow across that eventually that initially the first molecule is going to deposit, then the second molecule, then the third, then the 4th, right?

6:38

And this, this nature of the deposition, right?

6:42

Eventually the each of these we call these sites, each of these sites becomes what we'll call saturated.

6:47

So we go on the left from an unsaturated surface to the right having a saturated surface, because each of the sites is now occupied by a target molecule.

6:58

So this process from left to right is called absorption.

7:02

And as we'll go into a little bit in the next lecture, but there are two potential molecular mechanisms that are behind this.

7:09

I can either have chem absorption or physisorption.

7:12

Basically, chem absorption is where I'm going to have a bonding reactor, a bonding interaction between my target molecule and the surface.

7:19

And physisorption is where I'm going to exploit van der Waals or electrostatic forces to hold that molecule on the surface.

7:27

So I'm I have no chemical interaction or no chemical bond between the two.

7:32

I'm simply, it's preferred to sit there from an electrostatic perspective.

7:37

And we find that in most industrial processes, of course, we always want to use physisorption where I'm leveraging only van der Waals and electrostatic interactions because it means I can really easily regenerate that solid for you.

7:49

So I don't consume my solid in the to take it through one run of an absorption column.

7:57

So the challenge here, when I visualize from the left to the right, I can say, OK, this is no longer a steady state process, right?

8:06

I am expending if my solid is able to hold so many things initially.

8:13

Once those things, those sites become occupied, it's spent.

8:17

And so I am changing.

8:19

If I have a whole bunch of these solids, call them rocks, initially they're porous medium and I'm flowing say water across it where there's one component in the water that we really like to adsorb to the rock.

8:33

Well, once that fizzes or should take place, that rock, if it's saturated, all of its sites are saturated, that rock is no longer useful to me in the process, in the chemical process.

8:45

And so it becomes the next rock or the next sphere of material or the next solid object that then has still open sites.

8:57

So in an absorption process, we now have a time dependence.

9:02

Now we're still again using a columnar design and we're filling it with a whole bunch of small solids.

9:07

So we still have a bed, right, a bed of solids.

9:10

But now we can talk about.

9:12

And again, the considerations of fluidization are still directly relevant to this.

9:17

We tend not to flow at that kind of velocity because absorption can take a lot of time.

9:24

But I'm still flowing a fluid around a whole bunch of submerged, submerged objects.

9:28

And so I still have a bed, but now the bed is no longer performing a constant operation.

9:34

It's itself, its chemical nature is changing in time.

9:37

And as each of these sites becomes occupied, we say that that solid is saturated.

9:43

So eventually I go from having a few sites occupied to one of my particles or one layer of my particles in the bed is saturated and then the next layer starts absorbing or receiving more material until it becomes saturated and then the next layer and the next layer.

10:02

And so for this reason, we tend to operate absorption at relatively low flow rates.

10:08

And if I were to plot something so on this right hand side, this is going to be the effluent concentration.

10:14

So for my target component, maybe that will be something like CO₂ and error, right?

10:22

What I'm measuring here on the Y axis or the ordinate is at the outside or at the exit of the column.

10:28

How much?

10:29

If I'm using the metaphor with CO₂, how much CO₂ am I getting at the exit point, which is C relative to how much CO₂ I was injecting at the start.

10:39

So if we were looking to try to adsorb 350 PPM CO₂ out of the air, then what this plot would be showing me is that I initially am getting nothing coming out.

10:52

So all 350 PPM are adsorbing to my bed.

10:59

But over time, more and more and more of the bed becomes saturated more and more and more and more and even more and more and more until I start to see a little bit of CO₂ coming out of the end of the column right now.

11:12

What that?

11:13

What's that telling me?

11:14

Well, it doesn't mean I've exhausted the entirety of the bed.

11:18

It just means that for the flow channels that have been created right where the majority of flow is taking place because we try to make it homogeneous and isotropic, but it's not always perfect.

11:29

I'm going to get a little bit of preferential breakthrough CO₂ and then some not I shouldn't call it breakthrough, but I'm going to get a little bit of CO₂ coming out.

11:39

And the point that I'm looking for critically is what we call the breakthrough point.

11:44

So what I've marked here in red, that breakthrough point, we would typically assign the 5%.

11:51

So once my outlet is getting, if I start with 350 PPM CO₂, once my outlet sees 17.5 PPM CO₂, then at that point, right, I'm going to say, ah, now I have breakthrough.

12:14

So let's see.

12:17

So if I continue operating, which I usually would, I'm going to continue pushing more and more mass through that column, meaning I'm losing numbers of sites that are available for adsorption and we'll come back to this T star later on.

12:34

And then eventually I get the other end of this S curve where now beyond T star, a majority of occupied sites are occupied.

12:42

And I can continue adsorbing to what's left, but it's not going to be very effective.

12:45

And eventually when I recover back when the bed is fully exhausted.

12:49

So now 100% of sites are occupied at this point when the bed is fully exhausted, I'm now producing 350 PPM CO₂ for this example out the other side of the bed, right?

13:03

So now I'm my all of my adsorption bed is saturated and the process of flowing this fluid across the bed has no purpose.

13:14

It is not producing anything useful.

13:21

OK sorry not 17.515% where I was getting that from.

13:25

OK, So what does this look like in practice?

13:31

Here again, I have a model for a columnar design and I have probably some plate to hold up the bottom of the bed.

13:37

So as I inject feed from the top or the bottom, I'm able to ensure that it's distributed equally throughout.

13:46

But the, the core concept of an adsorption column is that you can't have just one.

13:52

Or if we do have just one, we're only going to be operating in batch mode.

13:57

So to operate an adsorption system continuously, which is what we're teaching here, that's that, you know, most industry works on a continuous process.

14:07

So to operate it continuously, we're going to have two beds operating in tandem and what that produces 1 bed will be adsorbing and the other bed will be desorbing.

14:21

So if I imagine initially, right, my feed is going to come in and it's going to feed this bed.

14:26

So I'm pushing from the top to the bottom, it's going to push flow down through this bed.

14:32

Now initially if the bed is unsaturated, then the first, you know, 99% of the absorption is

going to take place in the first row of solid material, of absorbent material until that's spent.

14:49

And then the absorption process goes to the 2nd and the 3rd and the 4th and 5th, all the way down to the bottom of the bed.

14:56

And once I get to within a few percent of the exit point, right in distance is where I'm going to start seeing what we just saw as breakthrough.

15:02

So now if the target was getting CO₂ out of error, now I'm going to start seeing a little bit of CO₂ coming out the bottom here when that very bottom few rows of the bed starts to become saturated.

15:14

And by the time I'm actively saturating the last row of material right now, I'm seeing a significant increase in CO₂.

15:23

And the flow coming out is now basically what I was putting in.

15:27

So my adsorption process is spent.

15:30

Now at that point, what I'm going to do is close this valve.

15:33

So I'm going to isolate this saturated bed from the feed, and I'm going to redirect open this valve so the feed is redirected into a clean bed.

15:43

That whole process starts over from the top to the bottom through this clean bed.

15:48

So in my spent or saturated bed, I now need to think about how to regenerate it.

15:53

And the way that I'm going to regenerate it in this case is using steam.

15:57

Now, there are a few different vehicles I can use here.

16:00

This is what's called temperature swing absorption.

16:02

I need bright temperature because steam is hot.

16:05

So I'm changing a temperature condition in the bed.

16:09

And in the process of adding more and more thermal energy to that those solid materials, it's going to provide an impetus, meaning a motivation for those adsorbed molecules to jump back up into the gas phase, right.

16:24
OK.

16:26
So as this jumps back up into the gas phase, if I start passing this steam line that's tracing through here, as this jumps, these molecules are warming up.

16:36
And so the adsorbent material and the molecules that are adsorbed to it, as those jump back up into the gas phase, they're going to be carried by the steam right up through the outlet here in now I'm, I'm not changing the nature of my adsorbent material or I shouldn't be.

16:59
If I am, I'm doing it wrong.

17:00
I'm not changing the nature of the adsorbent material by warming it.

17:03
I'm simply providing some.

17:05
If I go all the way back to, to basic thermodynamics, well, I can think about the warmer I make a molecule, the more it's able to load energy into its say, translational buckets of energy.

17:18
Well, once there's enough energy in those translational buckets, if there's more energy there than there is in the van der Waals or electrostatic interaction holding it to the solid, very simple molecule's going to jump, right?

17:31
Another way to think about it is I've given it enough, enough Monster Energy drink that it no longer can sit still on the solid.

17:39
It's going to jump up and in the process the steam is going to carry it out of the bed.

17:45
So this is going to initially regenerate the 1st row, the second row, the third row and so on and so forth.

17:50
So now what comes through this top line and into my I'm just showing a water condenser, but it could be any simple heat exchanger to cool it down, right to cool the steam down and liquefy it.

18:01
Now what I get out of the side here is either if my material is water soluble, it'll all go in a single aqueous phase exit, or if it's a hydrocarbon material, then it will phase separate with water and I'll have both an aqueous exit and a hydrocarbon exit.

18:19
Noting of course that because these are in intimate contact, I will have a portion of I'll have a saturated amount of hydrocarbon in the water, right, Some usually hundreds of

PPM and a saturated amount of water in the hydrocarbon could be hundreds to many, many thousands of PPM.

18:36

In exotic examples actually could be weight percent of water in oil.

18:42

So this, and here I'm showing steam could be anything warm, right for a temperature swing absorption.

18:47

The whole point is I need to warm this thing up and provide a very simple flow that's going to carry it across.

18:54

You could imagine this design could be varied by using a direct heating system.

18:58

Maybe I roll heating tape all the way around the outside.

19:02

So I'm not actually using a warm stream.

19:04

I'm just going to take an inert phase or an inert gas like nitrogen to flow it across.

19:09

All I need to do is figure out how to warm that vessel and provide it clean flow and in that limit, right?

19:17

Because I'm surely not going to be liquefying nitrogen through a simple heat exchanger.

19:21

If I were to use a nitrogen flow and heat tape or a direct heat source on this vessel, then what condenses back out is only going to be that pure component.

19:32

So there are variations that we can take.

19:34

Meanwhile, while I'm doing that whole thing, this this second bed is actively adsorbing.

19:40

And the whole point of this dual process is that when the engineer is done, by the time that first bed is done regenerating the second bed should be done, Desorb or adsorbing should be saturated, at which point I flip all the valves at the same time and redirect all the flow and the process starts from the very beginning all over again.

20:02

So why do we like this, right?

20:04

If I use that example of let's not directly heat with steam and then have to deal with water contamination, but maybe I can use a heating tape or a direct electrical source on that to warm it up and use an inert gas flow.

20:16

This is a vehicle through which I can remove, as long as I've picked the absorbent material correctly, I can remove it preferentially from a flow stream in a high purity and return it to a high purity environment.

20:31

So this is a, a really attractive thing for capturing.

20:35

So things like H₂S and CO₂ you might also be familiar with, you know, part of the emissions concern is around methane emissions, right?

20:45

They have a significantly significant or two orders of magnitude greater greenhouse gas potential, a greenhouse warming potential than CO₂.

20:54

So venting methane to the atmosphere is a really bad thing from a global warming standpoint.

21:01

Now it does have a much shorter half life in the atmosphere, but that's far outstripped by its contribution to the greenhouse effect.

21:08

So in fact, flu streams that are non combustible.

21:12

So if I drop down below say it's 30 or 40 mole percent methane, I can no longer combust well.

21:19

So if I have a really dilute methane stream often times right now, and this is throughout the world, independent of what type of industry you're working in, oftentimes those are bented.

21:30

If you can't ignite it, then you can't really do anything with it, right?

21:34

And so unfortunately the, the standard practice in most regions of the world is to vent it.

21:40

So developing ever new absorbent materials that are able to more effectively, more efficiently capture target components, where methane would be a really good one to, to capture that out of a flue gas before it's vented is a phenomenal thing from a a climate change and global warming perspective.

22:01

Well, in fact, UWA and the some of the research teams here have developed, patented and have taken now worldwide.

22:09

It's been a 10 year journey and there's a Nature comms paper, if anyone's interested that talks about what this journey was and how it was taken.

22:16

Have developed the world's best adsorbent material for capturing methane from these flue gas strains.

22:24

And they can capture it at such an effectiveness that you can feed this material.

22:28

And and this it uses a slightly different adsorbing system.

22:32

So instead of temperature swing, it's deployed in a pressure swing.

22:35

You can imagine in the same way if I operated a high pressure environment, when I drop the pressure down, there's less constraining force on the molecules, so they're more happy to jump off the solid, right?

22:46

The same principle just operating in with pressure inside a temperature.

22:50

So when deployed in a PSA or pressure swing absorption system, this novel zeolite is able to capture a dilute methane source out of a flue gas on the order of say 10% to such a purity that the outcome is now or the outlet of the process is producing, say on the order of 95 mole percent pure methane.

23:12

Right.

23:13

All of a sudden that methane is only one purification step away from being suitable for LNG manufacturing or conversion to hydrogen if you want.

23:26

It opens up an entire, not only does it save a huge source of, of climate change emissions and arguably the most important source from a, a temporal perspective because of the warming potential of it, it transforms it into a high purity chemical feedstock.

23:43

So this type of approach is exactly what I was talking about toward the beginning of our class or the beginning of our semester in terms of the impact that things like AI slash generative AI will have when applied to these complex chemical problems.

24:00

Right, when you can go through and not have, you know, just one or two or three materials to try, but you can start working through iterations on the order of millions of materials.

24:11

This is a huge arena in which chemical engineers and material scientists are poised to make an absolutely extraordinary impact in the coming decade.

24:21

Or at most to.

24:23

And so it's a really exciting point that I would highlight here.

24:28

Another really common application of absorption is in dehydration.

24:32

So, you know, it's easy enough to get most of the water, most of the relative humidity out of our air, or similarly most of the saturated water out of a gas stream if it's not air.

24:44

But if we want to take it down to the PPM level, so we really want all water out of a gas.

24:52

Adsorption is a great way to do that, right?

24:55

And when we apply it specifically in that context, we'll call our adsorbent material, we'll call it a molecular sieve.

25:02

So this is a much older term dating back to the 50s and 60s, but you'll hear older engineers talk about mole sieves or molecular sieves and what their meaning is adsorbent materials and that are specifically designed that are specifically deployed for dehydrating, removing the water molecules from a gas stream when when targeted.

25:26

These molesters are also sufficient in zeolite materials for separating oxygen and nitrogen.

25:32

So most of our like liquid nitrogen manufacturing comes from absorbing or absorbent bed application.

25:43

OK.

25:43

So the characteristics of these absorbents that we can then look at, if I imagine this was that profile in this again, the concentration at the outlet of the bed of the absorbing bed relative to my initial concentration material.

25:57

So in that metaphor, you know, if I have 350 PPM CO₂, this is how much CO₂ is coming out of the bed.

26:04

So when I'm at 0, I'm producing, I'm 100% effective and when I'm at one, I'm 0% effective.

26:12

And this is that profile where I'm going to go for some time.

26:15

I'll initially start to see a lift off right and we'll call breakthrough when 5% when the C on C not equals 5% and then we'll continue going and here's my midway mark.

26:28

So I'm now getting a negative marginal return for continuing my operation.

26:36

So if I were, you know, something like CO₂ where if it was a large scale process built to take 95% CO₂ out, then I would probably be inclined to stop the process at the at an earlier point around T star, right?

26:53

Because it, you know, if a marginal 10 PPM of CO₂ is is vented, it's not as going to be catastrophic, right?

27:01

Relative to being able to regen the bed faster and get back to 100% efficiency.

27:05

But if I were doing something like H₂S where one breath of 100 PPM or more H₂S is lethal instantly, then I cannot ever afford right to allow this T star position to be reached.

27:21

So the second I were to detect a lift off from this curve, if it were an H₂S absorbing bed, I would stop the operation and reverse it.

27:28

So just pointing this out in the sense of that the design premise and what we're going to be doing in our labs, this is very much for kind of the nominal application.

27:36

Doesn't have to be CO₂ or could be water, could be, you know, anything that itself is not acutely toxic to life.

27:44

We would, you know, take a bit more, we would allow the bed to exhaust a bit further before we're done.

27:51

But because adsorbent materials are applied to manage highly toxic things, something to be aware of in that scenario, we would be much more conservative about never allowing really any of that toxic content to make it into the outlets room.

28:09

So this right hand plot, you know, this is what we would look at.

28:14

We call it obviously a breakthrough curve because the whole point is to identify when is the breakthrough time.

28:20

But we can also call this a trend plot more generally in chemical engineering.

28:25

And it's a trend plot because it's defined, the whole thing is defined at one location.

28:29

And in this case the one location is the end of my absorbing bed, what's coming out of the end?

28:36

And it's plotting that point as a function of time.

28:39

Or another way to say that is it's looking at the trend of a single place in time.

28:46

So this is what we call a trend plot.

28:48

When the X axis is in time, the sibling to the trend plot is the profile plot.

28:57

So here I'm plotting the same Y axis, but now I'm looking at the profile of the entire bed, right?

29:07

And I'm looking at that profile for different snapshots in time.

29:12

So here might be my initial time I at the entry to the bed.

29:16

And at initial time one, I have 100% concentration of my target and it's going to be depleted as the bed as it is absorbed to the bed material.

29:27

Now very quickly this first, now I'm plotting bed length right for a profile plot.

29:33

So very quickly, this initial row of things of absorbent material becomes saturated.

29:39

And so by if I continue operating by the time I hit time two, I now see the emergence of this S curve.

29:44

Same thing for time three moves further down the bed now at time 3.

29:49

So if I grab my marker here for a minute, when I get to time 3, then at this point everything to the left of this bed is completely spent.

30:01

So to the left of that the adsorbent material is saturated.

30:04

It is useless to me.

30:06

The only thing I'm doing at that point is flowing my feedstock, my unmodified feedstock, across an additional layer of bed that is doing absolutely nothing for it.

30:19

And it's not until some length into the bed right at this point that I begin seeing adsorption take place.

30:27

And that region of adsorption carries through the bed.

30:32

So at time T3, which this annotation is for my region of adsorption, right, would be some middle of the bed.

30:45

And if I'm looking at this visually, right, and if we have an adsorbent as we do in the pilot lab, that is changing color as it adsorbs material that I can visually identify well, where is the region of absorption based on where the color change is taking place?

31:01

All right to the left.

31:02

At time three to the left of this, I should have all adsorbed or saturated material.

31:08

So it should be all the usually a darker color having adsorbed more material to it.

31:14

And it's the region of color change that indicates the region of adsorption.

31:18

And to the right of that is going to be unspent material at time three.

31:23

And this continues to time 4, right.

31:27

And the reason we draw time 4 like this is this is now indicating I have some percent of this coming out of the bed.

31:37

So this mass transfer zone which we would characterize again from 5 to 95% of the concentration profile, this will move from the inlet to the outlet of the column.

31:48

And the nature of the adsorbent material and the target chemistry dictates whether this is a sharp curve, the degree to which it's linear versus an S shaped curve, which is quite common.

32:00

That's where I get down to the chemistry of picking the right absorbance and the right and pairing it with the right target molecule.

32:06

So beyond the absorbing process, really important to take away, particularly as you go into your upper level engineering coursework and into industry, the concept of using profile and trend plots are really useful and common tool for engineers to help showcase either a point in space evolving in time or a point in time and how that looks across space.

32:35

OK, So I won't spend too long on this slide because we've just gone through the the discussion on temperature and pressure swing absorption in talking about UWA's innovation.

32:45

But effectively, if we go back to thermodynamics, the key concept here is if I have a molecule that has physics orbbed, meaning it is sharing an electrostatic interaction or a van der Waals interaction with some solid, right?

33:00

There is an energy potential well that is holding these two things together.

33:06

Now it's not bonded, so I don't have to put the kind of energy in to break bonds.

33:10

So heavens know they just are attracted to one another, right?

33:14

You can go back to almost that, that metaphor of the billiard balls as we went from the ideal gas equation of state, right?

33:21

And we thought about, well, we know that these are, we don't know what they are at that point, but we know that these are individual balls or, or individual objects of some sort, right?

33:32

Well, it was in fact the, the virial equation of state then first introduced to it.

33:37

Well, we have some concept where we have to think about the interactions of these balls.

33:41

And it was van der Waals, right?

33:44

And this is again why we call them van der Waals forces.

33:46

It was van der Waals who then took that virial equation and say it and said ah, well, if we think about this as not just a, an interaction of, of billiard balls on a table, but we, we can appreciate that these billiard balls are attractive, then deductively we could map out that energy potential.

34:05

Well, to identify well, there must then be some point at which the the attractive nature of these two billiard balls reaches a minimum, a minimum total energy in the system or well the system of the two billiard balls.

34:20

So the same thing is happening with my adsorption process.

34:25

It's just I have two different molecules, 1 molecule is locked in a crystalline lattice on the surface of my adsorbent material and the other molecules flowing freely by as, as if they are selected correctly and paired correctly, they're attractive to one another.

34:41

And so they're going to come into some a minimum energy distance between the two where they are relatively happy hanging out.

34:50

And in fact, if you recall back to Thermo, it was the minimum point of energy.

34:54

We called the the well depth van der Waals well depth for that for his derivation.

35:02

So using that same archetype, the concept of either right pressure swing or temperature swing is that that well depth is relative to this thermodynamic environment, the pressure and the temperature.

35:18

So there are two things I can do to change the environment such that the well depth is erased.

35:25

The molecules will go their separate ways and that's why I either add kinetic energy to the system, meaning I warm it up, temperature, swing adsorption, or I remove the constraining force of pressure, pressure swing, adsorption.

35:40

OK, so that's, that's all we're looking at here is the difference between these two.

35:47

The reason of course, in that application for UWA, the PSA would be used is that we're looking at much higher concentrations when you're talking about 10s of percent of a target molecule versus say 300 PPM.

35:59

Or if I'm, you know, in water, I might be down to 50 PPM for dehydration applications.

36:05

So if I'm thinking about how do I pick the right material, this, and again, this is a, you know, relatively frontier topic of chemical engineering, certainly in the research field.

36:16

So you're going to see a lot of innovation throughout your careers on this, You know, the nature of our adsorbent materials and how we're using them.

36:23

But these are characterized by their isotherm.

36:27

So an isotherm is going to mean how many grams of adsorbed material do I have per gram solid and solid in this case being the solid adsorbent material.

36:39

So this is plotted as a function of the concentration.

36:44

So how much of my target is in the surrounding fluid phase.

36:50

So as you can imagine, right, this is going to, the nature of these isotherms is going to change based on whether I'm coming from a liquid or a gas, right?

37:02

If I'm absorbing from a liquid or a gas, it's going to affect the isotherm.

37:06

Certainly the chemical that I'm targeting will affect the isotherm.

37:09

And critically, the isotherm is defined and the series of isotherms is defined for the solid of interest.

37:17

And so these are just a few exemplars kind of bounding conditions of the type of adsorption I can get.

37:24

Irreversible adsorption, right, is going to mean I have no variation in the amount adsorbed as a function of its concentration.

37:35

Whatever it is, it's going to instantly adsorb.

37:37

That's it.

37:39

Linear adsorption is probably the most logical.

37:42

The more stuff I have, the more stuff I can put down on the solid.

37:46

And around that linear point I can have either an inefficient bend or a hyper efficient bend.

37:55

So an inefficient bend would be the unfavorable side, meaning I have to get to higher and higher concentrations of stuff before I could start to realize meaningful levels of adsorption.

38:06

Whereas a hyper efficient bend, whether it's, you know, moderate or strong, even a little bit of stuff really likes to be on the solid, right?

38:15

And an irreversible adsorption, well, the second I expose even the first molecule, bang, it's adsorbed and everyone's happy.

38:23

Now, we don't tend to like irreversible adsorption because of course the nature of irreversible, this is an idealized condition.

38:30

So it's an upper limit that we're going to try to work to.

38:32

But the real effort is into trying to realize how can we get ever more favorable

absorption interactions by either designing these tiny porous solids with from a different set of building blocks.

38:48

I'm going into material science to do this, or perhaps modifying the chemical nature of my fluid to make it more compatible, make my target component more compatible with absorption.

38:59

So one way I might think about doing that is making the fluid less hospitable, if you will, for the target component, right?

39:07

The more the target component.

39:08

And if I think about something like an activity coefficient in liquids, the more I can increase the activity coefficient of the target component, the less it's going to want to hang out in that liquid.

39:18

And if I pick the solid that shows a favorable or strongly favorable adsorption isotherm, the more that target component, when it's in a hostile or a high activity coefficient environment, it's going to want to jump down onto the solid the second it has the opportunity.

39:34

So I can have a little bit of flexibility playing with the chemical nature of the fluid, but it's really, you know, the biggest gains are in thinking about and innovating on the solids that are used.

39:46

So within this, and I'm really not going to talk about this Freundlich equation, but it the Langmuir isotherm for adsorption is really the classic standard for how we can characterize these systems.

40:00

And what we're looking at here, right W_{Max} , this is the maximum.

40:06

Adsorbate loading.

40:07

So W here, it's in units of grams of adsorb material per gram of solid.

40:11

This is as good as it's going to get basically.

40:15

So if I take concentration to Infinity in this strongly favorable profile, this plateau point here, or if I extended the favorable profile out to a plateau point or could that would represent W_{Max} where W is basically for my conditions, what fraction of that am I going to get?

40:36

And the idea is that in these kind of curves we can characterize if we have the maximum plateau point done, we can characterize the rest of the curve through A2 parameters 1, the concentration of material.

40:47

So PPM in this case, or it'd be milligrams per litre and PPM.

40:53

And if I'm in liquid as well and a single Langmuir constant K.

40:59

So if you've heard before read discussing the Langmuir constants, this this is where they come in.

41:05

So I have one constant relative to the material that's characterizing the slope and shape of that curve as a function of concentration and 1 plateau point.

41:15

I can extend this, the Langmuir approach to multiple components.

41:18

So if maybe I have, you know, two highly similar target components I'm trying to remove, fair enough.

41:25

I can use a multi component modification to account for that.

41:29

So, and so let's with this then look at a few practical examples.

41:34

So these are now here we're looking at mole sieves for dehydration, right?

41:40

So molecular sieves, sorry in the middle we're looking at a molecular sieve for dehydration.

41:45

And what we want to highlight if we're obviously in this case taking dehydrating, so removing water from air and this is coming from Mccabes earlier.

41:54

So we're looking at imperial units of pounds of water per 100 lbs of dry solid, but for all intents and purposes we're still in an ordinate or Y axis of mass.

42:04

Per mass.

42:07

We're looking at how much can we absorb the W as a function of.

42:10

In this case, because it's a dehydration of air, we're plotting relative humidity from zero to 100%.

42:16

Same thing as corollary to concentration and a carefully selected mol sieve.

42:22

I can see here, sure I have a slightly favorable region showing up, but actually when I look at the stretch of this, this is pretty much an irreversible absorption.

42:31

This is almost operating an an ideal upper limit.

42:35

And that's of course in this case of a mole sieve, it's a four angstrom porous pore diameter, so very, very small relative to the diameter of a water molecule.

42:45

It allows the the mole sieve to hold the water quite tightly, nearly irreversible and it doesn't give it a lot of temperature dependence.

42:53

So this is tends to be an effective process, particularly these small diameters for like high temperature industrial processes.

43:01

I can compare this now to how like alumina or silica gel might work.

43:06

I can still achieve, you know, relatively either equal to or significantly greater than adsorbent well loading when I'm at really high relative humidities.

43:18

But in both cases, if I drop down say below 10%, then both alumina and silica gel in this example are a fraction of the effectiveness of a mole sib.

43:31

And where this can really make an impact and where dehydration matters a lot is gas pipelines.

43:38

So whether it's in the pipeline connecting Bunbury, it's not Bunbury, the Dampier Bunbury pipeline or if it's an offshore export line and perhaps taking it to an LNG processing.

43:49

Well, in those lines when they're exporting gas, the spec is on the order of 10s of PPM depending on time of year and the additional gas parameters.

43:59

There is no room for gas to be in that export system because it can corrode, right?

44:05

And to deal with corrosion, you either have to inject corrosion inhibitors that tend to be highly eco toxic and this is to protect against internal corrosion, or you start injecting additional fluids to adjust pH that then get very expensive and you don't want to be transporting liquid that's highly inefficient.

44:24

And so the easiest method to ensure that you don't have to pay for corrosion resistant alloy that tends to be 10 times the cost of a typical carbon steel pipe is by using a mole sieve upstream to remove water down to the PPM level, right well below the point at which it can condense.

44:41

And that's, you know, one common, probably the most common application of mole sieves in Washington right now.

44:49

So finally, and this is related more to the lab than anything, but when we talk about identifying these mass transfer zones, and I wanted to circle back and think about where should this T star point be?

45:01

We highlighted that the active mass transfer zone that we saw it sketched out earlier is tends to be bounded between 5 and 95% in the concentration profile or the relative concentration.

45:13

So if we call that the mass transfer zone, we can see it in a profile plot moving through the bed with time.

45:19

But I did highlight the nature of that adsorbing curve and it's going to depend on the material type.

45:24

It's going to vary with the adsorption isotherm, the upstream concentration, and of course the material type and size of porous and the porous size distribution in play.

45:38

So I can have something like a very narrow transfer zone.

45:41

I can have a very wide transfer zone.

45:43

And this is a consideration for the engineer to think about.

45:46

You know, again, this is one of those primary parameters if we're dealing with highly toxic materials, right?

45:52

In a toxic material, I really can't deal with a wide mass transfer zone because the second I get, you know, the first detectable molecule coming out of the end of the bed, I need to shut the process down.

46:04

Well, if I'm not, if I'm, I want to expended a maximal amount of the bed by that point, hence the more toxic the material.

46:13

I'd intend to want to see a narrow, an ever narrower mass transfer zone.

46:18

But in either case, you can see the nature of this S curve that's going to show up.

46:22

T star is basically the point that cuts this S curve in half no matter where it's at.

46:28

And it's it's coming from a geometric.

46:30

So this is a.

46:31

And if I were to integrate this T^* is the point at which it is bisecting 50% of the integrated curve.

46:38

So I can rearrange from a, a simple mass balance or sorry, from a simple integration, trapezoid integration to define T^* as a function of other things.

46:50

So the saturation loading, that's that plateau point in the isotherm, the initial loading of the material, we'd hope it's zero, but it might not be.

46:58

Density of the salt of the adsorbent solid.

47:01

The length of the bed, of course, because this, you know, the engineer gets to choose the length of the bed base so they can ensure the adsorbing and desorbing columns are matched in time.

47:12

The velocity material and the initial concentration so I can rearrange based on what's within this equation to, to provide a solution for where T^* will sit.

47:22

And certainly you know, this would be a good thing to apply into lab #4 to take a look at, you know how you can diagnose the breakthrough.

47:31

Sorry, not the breakthrough time where you can use T^* to then integrate or as a point of integration for the total amount of material that's been adsorbed in the bed.

47:41

So if you know where this T^* is at, you don't have to worry about integrating the entire S curve.

47:46

It allows you to integrate the rectangle basically.

47:49

OK, so as we come into the next lecture, this will be a kind of just a quick clean up on the nature of adsorption.

47:57

And we're actually going to look at a few applications beyond that of the laboratory.

48:01

So this will be all of the content that you need to work through the laboratory and the next will just be a bit forward-looking in terms of where you might come across adsorption in the rest of your career.

48:11

OK, have a good rest of your day everyone, and we'll talk to you soon.

48:13

Bye.

Lecture 10

0:10

OK, so welcome to lecture #10.

0:12

So now we're going beyond the description of adsorption design from lecture #9 and we're thinking about more of the practical implementations.

0:21

And I wanted to use the first bit of this lecture to kind of clean up a few of the concepts from a fundamental standpoint.

0:28

So again, this corresponds to that.

0:30

We're in the same module.

0:31

There's only one reader chapter for this fortnight as as that of 11 for adsorption, but this also corresponds to chapters 25 and 26 from the required unit textbook.

0:43

So diagrammatically from our last lecture, we were talking about the difference of chemisorption and physisorption.

0:49

I talked about the energy potential function of bringing basically a molecule closer and closer to this solid surface as a this energy as a function of that separation distance, right where the point at which these go upward toward Infinity is similar to the van der Waals radius of two molecules colliding right wherein they're basically hitting the the two billiard balls.

1:11

So the two hard spheres I cannot push together any tighter or in this metaphor, I cannot push one billiard ball any further into the table than that.

1:19

So the point I want to make is that both chemisorption and physisorption are energetically favorable in processes, but chemisorption, because I'm forming a bond between that molecule and its deposition surface, is a significantly greater energy potential.

1:36

Well, relative to something like physisorption where I'm controlled by van der Waals interactions, favourable van der Waals interactions that that bind a molecule to another molecule, in this case that of a crystal lattice in Mysol.

1:52

So if I think about how to regenerate these beds, right, this is what regenerating a chem something from chemisorption is going to take orders of magnitude more energy.

2:02

This is why we use physisorption in absorption processes because from either a temperature or a pressure variation, I'm modifying a small amount of energy in the system and that's sufficient to break those molecules off the surface.

2:17

Now thermodynamically, I can see where the very nature of ΔS if I write the Gibbs energy of this process of the process change ΔG by fundamentally is $\Delta H + T \Delta S$. We know this is a fun or foundational fun and foundational thermodynamics equation.

2:36

But intrinsically I know that ΔS must be negative, right of any process, the entropy change must be negative.

2:42

Therefore, ΔH sorry, ΔS must be positive, sorry.

2:49

As a consequence, ΔH must be negative.

2:52

And so the spontaneity of this process becomes exothermic or spontaneous processes are exothermic, so there's an energy released in the spontaneous absorption.

3:04

So I end up with a negative ΔG of this process when it's fully absorbed.

3:13

Again, this is a reminder about the absorption isotherms just to make the point that here we're going to be using K as a characteristic coefficient.

3:21

We see this show up in the Langmuir isotherm for both a single and a multi component absorption process.

3:26

But I can similarly take K or some variant on K in different types of absorption isotherms over different types of characterizations as this primary characterizing factor instantly.

3:40

If I were in a very strongly favorable region, this is where the Freundlich equation would be most typically employed.

3:46

But that is certainly not what we're working on in our labs here.

3:51

What I wanted to focus on for a minute.

3:53

So I appreciate that, you know, it probably feels a bit counter intuitive.

3:56

We've come all the way to the end of the process of talking about mass transfer operations, and now strangely, we've gone from a lot of math in Lab 3 for distillation to

what probably feels for most of you, like suspiciously not large enough amounts of math in lab 4.

4:15

And I wanted to go into detail about why because actually the absorption process being both space and time dependent involves a lot more mathematics than any of my continuous flow operations.

4:30

So the very nature of the absorption process is mathematically intense.

4:33

Now I'm not intending for anyone to go out and solve this.

4:37

I just want to show you what it looks like.

4:39

So when you go into your upper level course where you can get an appreciation for how these temporal or transient, meaning both time dependent processes look when we apply our chemical engineering mathematics to them.

4:52

So if we started with a very simple case of an irreversible adsorption, so this of the solids and fluids I could pair together, this is one of my or this is the simplest possible solution.

5:03

And what we're looking at here is this our concentration profile, but now we're plotting it as a function of time.

5:09

So recall when we were talking about N , this is the same N from our dimensionless transfer units that we looked at in AB, ABS orption.

5:17

It's coming up again in adsorption when we start solving the math out for it.

5:21

And τ is a dimensionless time that we'll go into more detail around in a minute.

5:25

So what I'm effectively plotting here is for a potential a point in space, how is the concentration profile changing in time?

5:33

And the point that we want to highlight is that we go through periods where we're controlled by both the external film, right?

5:41

It's controlling the overall rate of adsorption.

5:44

But then I start to go into a region where I have poured, well diffusion control through the pore.

5:49

So because each of these adsorbent solids is a porous material, like a dry kitchen sponge, but shrunk down to the order of microns, right, really tiny pores.

6:00

Well, at a certain point in concentration, when those sites become packed enough, the size of the pore becomes quite relevant, and in fact relevant enough to be controlling the overall transfer process.

6:13

So if I'm controlled only by the diffusion of material, right, this is my hydrodynamic boundary layer leading to a mass or a concentration gradient.

6:23

If I'm controlled only by that fluid flow around the solid, I get the profile of the solid black curve.

6:30

If I'm only controlled by diffusion through the pores, this would be consistent with Knudsen diffusion.

6:34

I get only this small dashed curve and if I have a balanced, a perfect balance between the two, I'd have the long dashed group which I can see showing up here.

6:45

And this starts to get me that that characteristic S gradient.

6:49

So where that S gradient comes from or that S profile comes from is a the nature of having a film, a transport resistance from a film.

7:00

That is my hydrodynamic boundary layer with an embodied concentration gradient, an intrinsic concentration gradient and flowing that around a porous media.

7:11

So it's the combination of those two things that produces the S curve profile.

7:16

Now in an irreversible adsorption, you remember the adsorption, the amount that I can load is independent of concentration.

7:24

It's a flat line.

7:26

So to characterize that, I need only one term and that's K_{FC} Functionally, the amount I'm going to absorb is not going to vary with that.

7:34

So I can integrate this directly to get that concentration profile, which again, thankfully here is flat.

7:41

And we can then take this E to the power of N , which we're then calling.

7:46

This is the definition of my transfer unit to plot that out in this definition.

7:52

So as I take that individual focus of the flow profile around a particle and then the flow through that particle being porous, if I zoom out from the particle and focus on the entirety of the bed.

8:04

Now again, don't panic because we're not going to go through these maps and solve them.

8:08

I just want to show you what the solution looks like.

8:11

What I can do is map out a region, not a region, but I can isolate a region DL, so some intermediate thickness region.

8:19

I can see there's a void fraction within this.

8:22

I can see there are solids, there's a differential concentration.

8:25

In this case, DC would be a negative number, right?

8:28

Because I'm probably, if I'm in an absorption region, I'm losing mass from the flow to the flow stream to the particles.

8:35

And I can balance and look at a balance in both space and time.

8:40

And in space here we're characterizing with length.

8:42

So we're assuming it's homogeneous in the cross section and I can write an engineering or a chemical engineering balance.

8:48

I can write a component material balance in both space and time as a function of now one spatial parameter length and one temporal parameter time.

9:00

So this would be an example of a first order partial differential equation and it's first order in.

9:06

So it's not 2nd order because I have two, but rather we would say it's first order in both space and time.

9:13

A second order would be $\frac{\partial}{\partial t} (A \frac{\partial C}{\partial L})$ or $\frac{\partial^2 C}{\partial L^2}$.

9:20

So I don't have a squared term in my partial differential.

9:23

Therefore it's not a second order.

9:25

But I do have a solution that is first order partial differential in both space and time.

9:30

So these kinds of equations, you're not going to come up against these kinds of equations very often in a bachelors level chemical engineering curriculum.

9:40

You tend to see this start to emerge at the masters level curriculum.

9:44

And certainly when you get into a doctor level curriculum is where these types of maths and chemical engineering are really what we spend a lot of our time either worrying about or attempting to solve or taking data to try to satisfy.

9:58

And there's an entire sub discipline at the interface between chemical engineering and mathematics dedicated to these types of solutions.

10:07

One really good example is a nicotine patch.

10:11

So a nicotine patch when applied to the skin, right, these patches are quite thin.

10:15

So you are working with an infinite reservoir that you're transferring across a porous media from a finite reservoir in the patch of nicotine.

10:25

And you then need to have an assessment because this is a medical application, you need to be able to predict the concentration profile both in the circulating bloodstream and the patch that's losing its chemical potential driving force as a function of time.

10:39

So that is a that would be an example of a second order partial differential in space because that patch usually they square a rectangle.

10:49

So I don't have an isotropic or probably don't have an isotropic consumption of nicotine from the patch, but I'd probably assume that it will be first order in time, at least for the initial solution.

11:04

Because I'm going to treat with that case, treat the body as an infinite circulating, not an infinite, but a circulating homogeneous reservoir.

11:11

Given that the one minute it takes for blood to go around the body and the hours and hours that the patch will be good for.

11:18

So the the whole point of going down this path is that when I can write out an equation like this for something like a variable concentration in both space and time, I can go to

that sub discipline at the interface of maths and and chem Ng to find there are only a handful of solutions in existence that have been done for this for these types of problems.

11:40

1st order in space and time tends to have, you know, depending on the assumptions and the bounding conditions and the initial condition, I tend to have a reasonably good run of being able to solve these.

11:53

And so in this

I CAN see here I CAN get a pretty good solution to this by approximating this driving force and replacing it with my overall mass transfer coefficient case of C AND the driving force for absorption so, concentration at any point in space and time and the equilibrium concentration so.

12:15

This representing a reduction of the chemical potential so.

12:20

To try to solve something like this, then I NEED to get large case of C.

12:25

WELL, To get that, this is where the approximation's going to come in.

12:29

I need to figure out a way to get AT, and this is my poor control.

12:32

And here I have, you know, some kind of local mass transfer resistance that I'm going to go after.

12:39

Ironically and maybe not ironically, we're going to see again another Sherwood correlation, this time for adsorbing systems.

12:48

And here we see the same kind of prefactor show up.

12:51

Our Schmidt is to the cube, Schmidt numbers to the cube root, and now we're taking Reynolds to the .585.

12:56

So this is the external film mass transfer coefficient for adsorption to a porous solid.

13:05

Now to to solve this, right?

13:08

So once I have that that differential equation set up, the art of how I go from that differential solution into a an analytical solution is what that sub discipline is is meant to do or is dedicated toward.

13:24

And these are not easy things to do.

13:27

This is the level for those that think I really like math.

13:30

This right here is the level of math at which I become quickly and easily frustrated.

13:35

It is extreme, can be fun, and the solutions can be really cool, but it's extremely complex and can be beyond my remit to understand.

13:45

So in this particular, because we're not super complex dealing with the 1st order in space and 1st order in time, what our solution strategy.

13:54

And again, I'm not expecting you to do this, but I want to show it to you so you can see how more and more complex chemical engineering problems are handled.

14:01

We tend to try to solve these.

14:03

So if it's first order in space and time, it means we need one initial condition and one spatial bounding condition.

14:09

And the method that we're going to use to solve this will invoke dimensionless, dimensionless quantities of our design and choosing.

14:18

So in most of your curriculum to date, you would have experienced everyone else telling you what dimensionless quantities to use.

14:25

Reynolds number, Schmidt number, Prandtl number, Sherwood number.

14:29

The solution to these complex differentials allows the chemical engineer to nominate their own dimensionless quantities.

14:36

Now we know that one quantity has to be temporally associated, meaning it's containing time and other stuff potentially and one dimensionless quantity has to be spatially associated, right?

14:51

So it has some definition of space within it.

14:54

But in either case, they're dimensionless.

14:56

So I have no units on either quantity.

14:59

If anyone's interested, I'm happy to go into this and, and some of the workshop

discussions, but there's we, there's a really good reason and rationale for why we go after the invocation of dimensionless quantities for our solutions.

15:12

So for that particular partial differential we would solve A.

15:16

We would invoke a dimensionless quantity Tau meaning t / t_{star} .

15:20

What is my actual time relative to T_{star} , meaning the equivalent time of bed saturation.

15:28

And as we solve the math out, this becomes the analytical definition of T on T_{star} , where I can see T is preserved here.

15:35

So I can calculate this.

15:37

The beauty is I can plot my Tau coordinates go from zero to 1 and that's one of the reasons we like it.

15:44

So as Tau goes from zero to one, this entire right hand equation also changes with the T inside of it changed from zero to one and the rest of the property is simply relating to the characteristics of the bed and the transfer process.

15:56

Similarly, my second dimensionless quantity is the number of transfer units and This is why this is a persevering approach in mass transfer in column operations.

16:07

Here I can see my overall mass transfer coefficient showing up, and here is the quantity that links me spatially to where I'm at in the bed.

16:15

So understanding or being able to solve this kind of method is effectively telling us what does the engineer get to decide?

16:25

So the properties that show up in the solution are the properties that we as the engineer get to be either creative or creative and judicious.

16:33

Hopefully in determining in this case, we would need to physically know three things about the bed.

16:40

The length void fraction, meaning how much is not solid, and the bulk density.

16:45

So an average density across the bed, common volumetrically averaged for the the solid and the fluid.

16:53

I need to know something about the velocity.

16:54

And in this case it'd be the superficial velocity.

16:57

So you know how much is flowing through the through the the void of the bed would be the actual velocity.

17:04

But if I divide that by the cross-sectional area in the absence of particles, I get I recover a superficial velocity.

17:11

So we tend to prefer superficial velocities because we're comparing apples to apples.

17:16

If we start changing things like the void fraction and the inlet concentration, right?

17:21

This is usually the parameter set in my problem.

17:23

This is the thing I have to work on.

17:26

And then of course the adsorbing characteristics.

17:28

So while we could relate that to the isotherm characteristics here, we're instead looking at the what those isotherm characteristics describe, which are two more foundational properties, the initial loading of the bed and the saturation loading.

17:42

It's it's ultimate point.

17:46

Now I'm not going to go too far into this because I don't really want to get into the kinetics of this process, the time dependence of it.

17:55

Well, I, we will get into it, but I, I don't want to confuse this with something like a, a chemical reaction kinetics, right?

18:01

We're going to follow the same formalism, but we're functionally describing 2 very, very different things being physisorption in this case and a chemical reaction or chemical bond formation in the, the case of reactions.

18:15

So for Chemisorb or sorry for physisorption, the way I would describe or the way I can describe the the reaction or the the absorption kinetics is to think about for my different types of solutions, what is the time dependence within them?

18:29

So my actual concentration as a function of space and time, what does it depend on?

18:35

Well, for AOTH order kinetics, that means the solution is not time dependent.

18:40

So we're following the same nomenclature, but it is different to reactions.

18:43

And I can see as I expand this outward with the the dimensionless definition of the transfer units, I have no time dependence in this thing.

18:51

So I'm A0TH order dependence because my, my my concentration is functionally dependent only on space.

19:00

And that makes sense for irreversible adsorption, right?

19:03

The second it finds molecule it adsorbs.

19:05

So it does not care about time, 1st order reaction adsorption kinetics.

19:11

And this is typically what will be present.

19:13

This is obviously what we were just looking at.

19:15

We were first order in space, first order in time.

19:18

So now that the rate of material flux is a function of time is going to be related to a first order kinetic constant and the driving force for this.

19:28

And again, I can go to a second order where I have a concentration dependence in time, but that's now relating or scaled with concentration squared.

19:36

So this would be associated with more chemically complex systems where I'm not just pulling one simple gas molecule out of an otherwise simple gas string.

19:45

OK, so again, the past, you know, three slides are not meant to ward anyone off, but I would be remiss if I didn't illustrate the connection of why absorption was our 4th and final unit operation and the third in mass transfer.

20:01

The actual math, when we get down into it, is one of the most complex applications we'll see in a baccalaureate engineering curriculum.

20:10

And if you were to carry on to masters level curriculum and certainly into a PhD, this would be the type of math that we would start to see unfolding.

20:21

So on to some more fun stuff.

20:22

Where do we see absorption as engineers on a more daily basis?

20:25

And that is chromatography, right?

20:27

So you probably would have come across chromatography and basic chemistry, but functionally the purpose of chromatography is to try to give me an insight as to what is the composition of the stuff that I'm working with.

20:41

And the basic premise of it is that if I have a chromatography set up containing an adsorbent material, well, my and I'm dealing with a chemically diverse system.

20:54

So I have different vapor pressures, different molecules, right.

20:58

Well, the stuff that likes to adsorb whereas more readily adsorbed will adsorb first.

21:03

And this stuff that doesn't like to adsorb is going to adsorb last.

21:07

So instead of a continuous injection until the bed is spent, what if I took my adsorbent bed and pulsed it with a known mass of material and then stopped?

21:21

Right.

21:21

So I'm not hitting it with material until the bed is spent.

21:24

I'm hitting it with only a pocket of material carrier moved by a carrier fluid through that bed.

21:32

So in this context we can start to look at the position at which that material adsorbs is related to its molecular weight.

21:45

Effectively heavy molecules want to adsorb earlier, lighter molecules can carry through a bed and end up adsorbing later.

21:54

So the chromatograms that are generated and these, these are well generated by or they're looking at the amount of material that's retained in the column as a function of time.

22:08

Now once I adsorb it through the bed, then I'm going to regenerate the bed.

22:12

So if I'm regenerating temperature swinging to warm up, right, then if I'm warming up, I can think about, well, a heavy molecule that's adsorbed many, meaning a high molecular

weight and a number of atoms built within it, meaning it's each of these atoms has a physisorption potential with the solid.

22:33

Well, the amount of energy that it's going to take to pull that big molecule off the surface is significantly greater than the amount of energy it's going to take to pull a really light and small molecule off a similar surface later in the column.

22:49

And so as I begin to warm, once I've pulsed the material through and it's deposited from heavy to light, I then start warming the column.

22:57

And as that warms up, it's going to lift the material back out in that order, or sorry, in the reverse order.

23:04

So for the lighter components, these jump out first and my heavier components are retained in the column until longer and longer times in the process.

23:13

So here's an example chromatogram where I'm looking at a signal and we'll come back to what that means in a minute as a function of this retention time in the column.

23:21

So after that initial pulse, how hard is it to pull it back off the columns material?

23:27

And one of the challenges of chromatography is that we don't have an analytical right.

23:33

So this is not as good as like a AGC, sorry, this is AGC.

23:38

It's not as good as a mass spec where we're getting an analytical breakdown of the portions of the molecule and how they break apart and where they go.

23:45

This is giving us a much more general, what's the, well, what's the approximate for, for a very basic GC would be what's the, the approximate molecular weight associated with this retention time for the column.

24:01

And we'll look at an example toward the end of this lecture where we can turn this up to a really extreme level.

24:07

But of course that type of chemistry gets very expensive very quick.

24:13

So in the chromatograph itself, what I would typically have is an absorbent solid.

24:18

I could use a liquid, but probably a solid and then I need some carrier gas.

24:23

So if I'm going to inject a material into the column, I needed something to carry it

because I'm not going to be injecting continuously as though it were an absorbent or an absorption column in a chromatography application.

24:36

It's a small pulse of material and a carrier gas to sweep.

24:39

So obviously helium would be good, but nitrogen would be the cheapest and most common.

24:46

So the feed is inject, in this case liquid, say injected in vaporizer.

24:50

If it was a gas, it would just be injected and it sweeps through the column, right And in that absorption process and then we reverse.

24:58

We reverse by heating up and we can see here this is a picture of the column components and on the right hand side a simple diagram.

25:08

So this would be our carrier gas, the injection.

25:11

So up in this syringe would be our small amount of material that's pulsed through.

25:15

Here is our, you know, quote UN quote column might be very long and spiral wound, but with a small arc.

25:20

So it functionally acts as a continuous length and then the detector.

25:25

So as this this pulse goes through and then the material is absorbed and then in a warm environment pulls back off the surface, it's going to show up in this detector.

25:36

So the detector is looking at, you know, what is there or what is coming across.

25:40

That's not the carrier gas.

25:43

So the the light molecules will pulse through very fast.

25:46

They might absorb and desorb quite quickly and bang into the detector.

25:51

Whereas the heavy molecules are going to be absorbed and retained in the column quite some time before they come out the other end.

25:57

And this allows us to take that tiny little pulse of material and smear it out functionally or as a function of its molecular weight.

26:09

OK, so for my chromatography relationship, I'm initially wanting to relate some nature of what's in the gas phase to the complex and non ideal liquid that was injected and vaporized.

26:24

So when those molecules are in contact, they're going to demonstrate liquid significant activity coefficient.

26:31

And here I can note the appearance of Raoult's law, but it's containing liquid activity with an idealized gas phase.

26:37

And I can also use a partial pressure relationship within this as a vehicle to relate something like the gas concentration that I observe with the activity coefficient.

26:48

And we'll look at how that plays through in a minute.

26:51

Similarly, I can rewrite this on a concentration basis for component A in a liquid simply by knowing its density and molecular weight on the average molecular weight.

27:01

And if I rearrange this together now I can look at the concentration component A in the liquid now as a function of my vapor pressure of the component, which is a thermodynamic property system pressure.

27:12

My densities of the average density of the liquid and gas phase and the concentration of the gas phase in critically I see the preservation of that activity coefficient.

27:22

So bringing those together and the reason that we can deploy this where we can have a cool application for chromatography.

27:32

If I think about the mass of my solvent that's coming through in this system, so per unit volume I'll relate is W the equilibrium amount of my component of interest, right?

27:46

Well, now this is going to be distributed between the amount that's in the core volume itself and the amount in the stationary phase around it.

27:55

So I can write the amount of this component A now as a function of, well, whatever gas concentration is within that matrix and whatever is L is in the outside, meaning in the outside of the porous media itself.

28:13

Now, if my gas, my carrier gas, is coming through this with a superficial velocity, we'll call U not on ϵ .

28:21

So that's meaning if I only think about if I'm removing the effect of a whole bunch of distributed solids, and I'm thinking only about the void fraction itself, then for an

individual component, and I'll try to slow down to emphasize this, that for an individual component, the time at which it's going to leave this column is related to the distance it had to flow the void fraction, meaning what fraction could it flow through and that superficial velocity.

28:55

So I've just done a simple mass balance to get there.

28:59

When an individual component then is partitioned of the solid phase, I can say, well, this is going to have a breakthrough curve.

29:08

It's not going to breakthrough at a point for that molecule.

29:11

It's going to breakthrough as a curve.

29:14

And in fact, the point, now it might be a very sharp curve, right?

29:17

It's not going to take ages.

29:18

But then the characteristic point of that curve I'm using in chromatography is this T star.

29:27

That's the key insight relating from our absorption column to a chromatograph.

29:34

So this T star that we've seen, I can write this now for component A itself.

29:39

This will be the median breakthrough time in the column.

29:44

And this is related now to again the length that it has to travel through on its superficial velocity.

29:51

Of course, I have my void fraction showing up as well, but I also have this case of a term and this is what we'll call a partition coefficient.

30:04

Now in my GLC system, so gas liquid chromatography, so I'm using a liquid and vaporizing it.

30:13

My partition coefficient is going to be much greater than the void fraction, which means functionally what's inside of this summation I can ascribe pretty much to just the partition coefficient case of A, right?

30:28

This will be the dominating term, meaning I can neglect epsilon.

30:33

Therefore I can write the retention time.

30:38

Let's focus on A for a minute.

30:39

I can write the retention time for component A at that medium point of breakthrough TA star.

30:44

It's saying that's basically case of A and case of A is basically or is equal to the activity coefficient of component A.

30:56

I'll explain the relationship here in a minute, but the relation or the activity coefficient of component A times its vapor pressure.

31:04

Now the challenge of gas chromatography and the reason we can't use this in isolation to get a perfect compositional profile.

31:10

The reason GCS are paired with Ms.

31:12

to a mass spectrometer to do a comprehensive characterization is that GCS are giving me only a relative quantity.

31:20

So this relationship holds.

31:23

But when I look at only when I look at TA star on TB star.

31:29

So the relation then of case of A on case of B is equal to the activity coefficient of component B and its state compression on the activity coefficient of component A on its state compression.

31:43

So the point of all this is if I know all right, if I did one application of this, if I know what my components are, but I do not know what their activity coefficients are in this complex mixture.

31:58

Well, from the components themselves, I can get the vapour pressures.

32:02

Therefore, once I can start relating or once I'm able to relate each retention time, median retention time TI star in my chromatograph to another, I can get a proportionality in the activity coefficients between these two components.

32:23

But this is not just good for a binary system, it's good for an N component system, right?

32:30

That's one of the powerful points of this is I can extract relative activity coefficients experimentally.

32:39

Now it should be said when I say multi component, there is a functional limit, the number of components for which this will work right And the minimal concentration that I can or the minimum detectable concentration scales with the cost and size of the GC that I buy.

32:58

So when I say multi component, if I want this profile for 10 components that are all present at 10 mole percent, then I can probably get away with a relatively inexpensive standard GFC.

33:10

What I'm going to show you in the next two slides are what happens when we try to apply this technique or what what we have to do to apply this technique to something like a field condensate.

33:21

So you know, naturally occurring sub well subterranean or subsea reservoir containing some condensate in gas or oil and gas condensate will just be a much lighter hydrocarbon distribution in terms of molecular weight.

33:37

But because these things are naturally occurring through biodegradation, I get a massive diversity in isomers, right.

33:45

Meaning for any one carbon chain length, I have hundreds, thousands, billions of permutations that are all occurring in a natural distribution.

33:55

So very difficult to to characterize chemically.

33:59

So for that kind of system, this is an example on the right hand side, this would what we looked at earlier would be signal, but this is we can also present as relative content as a function of that retention time in the GC.

34:11

So for a naturally occurring and this is actually a blend of a condensate and a crude oil and you can tell that because you have this lump of stuff in the middle that becomes very difficult to see.

34:22

It's not clean like we'll see in a minute.

34:25

This is a a nice GC and a middle of the road GC, but it's applied to a heavier condensate or a lighter crude oil where what we've done, and this comes from Brendan Graham for those of you that know him, what he's done is to relate the boiling point to the retention time and is using this to infer the carbon number.

34:42

So the further the retention time, we can say something about the carbon number, which is where these C10C20 and C30 peaks come from.

34:49

Now in this case, Brennan was using AGC again from a temperature ramp from 50 to 400° C So we can see that temperature swing come into play.

35:00

And again, when we start getting to things like C₂₀, we have 10 to the 10 to the five or 10 to the six isomers that are possible.

35:09

And that's part of the reason that we get this smearing behavior present and particularly in a crude oil, it will smear out because of both the number of isomers, but critically, the number of the the bias toward having what we'd call hetero com hetero atoms presence.

35:28

So I start to get linking behaviour between large hydrocarbon chains and I can start to get some really elaborate chemical structures that are emerging.

35:37

Again, if you're in an anoxic biodegradation environment for, you know, millions of years, you have a lot of time to go through chemical reaction processes.

35:49

What is a bit cleaner is when we look at a simpler condensate, so a very, very light, ironically light oil.

35:56

Even though we're showing a C-40 carbon chain here, this is a condensate that had a unique appearance of some of this.

36:05

But the nature of seeing these really clean spikes, this is what we would typically expect to see in a condensate, right?

36:12

And so if we were trying to get a really rough characterization of the district carbon distribution in a system, we would be looking at the relative peaks in this to say, OK, what is my based on the signal is is proportional to relative content.

36:26

Now, if it's a naturally occurring system ought to know the vapor pressures of these all of these isomers.

36:32

And I can't calculate it with multi flash.

36:34

There's a whole different domain of of organic chemistry that we have to go into to calculate these sorts of things for naturally occurring systems.

36:42

But on the left, this comes from a a late colleague at Chevron who went well was using a very, very one of the world's best chromatography systems to get a very high precision profile of the relative content as a function of retention time.

37:02

We can see C₂₀ to C₃₀ is down here on the right hand side.

37:06

And this natural peak here is much more characteristic.

37:11

I think Brendan calls it the Stegosaurus Peak because you can kind of see the arc on the back of the Stegosaurus here much more characteristic of the standard condensate.

37:19

Now by going to one of the world's most complex and most expensive chromatography systems, Doctor Creek was able to then have enough resolution that at least within the band of C5 to C10 or C8, so relatively short carbon chain link actually pulling out each of these isomers based on their retention time.

37:40

So these would all be associated with the same number of carbons in the system, but by arranging them differently, they'll have a slightly different retention time for the reason of having a different vapour pressure and different activity coefficient.

37:53

OK, so just a few applications to close this out.

37:57

You know, I think most of us in our careers will come across the use of chromatography, whether it's for oil, crude oil, condensate or a biofuel characterization or, or any kind of basic chemical characterization.

38:12

And so it's important to recognize that this is working on the basis of understanding or applying our absorption knowledge and mathematics, but to a very specific application of a small amount of mass deposits.

38:26

And then as I warm the system back up, I'm exploiting that principle of the low energy bounded business option to dictate the, the rate at which these will pull off the surface and I can then detect them.

38:39

OK, so if anyone's really enamoured with chromatography and interested in learning more, I, I know very little that Brendan is an absolute world expert at chromatography and he loves to talk about it.

38:49

So I'm sure he'd be delighted to to get questions about industrial uses for chromatography.

38:55

OK, so this will bring us now to the conclusion of our absorption module.

39:00

And in fact, this is really the end of our core content in lecture 11.

39:04

We're going to be cleaning up just a few things around pumps and, and making sure that we're comfortable with how fluids are pumped for unit operations.

39:12

And then we'll be going into a few basics around engineering design just to make sure we're we're primed to deliver the design report at the end of the semester.

39:20

Have a good rest of your day everyone, and we'll talk to you again soon.

39:23

Take care, yeah.

Lecture 11

0:11

OK and welcome to our final lecture #11 on engineering design.

0:16

So I will mention the last chapter of the reader on membrane separation.

0:22

So for dedicated toward reverse osmosis, this is not necessarily required reading and nor is the the associated textbook reading with these sections.

0:33

These are simply listed as optional.

0:36

If you want to go down the road of using membrane separation for the engineering design, the small engineering design project due at the end of the semester.

0:46

And so because this is also covered heavily in CHPR 3018, what I've done here is to include those sections in the reader and the references to the appropriate sections of the textbook.

0:57

Just to make sure that for anyone who might not either be Co enrolled in 3018 or have taken it previously as an ability to, to jump into this.

1:07

And of course, you know, for those that have taken it, please let me know if if you suggest any revision to those chapters or to the chapter of the reader.

1:16

But I'm, I'm not going to touch really on the membrane separation.

1:19

What I wanted to talk about here was to very quickly go through and kind of cover a few details around fluid flow pumping, but from the perspective of the practical operating engineer.

1:31

So, you know, when I'm dealing with, with pipe networks, fluid flow and in complex situations, meaning I, I might deal with erosion, corrosion and fouling of a different type or interaction of all three of these.

1:44

What are some of the considerations I as the engineer need to take to ensure that my, my design and my operation remains robust?

1:54

OK, so one of the 1st and it's relatively simple, but in a critical clarification to put forward, and this is shown, this is a figure or a table from appendix three of our textbook.

2:06

So when we talk about ducted flow and pipe flow diameter, most of the time in our basic engineering work, we would have simply talked about the characteristic length of flow.

2:18

So our mental model is refined on to this point.

2:22

What is the characteristic diameter of flow through which my material is going to move?

2:27

And that's all we concern ourselves with.

2:29

Now when we get out into purchasing materials to build engineering solutions, one of the key concerns is that, well, for the engineer and on my spreadsheet and in my graphs, I can really choose any diameter.

2:43

So from the perspective of the student, diameter is usually a continuum property, right?

2:50

Meaning I can choose any infinitesimal gradient and that's fine for my solution.

2:55

And part of that's reinforced by the problems we give you, right?

2:58

We give you problems in which a solution diameter might be two point O 4713 inches.

3:04

And yet in reality, if one were to ever go look for that diameter of pipe, it would exist.

3:10

And so one of the ways that the engineers bound their solutions to these problems is through pipe schedules.

3:16

Now, these are built on the basis of nominal diameter.

3:19

And this can be a bit of a confusing language to use or nomenclature because it can correspond to either the internal meaning the smallest, or the external meaning the largest diameter of the pipe.

3:30

So let's look at this particular schedule from Appendix 3 and unpack in a little bit that for a nominal, apologies again, this is in American imperial units.

3:40

If our nominal pipe diameter is 2 inches and we look at an outside diameter of 2.3, so this is a solid measurement of the diameter 2.375 inches.

3:50

We have two schedules available to us, Schedule 40 and Schedule 80.

3:55

The Schedule 40 has a, so we're defining it on the basis of the outside diameter.

4:01

And the Schedule 40 has a thinner wall than the Schedule 80, meaning our internal diameter for a 2 inch nominal pipe.

4:10

If I'm in schedule 40, the flow, the characteristic length that I will use for flow is actually a bit above 2 inches.

4:17

And if I have a schedule 80, the characteristic length is a bit below 2 inches.

4:22

And I can continue going down through this paper and look earth through this table and see that this exam for this is reflected over and over and over, right?

4:30

But it is not a perfect art.

4:31

If I come to a 12 inch nominal diameter, well under this smaller schedule of 40, my internal diameter is less than 12 and under schedule 80, it is significantly less than 12.

4:44

So it's important when we're thinking about pipes.

4:46

And again because it's not a continuum, these have to be manufactured right?

4:50

And we don't 3D print pipes, at least not yet and probably not for many decades to come.

4:56

So because we're manufacturing these in masks, it very much matters that I pick a pipe at an internal flow diameter.

5:04

I've consulted a pipe schedule to understand, well, what is the internal flow diameter available to me for the pipe I choose.

5:14

And often times this, and this gets back to the point of the engineering design process, it's really important that the engineer in charge of a project has actually gone through that process all the way to the end to understand the economic implications of picking a pipe diameter.

5:29

That is custom, right?

5:31

Surely it can be done, but at a cost that might put a zero behind the overall cost of the project and therefore be unacceptable.

5:39

So against this pipe diameter, we can, in this particular schedule, we can look at something like the flow capacity of water.

5:46

And of course we like water because it tends to be a very constant viscosity.

5:51

And so we get a nice clean flow profile.

5:53

We don't have to worry about any kind of viscoelastic effects in the flow.

5:58

But the main consideration here of why we would choose between Schedule 40 and Schedule 80 in this particular example would be constrained on two factors.

6:10

The first would be the burst pressure.

6:12

So as I come to Schedule 80 and I can see the wall has not doubled, but has increased by about 30% in thickness.

6:20

Well, the amount of pressure that this higher schedule number can take increases substantially, right?

6:26

And I can go to my colleagues in mechanical engineering to look up what are the burst pressure calculations for that pipe.

6:32

And of course, as an engineer, I always need to make sure that I've added a margin to that, that I'm not operating, you know, at the burst pressure or around it.

6:40

But I'm well within a margin of say 50% or more before I could ever achieve the burst pressure.

6:47

But similarly, I have to think about the weight, right?

6:50

So the thicker the wall gets, the higher the larger the weight.

6:53

And it should be pointed out that for every pipe in this schedule, and we typically use 10s to indicate the schedule number, so gradations of 10s.

7:02

But for every pipe shown here, none of these would be considered thick wall pipes, right?

7:07

Not even by a country mile.

7:08

They wouldn't be a thick walled pipe.

7:11

To get a thick walled pipe, we need a pipe thickness that's on the order meaning approximately similar in magnitude to the internal flow diameter of my pipe.

7:21

That's the the order of magnitude that we'd be operating on.

7:27

OK, so when we have liquids flowing through our pipes then, right, We've done a lot of pipe flow calculations to date.

7:33

And so the, the purpose of this is really to, to go more into making sure those practical aspects of how we move fluid through piping systems are covered when we're thinking about a global unit operation.

7:46

So with the the liquid phase, when I'm trying to pump it from one level to another, we would have done the Bernoulli equation in fluids.

7:54

We would be able to rewrite our pump work in terms of the amount of head that it's applying, right.

8:00

So from the very beginning of our class together, we talked about head is ρGH , effectively how much additional energy that's contained within this fluid as a function of the amount of work I've put into that pump.

8:14

And so the denominator in this case, the Greek letter little η is representing my pump efficiency from zero to 100%.

8:22

Now critically, the amount of, I shouldn't say not the amount of power, but the amount of work put into the fluid is $W_{sub P}$.

8:29

So the amount of power that we have to supply is then $P_{sub B}$, the amount related to the head of the fluid and the efficiency and the mass flow rate m . how much material am I moving through that pump to Gen.

8:44

that's generating this amount of head ΔH ?

8:48

So we're, we're setting this up in context because we need to understand if we're designing a, a whole system of unit operations, the overall energy requirements.

8:59

So as I go from something like the head of the fluid that is my actual purpose to delivering this higher pressure environment, what do I need to know?

9:08

I need to relate that head, which is my design spec to the mass flow rate of fluid coming through.

9:15

And then I need to know two parameters or one parameter about the pump and that's its efficiency.

9:20

This allows me to relate in three terms, the power that's supplied to the pump as well as the power that's delivered being proportional to the work put into the fluid.

9:31

Now, when I'm pumping, and I, and I talked about this a little bit toward the beginning, and I know that Jeremy's covered this in fluids before, so I won't go into too much detail, but it's, it's really important that we make sure when we're in a fluid pump environment, 99% of the, the liquid phase pumps out there are not designed to handle gas.

9:50

Meaning if I have any gas bubble formation upstream of that pump coming into that pump where I could have gas bubbles collapse in the pumping process, I can create a tremendous amount of force in the collapse of that bubble.

10:05

And if that collapse point occurs at the interface between the fluid and my metal, the pressure of the bubble collapse is able to erode a portion of the metal, effectively eating into it almost as though I had sprayed it with acid.

10:19

And so here are two examples of this process, of this erosion process where when it's taking place in a pump, we call it cavitation.

10:28

One where I can see a moderate cavitation on the exterior of a blade, but another in a circular configuration where I've actually eaten away at a core portion of that pump.

10:40

So I say that this applies to 99% of the pumps.

10:45

If you go into a large scale industry, and the energy industry is one of these in which fluid pumping is a critical aspect.

10:53

When you get into very large scale projects in which you have a large capital at your disposal, it is certainly possible to purchase pumps that are designed to work with a limited amount of gas.

11:06

So you typically are not going to ever be dealing with more than 50 volume percent gas going through a pump.

11:12

But it is certainly an emerging capacity that we can deliver multi phase pumps where I might have 10 or 20 volume percent gaps flowing.

11:23

And one of the key safety margins that will apply is considering the net positive suction head or NPSH for that pump.

11:30

And it's basically making the point that the pressure of the pump inlet needs to be greater than the vapour pressure by this net positive suction head.

11:39

All right.

11:41

So when we're looking at pump designs and if you're thinking in your design project about going out and, and applying a liquid phase pump, it's critical that you actually find these.

11:51

And we'll go into in a few slides, pump curves and some pump specifications from vendors where this material has already been assessed.

11:59

Because you know they're selling you the pumps.

12:01

So it's their responsibility to have measured and provide this detail and your responsibility to confirm it's been done appropriately to then apply it to your project.

12:11

So the types of pumps you may want to look at and I'm not going to go into great detail about these, but just a few.

12:16

So we have a sense, the 1st is a piston pump and this is the an exemplar of a reciprocating positive displacement pump.

12:24

So in this the design we have obviously a suction point where we're drawing in our liquid and we can see here we have a piston plunger right, which is driven by a crankshaft connected to a motor.

12:35

So our electricity is coming in driving this motor and effectively by varying this piston position and having a suction valve.

12:42

So it's a one way valve, we can only draw fluid from the bottom up and as it pushes it can only push fluid from the main cavity out.

12:52

So this typically is a useful and a commercial application up to 50 atmospheres of pressure.

12:58

So that might be reasonable for most say liquid water pumping applications, but

certainly if you got into high pressure gas or oil environments that would not be sufficient.

13:09

If you need to go to higher pressures, then plunger pumps are can be accessible up to about 1500 atmospheres commercially.

13:16

And the design of these works a bit differently.

13:18

We're still using a a piston displacement process and we're still using our suction valves to prevent backflow in the pump.

13:28

But the nature of of aligning this with the flow stream means that I'm changing where the momentum is distributed as that piston comes in and out of the the primary pump cavity.

13:38

Now in either application of these, we would typically expect efficiencies somewhere above 40%.

13:45

So if we're in a really small volume low pressure application, we're going to be down in the 40 or 50% region.

13:51

But if we get to a larger volume, you know operating up near its its reasonable pressures in the case of a piston pump maybe 30 or 40 atmospheres up around its design spec, then we might see 70 to 90% efficiencies.

14:08

So an alternative to using a piston to drive material is the concept of using a Rotary mechanism as a way to move material from one pressure environment and discharge it at a higher pressure.

14:20

So of our Rotary positive displacement pumps and here we can see on the left is what it's called a gear pump.

14:27

So we have two gears where the teeth of these are moving in opposite directions and in that process able to pull flow from one side and with a pressure communication push it out to the other side.

14:38

In the middle is a vane pump.

14:41

And so we can see here we have our central crankshaft just with the gear pump and this is driving teeth that are pulling fluid from an inlet side around and discharging to the right.

14:51

And then here is obviously a very old diagram, but of a screw pump where we have a central Rotary vein that's able to draw fluid up and discharge it.

15:00

So these are again suitable as with our other positive displacement pumps at relatively high pressure environment.

15:06

So we're looking at, you know, up to 200 atmospheres as long as we're again, we're not dealing with very viscous materials or severely non Newtonian materials, meaning we might have a yield stress associated.

15:20

And the nature of these is also such that they can be shrunk.

15:23

So in particular, this gear pump, if we were to shrink this down to the level of millimeters, we start to enter what's called a peristaltic pump.

15:31

And this can be used for a variety of of, you know, more intensive physics type science applications if we're trying to create really precision controlled pumping environment for the purpose of taking a laboratory measurement.

15:47

And then we also see these show up in medical environments where the volume flowing through in the pressure, obviously relatively low pressure and lower volumes relative to the human body.

15:58

And then finally, you know, what would happen if we didn't really need this high pressure environment that our positive displacement pumps can handle, but really we need to put through larger volumes of relatively moderate or low pressure environment.

16:11

And so this is where our centrifugal pumps can come in.

16:14

And this diagram in the middle here shows two axes of the centrifugal pump.

16:18

But effectively our core impeller is driven off a rotating shaft as shown here.

16:24

So the fluid is going to be drawn in through the center channel and spun outward.

16:29

So we can see our inlet here.

16:31

And as the fluid migrates into the channel, it's driven by these blades and flung outward.

16:37

The nature of this is not such that it's withstanding high pressure across the sides of the pump, but rather it's able to spin at a very, very high rate.

16:47

So, you know, up to say about 3500 RPM as a vehicle to discharge very large amounts of volume.

16:58
OK.

16:58
So again, we're not going into the details of the pump, but to highlight these are the key, the characteristic types of pumps, the positive displacement or Rotary depending on whether I'm going for high pressure or large volumetric flow rate.

17:14
But in either case, when I'm thinking about what pump do I apply, we recall back, we need that pump efficiency, right?

17:20
That's what's going to link the amount of work delivered to my fluid, which is what I'm really designing on to the amount of energy used that I have to draw in by plugging this into a wall or a grid.

17:32
And so the linking parameter here are what we're going to call pump curves.

17:37
If I look at the right hand side as an exemplar, the total head, so this is the ΔH , the amount of head delivered by the pump in feet of liquid that it's been rated for as a function of the flow rate through the pump.

17:50
Now in able to read these pump curves, what I'm looking at, and this would be for a centrifugal pump given the RPMS I'm dealing with, but what I'm looking for, I need to find for a given RPM, I'm able to then look at what size of the pump am I going after, right, right.

18:10
And what I'm trying to relate to is the amount of power that's going to be required for a given efficiency.

18:19
So if I wanted to take and that again, I would go to a pump vendor to obtain these.

18:24
These are fundamentally the pump vendor's responsibility to obtain or to provide to the engineer.

18:31
So if I wanted a centrifugal pump with a 5 inch impeller and I'm going to operate this, let's say at the highest RPM, then I would look here and say, well, OK, let's say I'm operating at this 3450 RPM.

18:44
And if I'm going to need say or I want a system that's operating at 80% efficiency delivering that RPM and this will give to me 200 gallons a minute.

18:56
So if that's my design spec, I'll trace up this vertical line and find, you know, where is this bisecting my required pump efficiency to make this work.

19:05
So if I want to operate at the limit of the pump efficiency that you know would be wise

given the capital cost, then I can infer from these horizontal or these diagonal dashed lines the amount of power that I actually need to draw to deliver this.

19:21

So I can see that the gradations of 123 and five horsepower here, again, apologies for the Imperial unitset, but I can extrapolate say, well, I'm going to estimate that on this, I need at least 5.5 horsepower or 4.1 kilowatts to drive this pump if I'm operating it as its maximal RPM to deliver 200 gallons a minute at 80% efficiency.

19:50

So that's how I go to read these things, right?

19:52

I'm nominating what is my flow rate and ideally what efficiency would I like to achieve?

19:57

Or am I operating in the best region of efficiency for that?

20:01

And that's going to tell me the bisection of, well, how fast is it probably going to be spinning to deliver that?

20:06

And critically, how much real power am I going to be drawing?

20:10

Now at this point if I choose this bisection of 80%, I can also trace left and see I'm delivering about 88 feet of liquid in head.

20:20

So that liquid head that I'm delivering relative to the 5.5 horsepower or 4.1 kilowatts required to deliver that head.

20:30

The relation of those two is my pump efficiency.

20:33

So in this case I would get 80%.

20:37

So, you know, an important consideration if I'm operating a system at this is for the centrifugal pumps.

20:45

So if I'm drawing something seawater to drive a process or I'm working in a large volumetric flow environment, if I'm thinking about varying pump, well, if I'm working with a constant diameter system, so I've purchased the pump, I cannot change the diameter and I want to modify the operation, then I can get an intuitive sense of how I can vary say the pump capacity based on the I, if I can vary the RPM.

21:10

So most of these pumps when they're designed or when they're purchased are going to be rated for a range of RPM for centrifugal pumps, meaning I can't go above or below those bounding points.

21:19

It's designed to operate in that region.

21:22

So even for the same pump, we would have to nominate the region it would be built and purchased on that.

21:28

So if I nominated the diameter, I'll have a range of RPM that I can work with, and variation thereof is my primary mechanism to vary pump capacity.

21:40

If I need to vary the head that's going to scale with the RPM squared so I get less.

21:46

I have a much smaller range of head that I can vary on a pump that's already existing at constant diameter, and if I need to vary the power, that's going to scale with the RPM cubed.

21:58

Now conversely, if I'm operating at a constant impeller speed, then these same 3 quantities scale progressively with the diameter to the first, second, and third power.

22:08

So the point of saying this is getting these pump curves and ensuring that you're operating in a range of flexibility, right?

22:16

So if you're picking out a pump for your engineering design, you do not want to be operating at the absolute limit of that pump design to meet your specifications.

22:28

And this might sound a bit counter intuitive, but this is one of those reasons that we would not operate at the limit of 80% efficiency in the example I put forward.

22:35

We would right, because the efficiency of 80% is linked intrinsically to the flow rate, the head and the power.

22:43

So functionally, if I need to give future engineers who might take over my project when I leave or retire, if I need to give them the ability to work within a range so that if something goes wrong, some fouling emergence, something unplanned that they need to deal with, they have a little bit of room at a minimum to be able to run that pump over a different region.

23:06

Appreciating that power is the most constraining specification, head second flow and capacity or flow rate less so.

23:17

OK, so a final point and in the last few slides, I just wanted to talk a bit about the extension concepts between what we've been doing in this class together and how this starts to connect to both the upper level coursework and really where things go from here for the rest of your career.

23:33

What are the frontiers of what we've talked about?

23:37

Now, those that would have had me in thermodynamics have probably seen this layout far too much and they're tired of seeing it.

23:44

And I'm not going to go through the definition of Gibbs energy again because I know you all know it by heart.

23:49

But what I want to highlight here is that fundamentally, because we are always working on a driving force of Gibbs energy, whether that presents as mechanical, thermal or chemical in its potential, what we are measuring, right, the engineer's ability to either solve a problem or optimize an existing solution is defined and fundamentally limited by the information that that engineer can take in.

24:16

So if we have, you know, a very, very elaborate process that's been designed and only a few measurement points, the engineer is doomed.

24:28

Doomed because they have no ability to, if that well, the first time that that process goes off specification in an unplanned way, the engineer is now flying blind.

24:41

They have no data.

24:42

If it's minimal in measurement, they have no data to help them solve or intuit new things.

24:49

And that can be highly problematic.

24:52

So for this reason, one of the progressive things we see in more modernized engineering designs is the increase in the amount of instrumentation and measurements around these, right?

25:04

Particularly as we're approaching through the 4th industrial revolution and we see Internet of Things becoming, you know, a key pillar of that.

25:11

Well, that fun Internet of Things is fundamentally not about having ATV screen on every refrigerator.

25:18

It's about having data from everything, data collection and measurement everywhere, practical and connected to everything so that we're constantly reading in data.

25:30

Now, with that said, where do the domains of data sit?

25:35

Right.

25:35

It's critical when we're measuring things like length or mass or, you know, volumetric properties.

25:43

These are data that intrinsically operate in the domain of mechanical potential.

25:50

So I can measure mass, momentum, flow rate, volume.

25:54

I can measure all these things, but I'm really only I can measure them 1000 times more than I need to, and I'm still characterizing one of the three potential domains.

26:08

Similarly, I can have temperature measurements distributed throughout my entire system, right?

26:15

But I'm I it doesn't matter how many temperature measurements I take.

26:18

After I know the OR, I can relatively intuit the temperature flow throughout my my flow system.

26:25

Then at that point any excess temperature measurements are irrelevant because I'm simply loading on more data in the same entropic domain that's been characterized.

26:36

So whilst we tend to work with temperature, pressure, volume measurements, intrinsically most of the 20th century engineering designs are characterizing only the the mechanical and thermal potentials.

26:54

But we would have appreciated, we just spend, you know, the better part of a semester really working out unit operations for chemical potentials for mass transfer.

27:05

And ironically, this is also, well, not ironically, as expected, coming through the 20th century.

27:11

This is the least characterized of my three domains.

27:14

It's the hardest thing to measure measuring composition in a static system.

27:19

Like if we go back to the chromatographic graph, which is really an estimate of molecular weight distribution in a complex system, it's certainly not what we'd call a precision measurement.

27:30

That measurement itself has evolved over the course of 50 years to the point that now if we're in small hydrocarbon systems and we're spending a phenomenal amount of money to buy one of the best systems on the planet.

27:44

Yeah, OK, we can start to get a picture of the isomers of those say octane and below.

27:51

However, if we start going into to ionic systems where we have a, a distribution of say different either chemistries dissolvable in, in aqueous the, the aqueous phase or a lot of ion chemistry.

28:04

This is a very, very dynamic domain of measurement that is evolving rapidly in time.

28:12

Many of the technology providers and the engineering domain that we would, you know, see as huge employers in the future, a lot of the internal projects are around how can we exploit principles of physics to conquer measurements in the chemical potential domain.

28:30

Meaning I'm measuring concentration on the fly.

28:35

One of these examples is the use of inline ramen spectroscopy.

28:39

So very simply, ramen spectroscopy is when I'm going to hit a molecule with some energy and I'm going to be measuring and observing the band of the relaxation of those bonds, right.

28:51

So by their, you know, each bond and what it's the two atoms it's connected to is going to have a characteristic relaxation energy.

28:58

So the amount of energy it takes into the bond and then releases back out to the environment once I start observing will tell me something about the character or the nature of the bond and the two atoms it's connected to.

29:10

Well, as you can imagine doing this in a closed environment, you know, in a precision controlled environment right now with a high caliber Ramon is about the size of a small car, right?

29:22

And it typically needs a APHD's worth of training to be able to operate in a research or or a frontier capacity.

29:29

It's not an easy thing to do experimentally.

29:33

Well, from, you know, the past 10 years, we're starting to now see a migration toward things like, well, can I deploy a Roman system, maybe not measuring the entire range of bond energies, but all if I'm only looking for one signature bond, maybe what I'm trying to do is detect and pick up the presence or emergence of a toxin in my, my flow stream.

29:55

So I don't really care about everything else.

29:56

I care about only that toxin.

29:59

So can I take my my ramen system and fine tune it so that it's only looking for the bond characteristic or that's present in that toxin?

30:08

That's the only thing it can measure.

30:10

Is it here or not?

30:11

And if it is, how much is it present and deploying that in line complementing pressure and temperature measurements such that now the engineer has access to this third domain of potential.

30:24

And I raise this because from an Internet of Things standpoint, when we start deploying digital twins that are using flow simulation, the fidelity, the resolution of that flow simulation that can do things like characterize where my problem is AT.

30:40

Or conversely look ahead 24 hours or 24 days and tell me what kind of problem might be emerging.

30:48

That is enabled as a function of both the number of measurements and the number of domains.

30:57

So the, the breakthroughs in in measurement technology of the past 20 years and certainly those that are going to be coming in the next 20, these are defined not by the 1st by the number of measurements, but by the number of energy or potential of Gibbs energy domains that they're operating in.

31:18

So for this reason, the emergence of digital twins of the Internet of Things sensors, the focus on compositional measurement is absolutely a critical path to the engineer's ability to solve problems on the fly or to look ahead and prevent problems from emerging.

31:36

And you know, there's only so many ways we can measure pressure and temperature.

31:40

So opening up this chemical potential domain, and we are very much just at the beginning of this, right.

31:47

There are very, very, very few systems that can do this.

31:50

And they are extraordinarily expensive, like on the order of half of the E zone building, expensive to do right now in high pressure environments.

32:01

So we're going to see this starting to emerge as a progressive domain and this will be certainly an enabling characteristic for the engineer as our systems become more elaborate.

32:14

So the next few things I wanted to touch on are just extension concepts and how these connect to some of our upper level coursework.

32:22

So I think I would have shown this in thermodynamics and we've talked a bit about in Thermo, what is a surface tension, right?

32:30

Fundamentally, this is the collapse of pressure at the two dimension when I'm in A2 dimensional environment.

32:37

So what pressure is to a 3D volume, surface tension is to a 2D interface.

32:43

But I raise this because the other big domain that we're starting to see emerging is the intentional and clever use of surfactants or the chemical control of surface tension as a vehicle to control multiphase flow or a vehicle to control the interface between two phases.

33:03

So in this example I'm showing here, we can see this is a computational fluid dynamic simulation.

33:09

But I can see that going from if I'm at an intermediate surface tension, then as I take a static system and put it in flow, well, all those little bubbles are going to want to coalesce under a flowing environment.

33:22

So I end up seeing really large coalescence in my dispersed phase because I have an intermediate surface tension.

33:28

So low to intermediate, the 20s, not bad if I used a chemistry or modified.

33:34

So I used surfactant chemistry that can absorb to this interface and it is absorption AD absorption.

33:40

It's a total different domain of absorption, but it's surfactant absorption.

33:45

If anyone's interesting, this is one of my favorite research topics.

33:48

So come ask me.

33:50

But if I use a chemical absorption to that interface that reduces intrinsically the surface tension, then when I put that same system under flow, I get less coalescence.

34:00

So I'm able to move it whilst maintaining a much higher interfacial area.

34:07

So this sort of both on this slide and the next, this is one of the domains of CHPR 5521 gas processing one and flow, I think well flow assurance for future energy solutions.

34:21

So it's looking at, you know, we call this type of engineering workflow assurance because you're trying to assure the delivery of flow across a wide network on time and within spec.

34:34

And when that wide or long network starts getting into the hundreds of kilometers, that can be a very elaborate problem to solve.

34:43

Coupled with this as an extension concept, and this is also from 5521, an extension concept that goes beyond the relatively common types of flow behaviors that we would have seen.

34:56

So if you imagine that from fluid mechanics, you would have seen laminar transition, turbulent flow.

35:01

But these are all in a single phase environment once I start getting two phase flow.

35:07

So if I have gas and liquid moving together.

35:10

All right, let me see if I can play this video again.

35:15

Nope.

35:15

OK, so it's not going to play again, but once I get into a two phase environment, we can see from that video that was playing the types of illustrations that are shown here.

35:25

These are kind of the cartoon representations of that.

35:28

But depending on both the momentum energy of the flow and the volume fractions of the phases in play, I can get wildly different types of flow patterns emerging.

35:39

So I can have huge waves within a pipe, I can have different types of waves emerging, and each of these is going to create a different interfacial area.

35:49

Meaning that if I have some kind of fouling behavior going on or if I'm trying to control the interfacial area, I now need to think about, well, how do I either modify my momentum boundaries or play with the chemistry in the system as a vehicle to control the risk of an inappropriate or potentially harmful flow regime?

36:11

Right.

36:13

So this, I won't go into detail here, but this is also one of the domains of 5521.

36:18

And if you do end up taking that, that gets into some of the kind of frontier research and engineering simulation tech that we used to help diagnose and predict, predict risks and, and obstacles in these types of flow regimes.

36:37

So finally, I wanted to, I know I talked about this a little bit when we were in thermodynamics, but in particular the ability to form crystals is a vehicle, a phase change.

36:55

Well, in most of our engineering curriculum when we talk about phase change, we assume we change at the thermodynamic boundary.

37:02

Now I know in our very first thermodynamics lab, we tried to hit home the concept that actually the formation of ice does not take place at 0°C as we've always been LED 0°C is the phase transition for ice, not entirely.

37:18

It's the melting transition.

37:20

Similarly, the point at which a bubble is going to emerge is not necessarily at that point.

37:26

I still have a similar nucleation, heterogeneous nucleation phenomena, meaning that there is a stochastic or a random nature to where this new phase is going to emerge out of the old phase.

37:39

So the point I want to make here is that not that you need to be an expert by any means in predicting this kind of behaviour.

37:47

And, and that's a something that is still, we spent decades working on and are still just beginning to crack the surface of, no pun intended, but rather that when you get into the industry, it's really, really important.

38:00

And you're probably going to find engineers that will incorrectly make this assumption more than once.

38:06

It's critically important that you do not assume, just because you have crossed into a new phase region thermodynamically, that that phase emerges instantly in time.

38:18

There can be a significant and in some cases severe time lag before you're going to see the emergence of what we would call the thermodynamically stable phase.

38:30

And so in particular, if you're trying to avoid the emergence of that phase because it

presents a risk to your engineering process, right, a hazardous risk, then you want to make sure you've done some reading into what phase am I trying to prevent?

38:47

What are its characteristics?

38:48

What does it take to emerge?

38:50

And have any studies been done on what we would call the induction time or nucleation induction of that phase?

38:58

If you don't have any data or insight, then it's from the peer reviewed literature, then it's probably important to go out and measure it, right.

39:04

Not something at least now and probably not for the next decade or two.

39:08

We have the ability to predict accurately from fundamental physics across a wide variety of systems.

39:14

But it's something that can be measured, right?

39:16

And it's measured through repetition.

39:19

You create the, you, you design a system that mimics that of your industrial process and you observe nucleation over and over and over.

39:27

And you start to build observation curves, right as a, what's the probability of observing this phase forming as a function of time?

39:36

And that allows you, if you've done a bit of scaling around it allows you to relate that back to your industrial process to say, look, you know, the industrial process is going to dip into this region of thermodynamic stability for only 5 seconds after we've conducted, you know, 100 nucleation run measurements is good, 1000 is better.

39:57

So if we've conducted 1000 measurements of this or 100 minimum, we have not observed a single observation in less than and you want a really wide buffer on this, but in less than say 10 minutes.

40:11

So we're at least two orders of magnitude away from where this might occur in time.

40:17

And that might help give some confidence that, OK, we don't need to take another step industrially to continually dose the industrial process to prevent the onset of that fouling phase, but rather we think we can escape for this 5 second exposure window.

40:35

So the point I'm trying to make here is that when you go into the industry, the formation of a crystal, if it's a bad thing or the formation of a new phase, if it's considered a bad thing is not necessarily linked to the thermodynamic region in which it's stable.

40:49

There is a time component that links these and that is still a frontier domain of research.

40:56

OK.

40:56

So finally, I'd like to leave you with this final slide about project development.

41:01

And this is called the eagle's beak coming from Chevron.

41:07

So these are coming courtesy of two guest lectures that at UWA in 2019 and the concept, the concept of the Eagle's Beacon.

41:17

The point that I'm trying to make with this here, we're plotting this is the value of a project.

41:22

Now this is coming from Chevron.

41:23

So it's historical application as to oil and gas projects, but it really applies to any large scale industry project right, of any kind where we're bringing together a number of unit operations.

41:36

We have a complex engineering principle in play, and we have a lot of stakeholders, a lot of inputs, a lot of outputs.

41:44

You know, we're talking teams of hundreds of people on this type of project.

41:47

So for this type of project, the value of the project that the engineer can deliver is plotted here on the Y axis across what you know Chevron has characterized as five phases.

42:01

Other companies will break these into different gates, also called decision gates to go from one stage to the next or a different number of phases.

42:09

But generally they all follow the same flow in in the first step, which Chevron would call opportunity identified.

42:16

OK.

42:17

So we think we have an, we're quite sure we have an opportunity to deliver engineering, to deliver a solution and as a consequence create value in the engineering application.

42:29

However, we don't know what we're going to do about that yet.

42:32

So this next step and this can be broken into a number of steps, but generally the next step is, OK, what could we do?

42:41

And the critical mental link here is that when we say what could we do, we must resist as engineers using inductive logic to get there.

42:51

So not what do I want to do and how can I do it?

42:55

No.

42:55

What could we do in terms of deductively, if we have this opportunity, what is every possible vehicle known to human physics we could exploit to get there?

43:08

Everything's on the table.

43:10

We only start crossing out opportunities after we've concluded that we have identified everything.

43:17

And this difference of approach of inductive and deductive logic is a critical, probably the second most important thing.

43:25

I hope you can leave this series of classes appreciating if we've studied physics and chemistry and engineering and we're pretty comfortable across them, unfortunately, we can use inductive logic to justify pretty much anything we want, not anything but within reason as an engineer.

43:45

And that is a fatal trap for us and the people around us.

43:50

Deductive logic says that OK, I'm not going to allow my biases to enter my way of thinking.

43:57

I'm going to use my engineering mind as a purely a purely objective framework to look at absolutely everything 1st.

44:08

And once I am confident every potential pathway to the engineering solution has been identified, then I allow my intuition, my creative logic, my all of these complementary skill sets, then I apply them as I go through the latter half of this generation side.

44:31

OK, and I'll come back and conclude on this point in a minute.

44:35

So once we know what the alternatives could be, then we can use a decision framework.

44:41

So maybe we're trying to maximize value, we're trying to minimize emissions, we're trying to minimize litigious risks, We're trying whatever the constraints of the project are, they are.

44:53

And so we would identify the best alternatives.

44:56

And perhaps we're not going to develop one because we don't want to go through this twice.

44:59

So maybe we'll develop two or three initially of the best based on the constraints in the system and then from that point we hand it off to our colleagues in the complementary engineering discipline.

45:11

So this will start getting into construction.

45:13

So we'll work with civil engineers, certainly Mechanical Engineers, right the whole team start diversifying around this as to the different disciplines we need to bring to bear to build something big.

45:23

And then of course, once it's in play, it operates until it's end of life project's over, solutions implemented.

45:30

So coming back to this for a minute, the point of the Eagles B is that the impact of the engineer is in this shaded region that looks like an eagle's beak.

45:42

That's where the engineer has the ability to make maximal impact on the design process.

45:48

And they, the engineer does that in two ways, taking the opportunity right and and identifying the most thoughtful opportunity they can.

46:00

So if there are, you know, different perspectives, different exploitative potentials for an opportunity, ensuring that they pick the one that has the greatest room to run.

46:09

Now that can mean a number of things to a number of people, right?

46:14

But we're not going to get too down into the weeds there.

46:17

But once that opportunity has been identified, if we've defined the well, we've defined the opportunity.

46:23

It is in this link of do I use inductive logic?

46:28

I'm going to follow the bottom part of the eagle's beak.

46:32

So I another parlance for that is to say I have a poor project definition.

46:37

I've defined the solution approach in a suboptimal way, and that is because I have induced the solution I want to do, right?

46:53

Well, this comes from a historical, a long term historical tried and true method when you induce the logic of what you as the engineer want to see.

47:04

Meaning another way you'd hear this in, in less technical parlance is cherry picking facts, right?

47:10

So if you turn on like news media, it's like cherry picking facts.

47:14

Well, engineers are not, are not immune to this.

47:17

We too can cherry pick facts.

47:19

Well, we shouldn't, but we can as human beings if we want to just find argument, that's another way to say that is using inductive logic.

47:27

And we are at particular risk of engineers in doing that because if we've, you know, done our jobs, then we know enough about chemistry and physics and engineering to induce the solution that we would like to see.

47:41

The point of the Eagle speak is that that never, ever, ever returns a, a optimal outcome ever.

47:49

And if the purpose of the engineer is to serve a community, to provide a solution to a community that in delivering a suboptimal outcome, we are ultimately harming the community we have been hired to serve in some capacity.

48:04

By using deductive logic, by removing our bias, our emotions from that table when we select what are all of the potential solutions being as cold and objective as humanly possible.

48:20

And then and only then filtering those down based on our constraints to the optimal, say two or three approaches that we're going to further develop.

48:28

This is where the value of the project and subsequently the value to a community comes from, is in ensuring we do not look at these types of decisions from an emotional or personal or biased standpoint, but we are able to apply only our objective mindset to it.

48:52

And this is also by having a multidisciplinary, multifaceted team is helpful because half the time we don't know when we're biasing the solution.

49:02

And so having more people at the table helps us check that against each other to say, are we really sure that this is a deductively right way to go and if we can master that, And this is not an easy thing to master, right?

49:14

Certainly I can't master it or haven't.

49:17

And most of the people, we're still growing, we still practice, and we still, every time we try to apply an engineering solution, continually try to remove our bias from our own thinking.

49:28

It isn't defining the project definition, but this is the skill set that will allow you as the engineer to continue, if you continually work on refining this, to deliver ever and ever greater value, both either for, well for the client that you serve or the community that's being served by the project.

49:48

And it really has a very minor later impact on whether it's executed and operated well.

49:55

Even if it's poorly operated, poorly executed, we're still dealing with a massive amount of value, in fact, far, far greater than a flawless execution.

50:05

And this can span 30 years.

50:08

A flawless execution of an engineering design whose logic has been induced is going to always return a lower value than a terrible execution of a project whose design has been deduced by an engineer who who is self aware of where their biases are and are able to remove that in the process.

50:31

OK, so I've always found this a very, very helpful diagram to use when I'm thinking about project design, constructing something new.

50:40

It's a useful mentality even beyond that for the engineer to take because it helps us know when is it OK for us to lean in emotionally, to lean in personally to a situation or to a discussion technically or to rather to a technical discussion?

50:58

And at what point is it truly not just an hour, but the, the broader community's best interest for us to pull back and allow our, our objective technical mind to take over and assess the project in play.

51:11

OK, so that's the end of our lecture.

51:13

I hope that you've enjoyed the reader and the lectures this semester.

51:17

As always, please don't hesitate to send me.

51:20

You know, if you found things in the reader that should be improved that you'd like to add in or that you found really help something click for you that wasn't in the reader and wasn't in the book, please don't hesitate to send that to me.

51:34

This reader is meant to be a living document as we go through the semesters and so I'm really keen to make sure that we're improving it year on year.

51:42

OK, take care everyone, and we will see you in class for the final meeting.

51:46

OK, bye.