Fluid Mechanics

Topic 5

Mixing tanks

Mixing

Why is mixing important?

Mixing is use extensively in the chemical process industry and also in civil engineering applications such as waste water treatment

We want to mix systems in order to improve homogeneity and uniformity thus reducing gradients with in the system

- **Concentration**. Disperse an additive homogeneously throughout a liquid. For example chlorine or ozone in order to sterilize water for use as drinking water. Also, to create uniform reaction kinetics by evenly dispersing reactants in a stirred tank reactor
- **Temperature**. To generate uniform reaction kinetics by evenly distributing heat throughout a system
- **Color**. Homogenize color additives in order to create a streak-free paint
- **Etc**…

Mixing processes

There are many types of mixing processes

- Liquid-liquid mixing
- Liquid solid mixing
- Liquid gas mixing
- Gas-gas mixing
- Solid-solid mixing

Since this is a fluid mechanics class, we're interested in mixing the involves a liquid phase

Types of mixing involving liquids and examples

- **Miscible liquid-liquid mixing**. Diluting a liquid sterilizing agent or fluoride into drinking water. Homogeneous catalysis, etc…
- **Immiscible liquid-liquid mixing**. Emulsions such as those used in emulsion polymerization or the in the production of cosmetics (hand lotion) or food (milk processing)
- **Solid liquid mixing**. Heterogeneous catalysis. Mixing of concrete
- **Gas-liquid mixing**. Stripping, removing volatiles from a liquid phase by contacting with gas phase. Absorber removes contaminants from a gas into a liquid phase. The mixing greatly improves mass transfer between phases

Mixing processes?

But really, how hard can mixing be? It's rather self-explanatory. Do we really need a whole lesson dedicated to it?

Fudge the Cat brings up a good point. Mixing is rather self explanatory

However, in engineering, we're interested in accomplishing tasks as **efficiently** and **effectively** as possible as we know that in industry this is directly related to **money**

Therefore, this class focuses on the design of mixing tanks in order to accomplish the mixing task in the best way possible

The mixing tank

We will talk about three fundamental pieces of equipment used in mixing tanks: the tank, the impeller, and the baffles. The first is the tank itself

The mixing tank is the vessel in which the mixing occurs

Design criteria that must be considered when choosing a mixing tank

- **Capacity**. How big does my tank need to be?
- **Single tank, series, or parallel**. Is mixing best achieved in a single tank or in multiple connected tanks?
- **Fluid movement**. How will fluid be pumped into/out of the tank
- **Tank material**. What material is best to construct the tank from? This includes system pressure, corrosiveness of fluid, heat of tank, etc…
- **Open or closed**. Will the tank be open to the atmosphere or will it be closed? Ease of maintenance, hazard of fluid, sensitivity of fluid to environmental factors, etc…

The mixing tank

Illustrations of various mixing tanks

- Various sizes
- Metal versus plastic
- Single mixers versus parallel or series
- Fluid inserted or removed from top or bottom
- Opened and closed models

Open to Atmospheric

Impellers (agitators)

The second piece of equipment we will consider is the mixing **impeller**

This is the rotating blade that **transfers momentum** to the liquid and causes the fluid to mix through **forced convection**

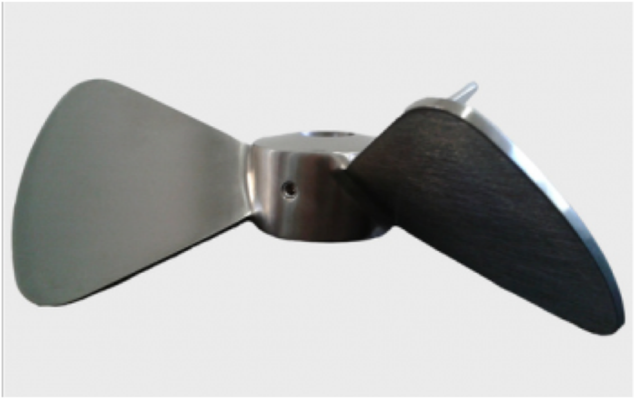
There are a huge number of impeller designs. We will look at four impeller designs in more detail

- Propellers
- Turbine impellers
- Paddle impellers
- Helical (or ribbon) impellers

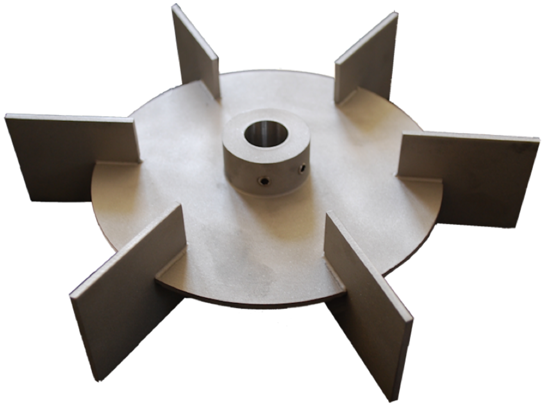
Each of these impeller types has distinct flow characteristics and uses in the mixing field

Impellers (agitators)

Propeller



Turbine impeller



Paddle impeller

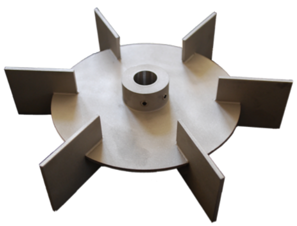
Why do we need so many different types of impellers?

Helical (ribbon) impeller

Impeller selection and fluid viscosity

The impeller is largely chosen based on fluid **viscosity**. Viscous fluids require slower **impeller speed** but impeller blades with greater **surface area**

Propellers
400 - 2000rpm
For μ < 3000cp

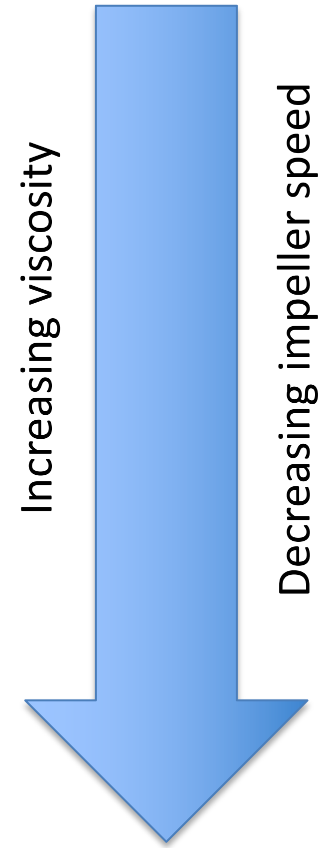


Turbine impellers
100 - 200rpm
For μ < 100,000cp

Paddle impellers
50 - 150rpm
For 50,000 < μ < 500,000cp

Helical (ribbon) impellers
15 - 50rpm
For μ > 500,000cp

Turbulent mixing



Laminar mixing

Low viscosity mixing

Let us focus on **low viscosity mixing** using propellers or turbine impellers

We have our tank and our impeller, let's place the impeller in the center of the impeller in the tank and start mixing!

What?! Are you an idiot? If you use just a centered impeller in a low viscosity fluid, you're going to get horrible mixing

What do you mean? It will stir the fluid and homogenize it, right?

You are daft. Everyone knows that a centered impeller will cause swirling, not homogenization of the fluid!

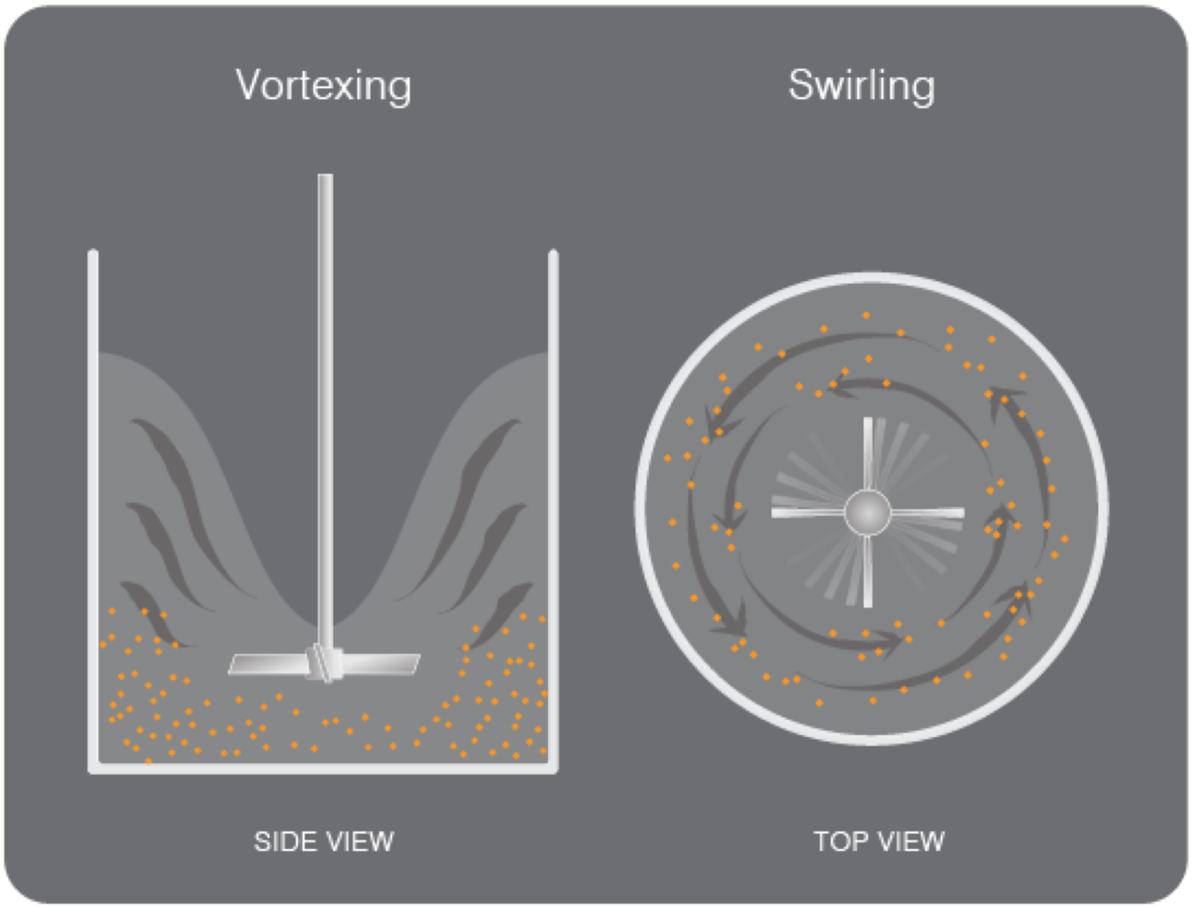
But swirling is okay, right?

Eventually swirling will get the job done but it will take ***forever***. Gah, I can't talk to you anymore, just watch this video

Video1, swirling during mixing: https://www.youtube.com/watch?v=4Kyy55EjyXQ

Swirling of fluid elements in low μ mixing

When swirling occurs, fluid elements just move around in circles instead of being mixed and homogenized with one another. This flow pattern leads to very poor mixing, meaning it takes a long time to achieve homogenization

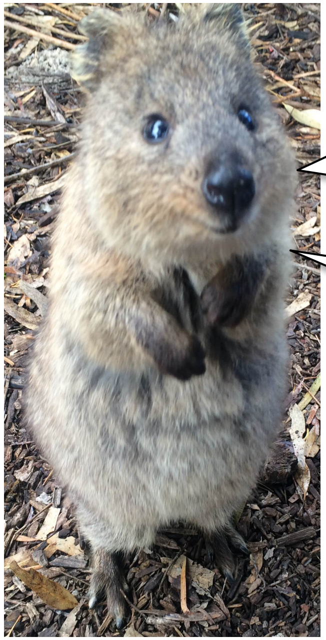


When working with small volumes, a telltale sign of swirling is vortexing

However, large volumes may also be swirling and not exhibit vortexing

How to prevent swirling in low μ mixing

How do we prevent swirling from occurring in **low viscosity mixing** systems?



There are two main ways of preventing swirling. The first is **impeller offset**. The second, and more used method is to insert **baffles** into the mixing tank

Gah, just watch these videos!

Video 2, impeller offset: https://www.youtube.com/watch?v=DgdCFwwRMcg

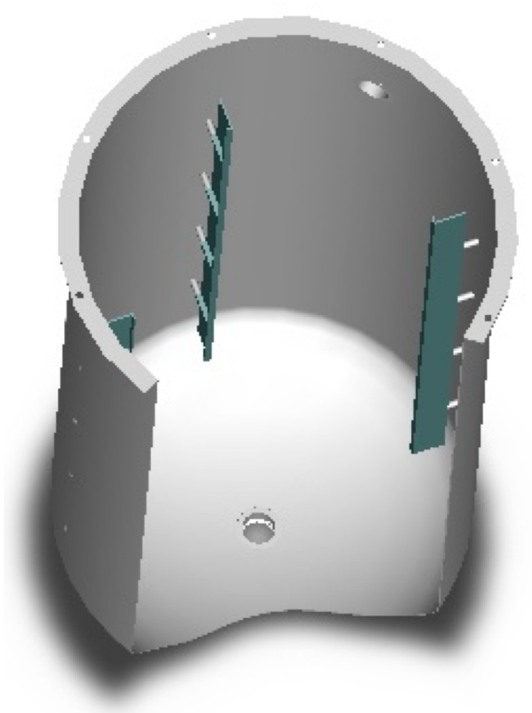
Video 3, use of baffles: https://www.youtube.com/watch?v=6E2-y96uYR4

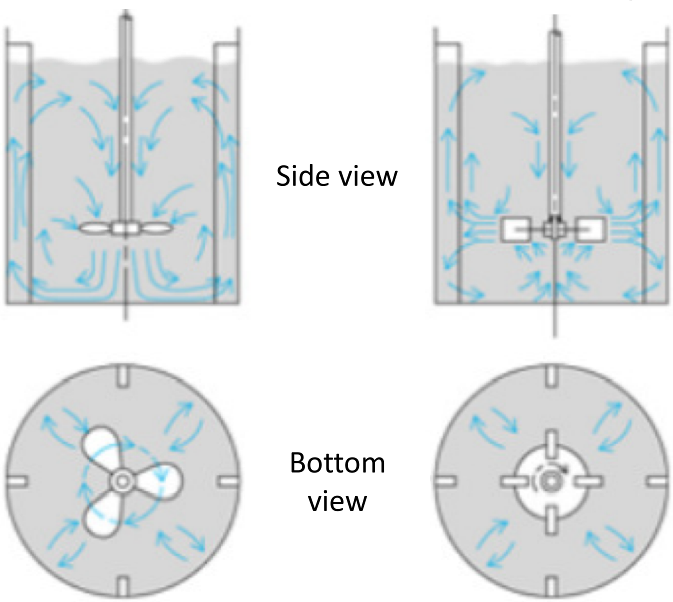
Video 4, use of baffles: https://www.youtube.com/watch?v=t7C-ErQVmvo

Baffles

Industrially, **baffles** are more often used than impeller offset to eliminate swirling and to enhance mixing. A tilted impeller is limited to small systems because of forces on the impeller shaft

Baffles are essentially small walls inside the mixing tank that block the swirling motion of the fluid

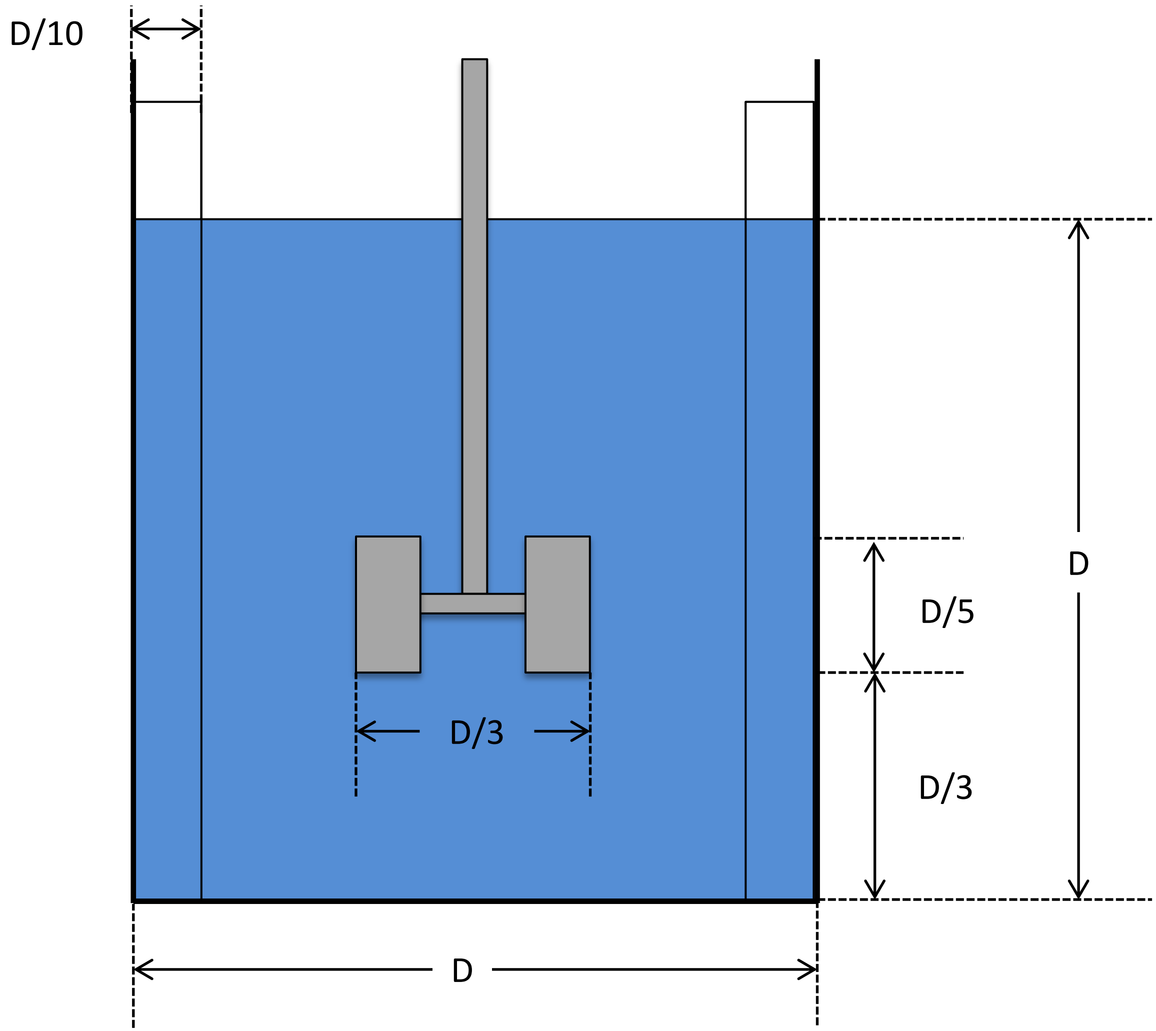




Baffles eliminate swirling and result in top to bottom fluid turn over for low viscosity fluids

Standard mixing tank for low μ fluids

Mixing tanks need to be designed specifically for an application. However, below is a schematic for the configuration of a standard mixing tank



Low μ vs high μ mixing strategies

Why do **impellers** with **larger surface area** need to be used to mix **high viscosity fluids**?

In low viscosity mixing the impellers have small surface area but move at high speed providing a lot of momentum to a few fluid elements. Mixing in this scenario is driven by the inertia of those fluid elements as they travel and disrupt the bulk of the fluid

If you tried to use a similar mixing technique for high viscosity fluids you may get mixing in the area immediately around the impeller, but the high viscosity of the fluid would result in the fluid motion being dampened very quickly. You would not achieve large scale mixing

Baffles are not needed for fluids with **viscosities above 5000cp** as little swirling occurs at higher viscosities

Low μ vs high μ mixing strategies

A better strategy for **high viscosity mixing** is to utilise **impellers with larger surface area** that span the entire mixing volume (helical/ribbon impellers)

This strategy does not require the inertia of the fluid elements to drive mixing. Instead all regions of the mixing tank are homogenized directly by the motion of the impeller

High viscosity mixing does not use baffles as swirling is not a problem. Furthermore, you want the helical impeller to travel close to the wall of the vessel, and the presence of baffles would not allow this

Here are three videos of high viscosity mixing

Video 5, large paddle impeller: https://www.youtube.com/watch?v=Q0rmmbtXsvk

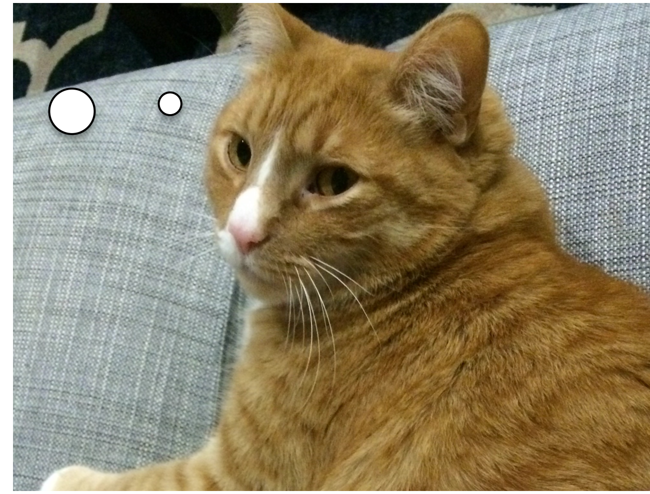
Video 6, helical impeller motions: https://www.youtube.com/watch?v=BHgV05t3ITQ

Video 7, vertical helical mixer: https://www.youtube.com/watch?v=dua435wZdd4

Power consumption of mixing process

So we've talked a lot about the design of mixing tanks

But you need to supply power in order to turn the impeller. How much power is required to run a mixing process?



As always, ***Fudge the Cat*** asks an insightful question

The theory relating to mixing processes is poorly understood.

Therefore, in order to predict the power necessary to perform a mixing process, we must rely on empirical relationships

We will discuss this process on the next several slides

Power consumption of a mixing process

Mixing processes require power in order to rotate the impeller and mix the fluid

Power consumption is based on many parameters of the mixing system

- Fluid density (ρ)
- Fluid viscosity (μ)
- Rotation speed of impeller (N)
- Diameter of impeller (D_a)

To calculate the power necessary to mix a system, we will need to utilize two dimensionless numbers

- **The impeller Reynolds number** (N'_{Re})
- **The power number** (N_P)

Power consumption of a mixing process

The **impeller Reynolds number** (**N'_{Re}**) is very analogous to the Reynolds number that we utilize when discussing pipe flow

It is a ratio of inertial and viscous forces within the system and it **predicts the presence of turbulence** in the mixing system

The impeller Reynolds Number is different than for pipe flow

$$\boxed{N'_{\mathrm{Re}} = \frac{D_a^2 N \rho}{\mu}}$$

The value of the impeller Reynolds number predicts turbulence

- The system is laminar for $N'_{Re} < 10$
- The system is turbulent for $N'_{Re} > 10^4$
- The system is transitional for intermediate values; turbulent around the impeller and laminar in distant parts of the vessel

Power consumption of a mixing process

The **power number** (**N_P**) compares resistant forces and inertial forces

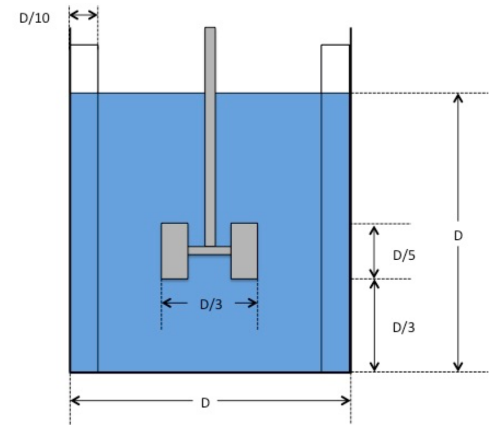
$$\boxed{N_P = \frac{P}{\rho N^3 D_a^5}}$$

The power number contains the value of P, the power we must supply to the impeller in order to achieve a certain Reynolds number within the fluid

In order to relate the **power number** and the **impeller Reynolds number** we must use a **power correlation plot**

Power consumption of a mixing process

Remember that we described the **"standard" mixing set up**. Although this is a commonly used configuration. There are almost an **unlimited variety of different designs**.



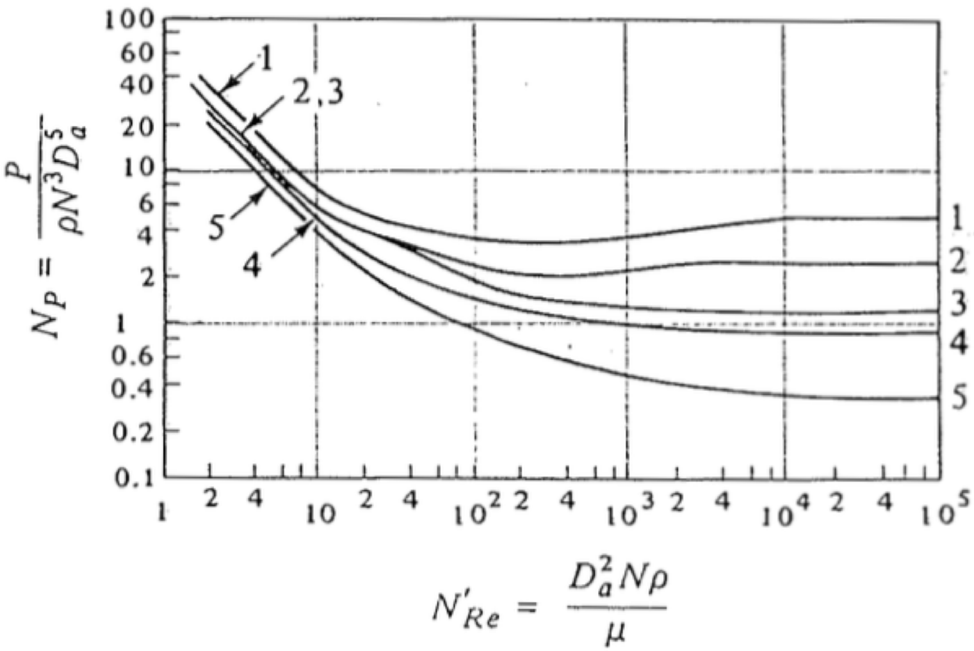
For instance, selecting a different tank shape, a different impeller, a different diameter of impeller, a different sized baffle, a different number of baffles, etc will all result in different mixing behaviours and power requirements for your mixer

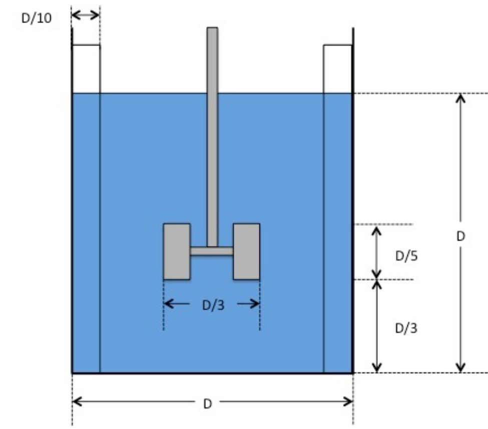
Each of these different configuration will have a unique relationship between the power number and the impeller Reynolds number

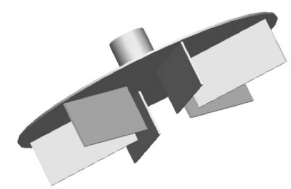
These unique relationships are described in **power correlation plots**

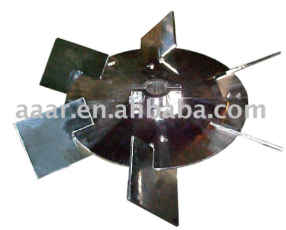
Power consumption of a mixing process

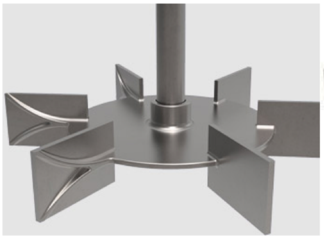
Below is a sample **power correlation plot** for five different mixer configurations that use different impellers and/or number of baffles











Curve 1. Flat six blade turbine with disk. Diameter to height of impeller = 5. Four baffles, each 1/12 tank diameter

Curve 2. Flat six blade open turbine. Diameter to height of impeller = 8, Four baffles, each 1/12 tank diameter

Curve 3. Six blade open turbine with 45° blades. Diameter to height of impeller = 8, Four baffles, each 1/12 tank diameter

Curve 4. Propeller, pitch = 2*impeller diameter. Four baffles each 1/10 tank diameter

Curve 5. Propeller, pitch = impeller diameter. Four baffles each 1/10 tank diameter

Power consumption of a mixing process

To predict the power consumption of a mixing tank, you must have a power correlation plot

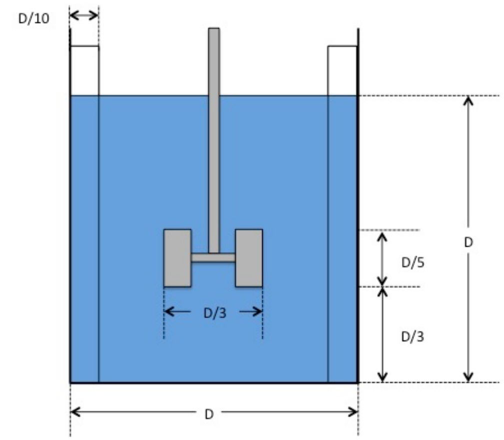
The plot must be provided to you, usually by the company selling you the mixing tank

This means that the company will have to manually build each configuration of the mixing vessel and run experiments in order to develop each plot

Now we will use an example to show how these plots are used

Example problem on power consumption

Your processes uses a mixing tank fitted with a flat-blade turbine impeller with disk having six blades. The tank diameter (D) is 1.83m, the turbine diameter (D_a) is 0.61m, the height of the turbine blades is 0.122m. The tank contains four baffles each with a width of 0.15m. The turbine is currently operating at 90rpm, the liquid has a viscosity of 10cp and a density of 929 kg/m^3



A) At current operating conditions, what is the required power for the mixer?

B) You are interested in using the same mixer to process a fluid with the same density but with a viscosity of 100,000cp. What is the required power for the new setup?

Example problem on power consumption

In order to solve **Part A** of this problem, we will need to complete the following steps

- Calculate the **impeller Reynolds number** for this system
- Determine which curve on the **power correlation plot** describes out system
- Use the power correlation plot to determine the **power number** for our system
- Manipulate the power number in order to determine the **power** being supplied to the mixer

First, let us calculate the **impeller Reynolds number** for our system

$$N'_{\mathrm{Re}} = \frac{D_a^2 N \rho}{\mu}$$

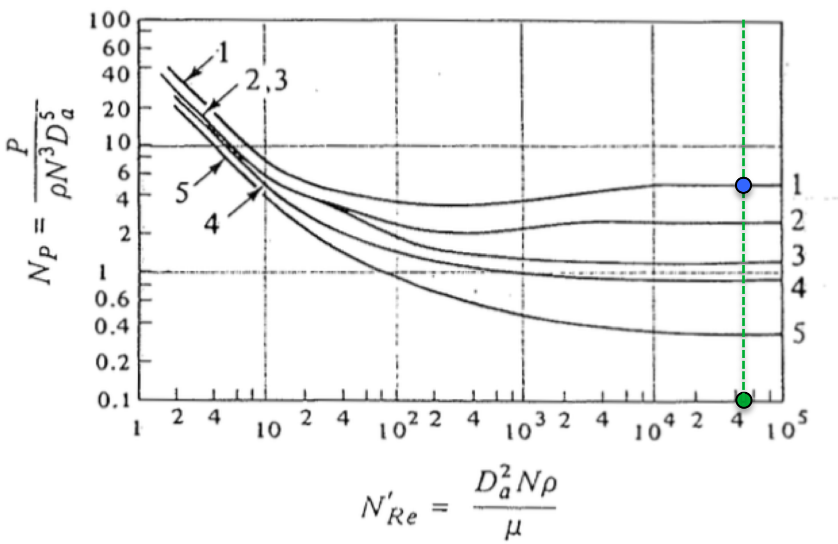
D_a = 0.61 m
ρ = 929 kg/m3
μ = 10 cp = 0.01 Pa*s
N = 90rpm = 1.5 rps

All quantities must be in SI units

$$N'_{\mathrm{Re}} = 5.185x10^4$$

Example problem on power consumption

First we can place our value for the Reynolds number on the plot. Then we must determine which of the curve describes our system



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Curve 2. Flat sex blade open turbine. Diameter to height of impeller = 8, Four baffles, each 1/12 tank diameter

Curve 3. Six blade open turbine with 45° blades. Diameter to height of impeller = 8, Four baffles, each 1/12 tank diameter

Curve 4. Propeller, pitch = 2*impeller diameter. Four baffles each 1/10 tank diameter

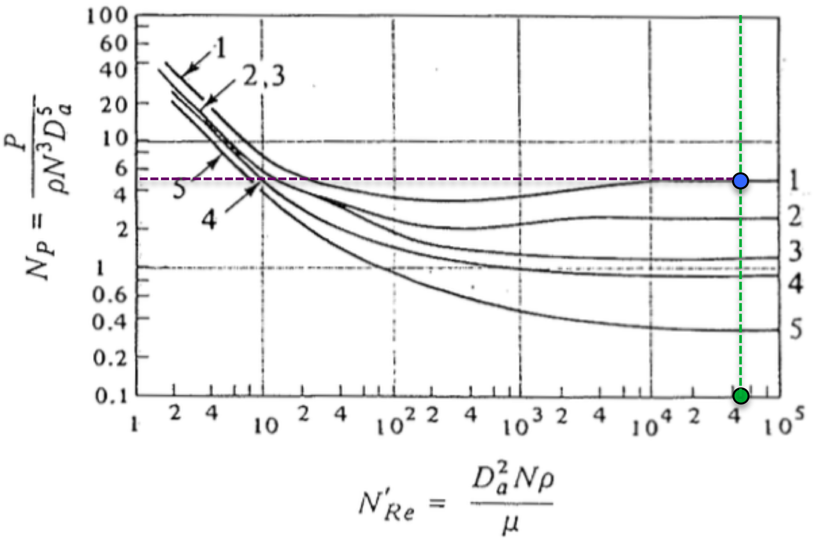
Curve 5. Propeller, pitch = impeller diameter. Four baffles each 1/10 tank diameter

In the problem statement we are told that the impeller is a 6 blade turbine with disk, he diameter to the height of the impeller is 5, and that we have four baffles that are each 1/12 of the tank diameter.

This means that **curve one** is the power correlation that describes out system

Example problem on power consumption

From the plot, we can read off the value of the **power number** for our system



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The **power number** for our system is $N_P = 5$

Now that we have the value of the power number, we can back calculate the **power** that is being supplied to the mixer

$$N_P = \frac{P}{\rho N^3 D_a^5} \rightarrow P = N_P \rho N^3 D_a \rightarrow \boxed{P = 1324 J/s}$$

Example problem on power consumption

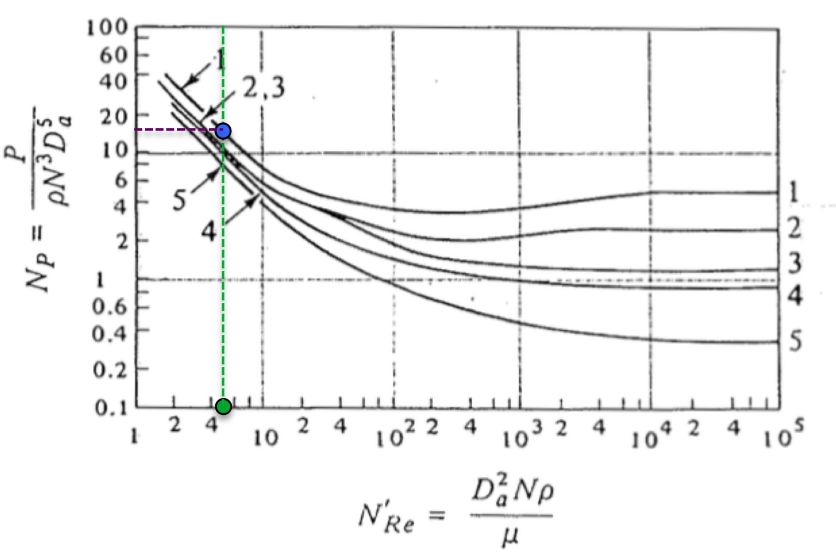
Part B asks you to calculate the power consumption if the same mixing tank were used under the same operating conditions to mix a fluid with a viscosity of 100,000 cp

First calculate the **impeller Reynolds number** $N'_{\mathrm{Re}} = 5.185$

Curve 1 still describes the geometry of this system as the mixing tank did not change

Using the plot, we can read of the value of the **power number** $N_P = 14$

Solve for the **power** that must be supplied to the system $\boxed{P = 3707 J / s}$



Does the value of the impeller Reynolds number make sense?

Does the value of the power make sense?

Summary (part 1)

There are two or three main components of a mixing system

- The tank
- The impeller
- Baffles (for low viscosity mixing)

The material, the size, and if tanks are in series or parallel depends on your unique mixing scenario

The size and shape of the impeller depends largely on the viscosity of the solution you're mixing

The use of baffles is helpful in low viscosity mixing to reduce swirling and to promote good mixing

Summary (part 2)

Predicting the amount of energy required by a mixer requires the use of two dimensionless numbers and an empirical plot

- The impeller Reynolds number
- The power number
- A power correlation plot

The power correlation plot is specific to each mixer configuration. This means that it must be experimentally determined for each arrangement of impeller, baffle, and vessel

Scaling up mixers is necessary to move from a pilot plant scale to a full plant scale. We looked at a scale up method that retained geometric similarity through the use of the scale up factor, R. The change in impeller rotation rate depended on what type of mixing operation you were performing

Scale up of mixing tanks

In the chemical processing industry, a company will never invest the millions (if not billions) of dollars needed to build a new production plant without assurance that it will work appropriately

For these reasons there are often various stages of development for production plants. Let us focus on the refinement of petroleum

- **Lab scale production**. Develops techniques that can process grams or liters of crude oil per day
- **Pilot plant scale production**. Can process maybe 100 barrels of crude oil per day
- **Full plant scale production**. The average petroleum refinery in the US can process 120,000 barrels of crude oil each day (2010 data)

A major obstacle in moving from a pilot plant to a full plant is **scale up**. You have developed a small industrial process that can be used to produce the desired product. However, how do you build a larger production plant to meet demand for the product?

Scale up is a particular challenge in mixing systems

Scale up of mixing tanks

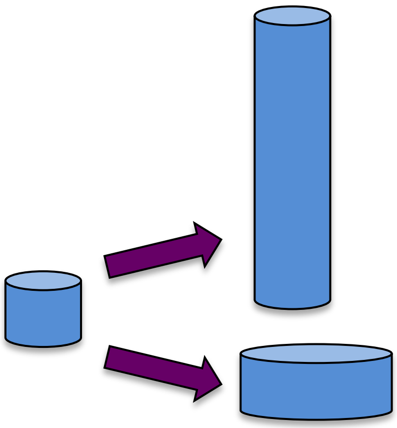
You have been working with a pilot-scale mixer. You want to scale your mixer up to one with four times the capacity. How would you achieve this?

By what factor would you change the volume of the tank?

Would you make the new tank tall and skinny or short and fat or somewhere in between?

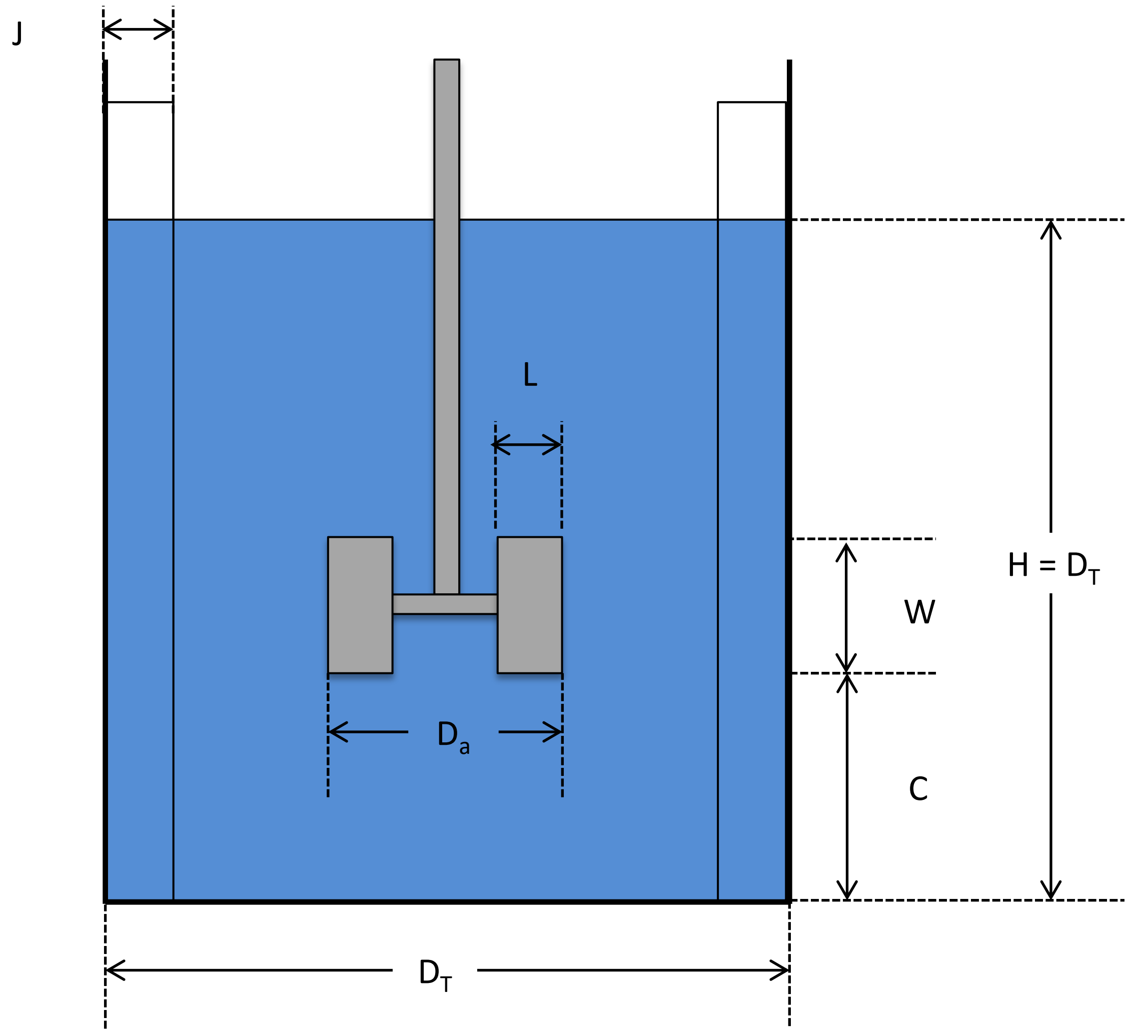
Similarly, how would you change the size of the impeller? Would it be four times in diameter? Four time the surface are of the blades?

Would it spin at the same rate or would it spin with four times the velocity of pilot plant model?



Scale up of mixing tanks

We will label the length dimensions of the mixing tank as follows



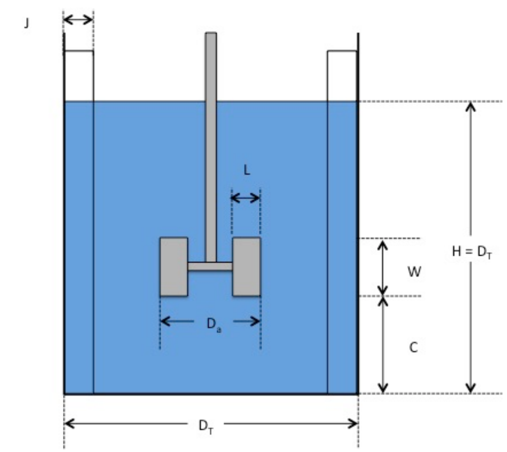
Scale up of mixing tanks

In order to scale up the size of our mixer, we will need to find the **scale-up ratio** (**R**)

To find the **scale up ratio**, **R**, we must compare the **volume of our pilot plant mixer** (**V_1**) and the desired **volume of our full scale mixer** (**V_2**)

Determine the volume of the pilot-scale mixing tank

$$V_1 = \frac{\pi D_{T1}^2}{4} H \quad \text{But } H = D_T \quad \Rightarrow \quad V_1 = \frac{\pi D_{T1}^3}{4}$$



Ratio the volume of the full-scale and pilot-scale mixer volumes

$$\frac{V_2}{V_1} = \frac{4\pi D_{T2}^3}{4\pi D_{T1}^3} \quad \Rightarrow \quad \frac{V_2}{V_1} = \frac{D_{T2}^3}{D_{T1}^3}$$

Solve the above expression for D_{T2}/D_{T1}

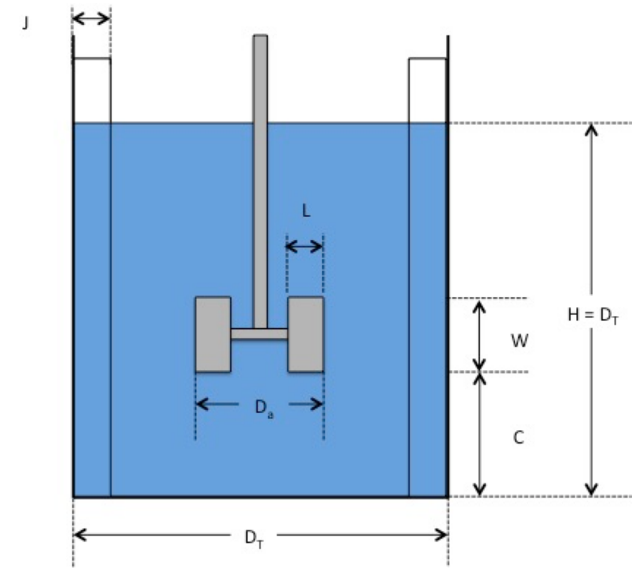
$$\frac{V_2}{V_1} = \frac{D_{T2}^3}{D_{T1}^3} \quad \Rightarrow \quad \boxed{R = \left(\frac{V_2}{V_1}\right)^{1/3} = \frac{D_{T2}}{D_{T1}}}$$

R is the scale-up ratio. It is the factor by which you multiply all the linear length scales in your system

Scale up of mixing tanks

The linear lengths in your pilot scale mixer are multiplied by the scaling factor, R, in order to determine the linear lengths in your full scale mixer

Pilot scale mixer	Full scale mixer
D_T	$R*D_T$
D_a	$R*D_a$
H	R*H
J	R*J
L	R*L
C	R*C
W	R*W



What is value for the scaling factor, R, if you want to quadruple the capacity of your mixer?

R = (4/1)^(1/3) ~= D(r2)/D(r1) ~=1.57…. (More to add)

Scale up of mixing tanks

In addition to the length scales of our mixer, we also will need to adjust the **rotation rate of the impeller** (**N**)

The following **empirical formula** is used to scale up the rotation speed of the impeller

$$N_2 = N_1 \left(\frac{1}{R} \right)^n$$

The value of 'n' varies depending on the application

- **n = 1** for the blending of liquids
- **n = 3/4** for equal suspension of solids in a liquid phase
- **n = 2/3** for equal rates of mass transfer

More to add

Previously we have discussed how we want to quadruple the capacity of the mixer. In this scenario, by what factor would our impeller speed change if:

The mixer is an absorber where contaminated gas is being bubbled through to absorb the contaminate into a liquid phase?

The mixer is used to blend acidic waste water with a basic solution before being released into the environment?

The mixer is used to prepare a cement?

Summary

Mixing tanks are used in a wide variety of chemical and civil engineering applications

We discussed the different equipment used in the mixing process

- Mixing tanks
- Impellers
- Baffles

Additionally, we discussed the unique challenges associated with low viscosity mixing (swirling) and high viscosity mixing (the need to use large impeller blades)