Topic: Introduction to Thermodynamics
Lecture - 1

Disclaimer:

The study materials/presentations are solely meant for academic purposes and they can be reused, reproduced, modified, and distributed by others for academic purposes only with proper acknowledgements.

Course Objectives:

CO1 ⊟ To learn the basics of Fluid Mechanics

CO2 ⊟ To learn the basics of Hydraulic machines

CO3 ⊟ To learn the basics of Thermodynamics

CO4 ⊟ To learn the basics of Power Plant Engineering

Topics to be covered:

Preliminary concepts, Energy and first law, 2nd law of thermodynamics, Entropy, Exergy, Vapor power and Gas power systems, Refrigeration and Heat Pumps

References and acknowledgement:

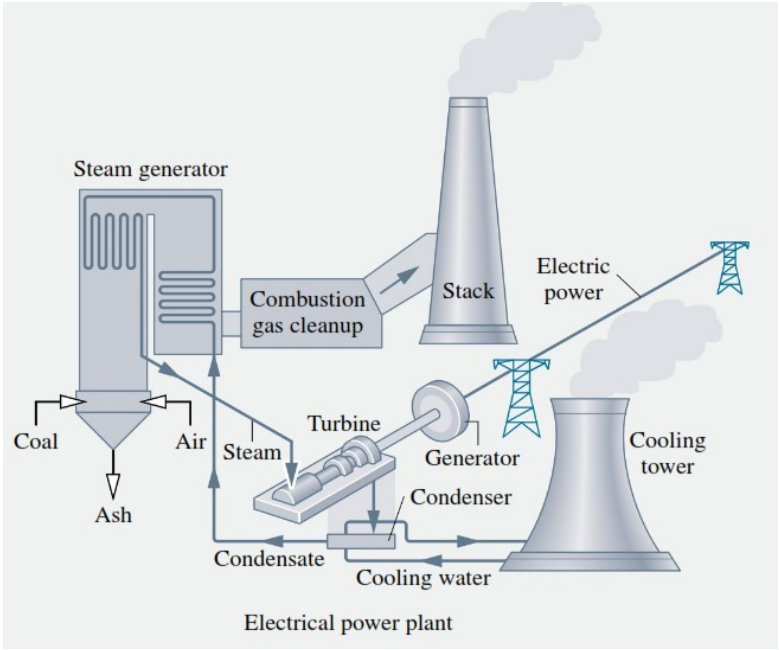
- Fundamentals of Engineering Thermodynamics – **Michael J. Moran, Howard N. Shapiro, Daisie D. Boettner, and Margaret B. Bailey** (Wiley)
- Fundamentals of Thermodynamics – **C. Borgnakke, and Richard E. Sonntag** (Wiley)

Thermodynamics

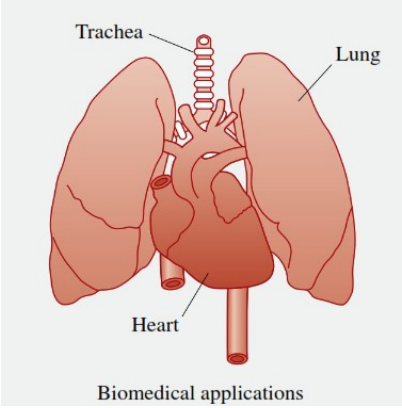
- The **scope** of thermodynamics **was** to deal with the capacity of hot objects to produce work.
- Today the scope is **much larger** to include using fossil fuels more effectively, developing renewable energy technologies, and more fuel-efficient means of transportation, etc.
- Thermodynamics is a branch of both **Science and Engineering**.
- The **scientist** is normally interested in the physical and chemical behavior of **fixed quantities of matter at rest**.
- **Engineers** are generally interested in studying systems and **how they interact** with their surroundings.
- To facilitate this, thermodynamics has been **extended** to the study of systems through which **matter flows**.

Thermodynamics

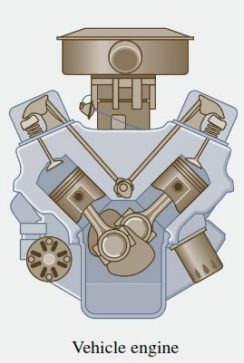
- Engineering **applications** of thermodynamics include **surface and air transportation, space flight, electricity generation and transmission, heating and cooling, and biomedical application**.

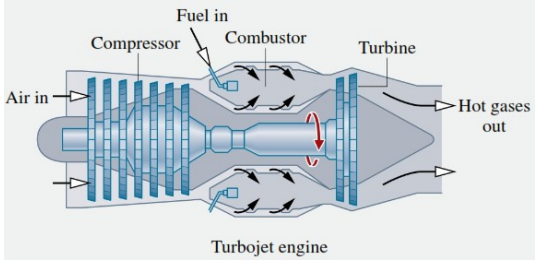


Electrical power plant

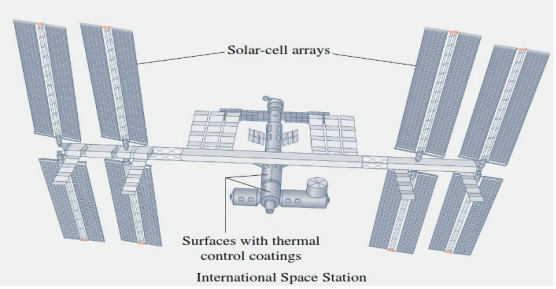


Biomedical applications


Vehicle engine



Turbojet engine



International Space Station

Thermodynamics

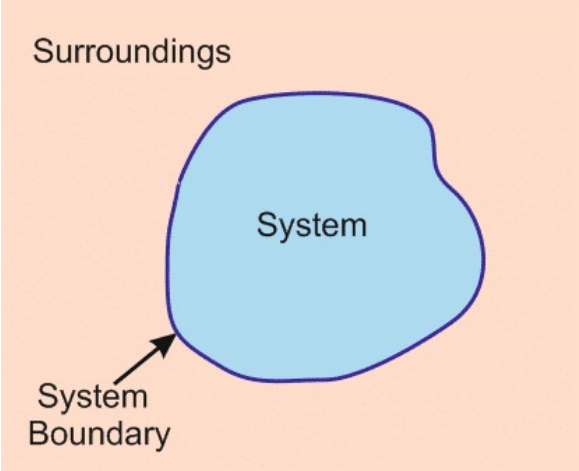
- Let us introduce some of the **fundamental concepts and definitions**.

Defining Systems:

- The initial step in any thermodynamic / engineering analysis is to **describe precisely what is being studied**.
- In thermodynamics the term **"system"** is used to identify the subject of the analysis.
- The system is **whatever we want to study**. It may be **as simple as** a free body or **as complex as** an entire chemical refinery.
- It can be a **fixed** quantity of matter or something **flowing** through it.
- The **composition of the matter** inside the system may be **fixed or may be changing** through chemical or nuclear reactions.

Thermodynamics

- The **shape or volume** of the system being analyzed is **not necessarily constant**, as when a gas in a cylinder is compressed by a piston or a balloon is inflated.

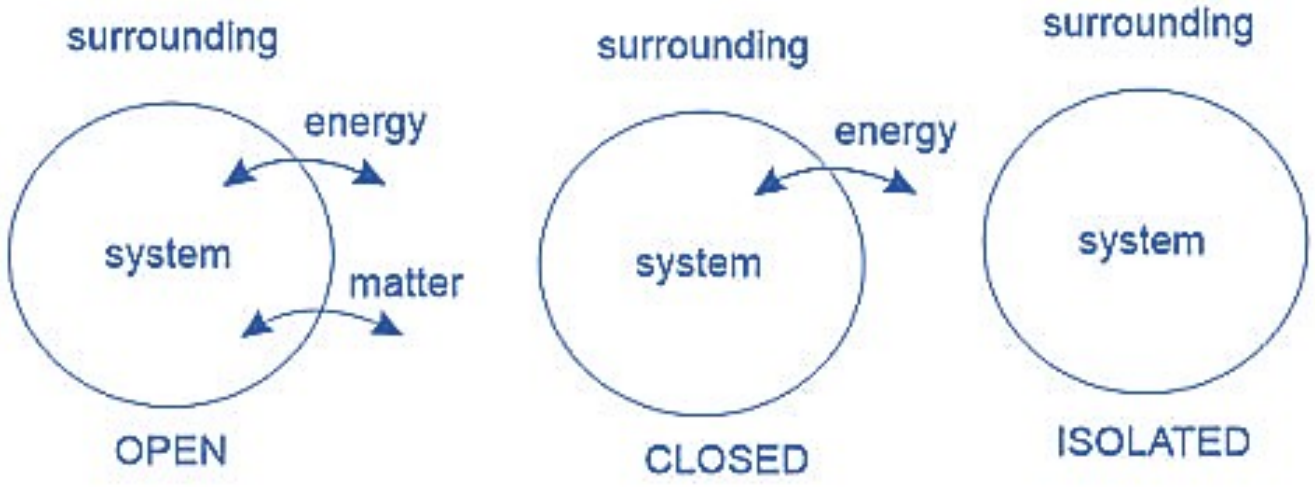


- Everything **external to the system** is considered to be part of the system's **surroundings**.

- The system is distinguished from its surroundings by a specified **boundary**, which **may be at rest or in motion**.

- Two basic **kinds** of systems are there. These are referred to, respectively, as **closed systems** and **control volumes**.

Thermodynamics



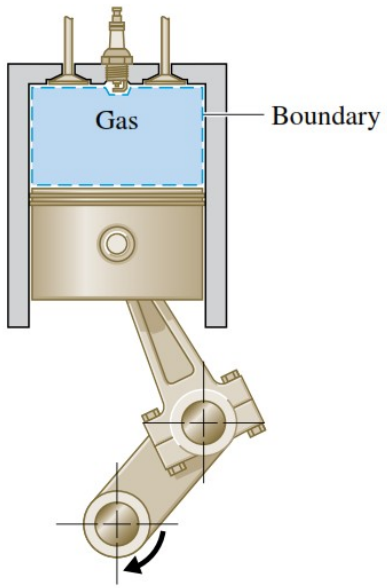
- A **closed system** refers to a **fixed quantity of matter**, whereas a **control volume** is a **region of space** through which **mass may flow**.

- A **closed system** always contains the same matter. There can be no transfer of mass across its boundary. The term **control mass** is sometimes used in place of closed system.

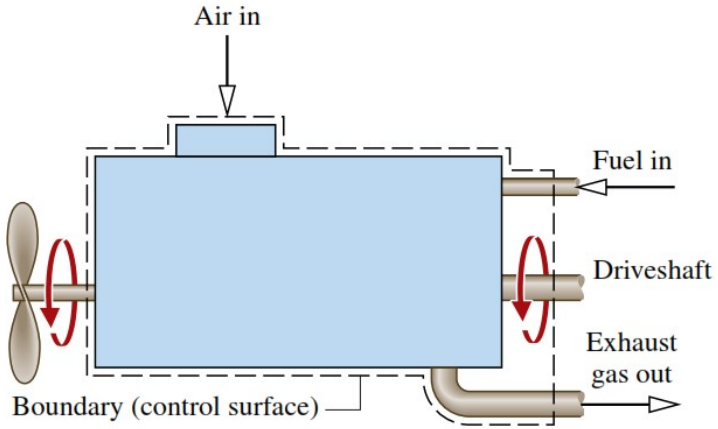
- A **special type of closed system** that does not interact in any way (neither mass nor energy) with its surroundings is called an **isolated system**.

Thermodynamics

- An **example** of a closed system is a **gas in a piston–cylinder** assembly.

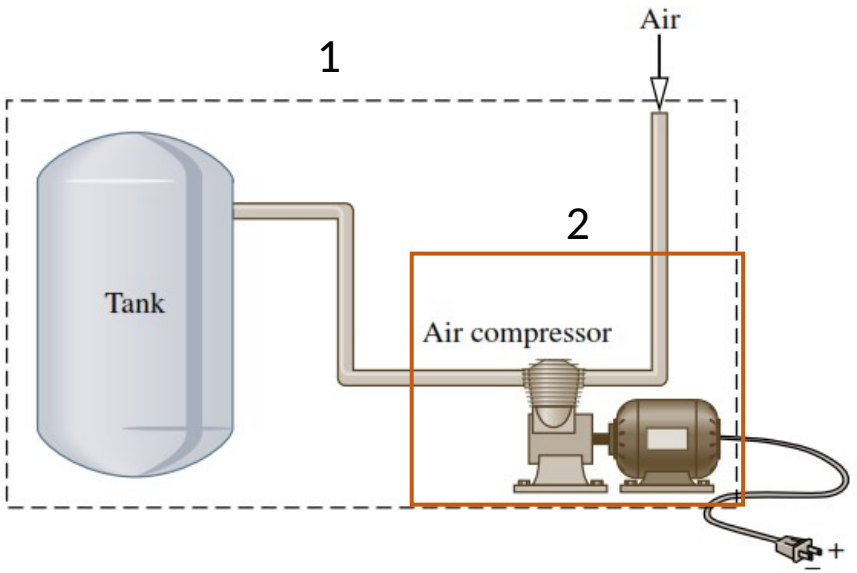


- In the picture of piston-cylinder assembly, **when the valves are closed**, we can consider the gas to be a **closed system**.
- The term **open system** is used interchangeably with control volume.
- When the terms control mass and control volume are used, the system boundary is often referred to as a **control surface**.
- A diagram of an engine is shown. The dashed line defines a **control volume that surrounds the engine**.



- The **choice of a system boundary** depends on the convenience it offers in the subsequent analysis.

- In general, the choice of system boundary is **governed by two considerations**:
  (1) what is **known about** a possible system, particularly at its boundaries, and
  (2) the **objective** of the analysis.



- Case 1: Electric power, Air inflow is **known** and **objective** is to calculate the time to reach a specified pressure

- Case 2: Air inflow and outflow is **known**, and **objective** is to determine electric power input

- There are two **different viewpoints** to study the system.

Thermodynamics

Macroscopic and Microscopic views of thermodynamics

- The **macroscopic approach** to thermodynamics is concerned with the **gross or overall behavior**. This is sometimes called **classical thermodynamics**.
- The **structure of matter** at the molecular, atomic, and subatomic levels is **not directly involved** in this approach.
- The **microscopic approach** to thermodynamics, known as **statistical thermodynamics**, is concerned directly with the **structure of matter**.
- The system is characterized **by statistical means,** the **average behavior of the particles** making up a system and relate this information to the observed macroscopic behavior.
- Classical thermodynamics provides a **direct approach** for analysis and requires far **fewer mathematical complications**, therefore adopted for a wide range of engineering applications.

Topic: Introduction to Thermodynamics
Lecture - 2

Disclaimer:

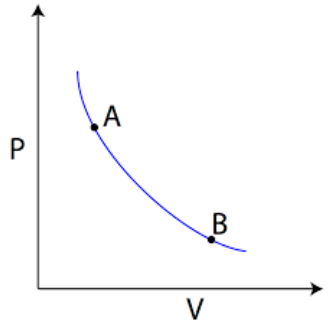
The study materials/presentations are solely meant for academic purposes and they can be reused, reproduced, modified, and distributed by others for academic purposes only with proper acknowledgements.

Property, State and Process

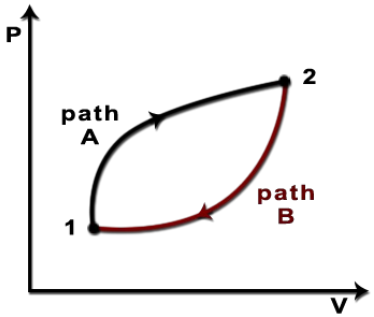
- To **describe** a system completely, the knowledge of its **properties** is required.
- A **property** is a **macroscopic characteristic** of a system to which a numerical value can be assigned at a given time **without** knowledge of the previous behavior.
- **Examples** of properties: Mass, volume, energy, pressure, and temperature etc.
- Thermodynamics also deals with quantities that are **not properties**, such as **mass flow rates** and **energy transfers** by work and heat, etc.
- The word **state** refers to the **condition of a system** as described by its properties.
- A state often can be **specified by a subset** of the properties. All other properties can be determined in terms of these few.

Thermodynamics

- When any of the properties of a system changes, the **state changes** and the system is said to undergo a **process**.



- In other words, a process is a **transformation from one state to another**.
- A system is said to be at **steady state** if none of its properties changes with time.
- How to determine **whether a quantity is a property**?
- A quantity is a property **if, and only if**, its change in value between two states is **independent** of the process, and **depends solely on the end states**.



- There is special kind of process, known as **thermodynamic cycle**.
- It is a **sequence of processes** that **begins and ends at the same state**, and the cycle is periodically repeated.

- Therefore, over the cycle, there is **no net change in any property values**.
- Example: The **steam circulating through electrical power plant** executes a cycle.

Extensive and Intensive properties:

- A property is called **extensive** if its value for an overall system is the **sum of its values** for the parts into which the system is divided.
- Mass, volume, energy, and several other properties introduced later are **extensive**. Extensive properties **depend on** the size or extent of a system.
- Intensive properties are **independent of the size** or extent of a system and **may vary from place to place within the system** at any moment.
- **Example**: Specific volume, pressure, and temperature are important intensive properties.

Thermodynamics

- Intensive properties are **not additive** in the sense previously considered.

- Intensive properties may be **functions of both position and time**, whereas extensive properties can vary **only with time**.

Concept of equilibrium:

- Classical thermodynamics places primary **emphasis on equilibrium** states and changes from one equilibrium state to another.

- The thermodynamic, or complete equilibrium refers to **mechanical, thermal, phase, and chemical** equilibrium.

- Isolate the system from its surroundings and if there are no changes in its observable properties, the system can be said to be at an **equilibrium state**.

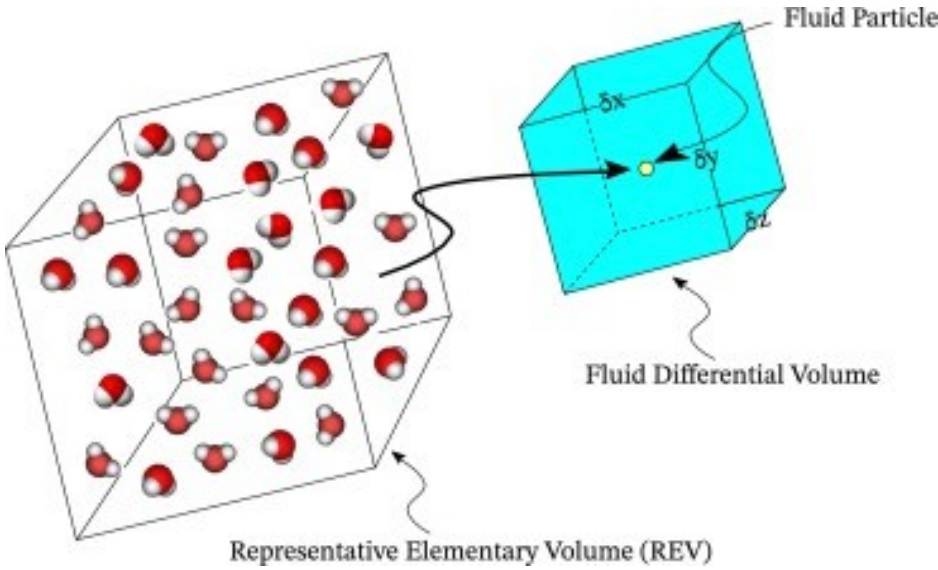
Thermodynamics

- At equilibrium, **temperature is uniform** throughout the system. Also, **pressure is uniform** throughout as long as the effect of gravity is not significant.

Important properties in engineering thermodynamics:

- Three measurable intensive properties that are particularly important are **specific volume, pressure, and temperature**.

- From the **macroscopic viewpoint**, the description of matter is simplified by considering it to be **distributed continuously** throughout a region, known as the **continuum hypothesis**.



Thermodynamics

- When substances can be treated as **continua**, it is possible to define the intensive thermodynamic properties "**at a point**."

- Thus, at any instant, the **density at a point is defined** as

$$\rho = \lim_{V \to V'} \left(\frac{m}{V} \right)$$

- where is the **smallest volume** for which a value of the ratio exists. is **small enough** that it can be considered a "point" and **large enough** to contains particles for **statistical averages** to be significant.

- The density, or local mass per unit volume, is an **intensive property** that may **vary from point to point** within a system.

- The specific volume is defined as the **reciprocal** of the density, .

Thermodynamics

- Similarly, **pressure** , at the specified point is **defined as** the limit

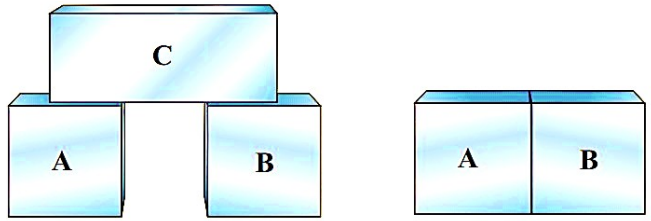
$$p = \lim_{A \to A'} \left(\frac{F_{\text{normal}}}{A} \right)$$

- where is the area at the "point" in the **same limiting sense** as used in the definition of density.

- The temperature is **a property** which **determines** the state of **thermal equilibrium**.

- **When two objects are in thermal equilibrium with a third object, they are in thermal equilibrium with one another.**

- This statement is called the **zeroth law of thermodynamics**.



- This law is **implicitly assumed** in every measurement of temperature.

Thermodynamics

- Energy is a **fundamental concept** in thermodynamics. Energy **can be stored** within the system in various forms; it **can be converted** from one form to another; and it **can be transferred** by work and heat transfer.

- In classical mechanics, we get a **general description** of energy in the form of work done, kinetic energy and potential energy.

- The quantity is the **kinetic energy** () of a body of mass, , and moving at velocity, .

- Kinetic energy is a **scalar quantity**. The change in kinetic energy () of the body is therefore, .

- The change in kinetic energy is the **work done** by the force acting on the body as the body moves from to along a defined path.

Thermodynamics

- Therefore,

- In other words, the **work done by a resultant force** on the body equals the change in its kinetic energy. Work is also a **scalar quantity**.

- When a body is accelerated by the resultant force, the work done on the body can be considered a **transfer of energy** to the body, where it is **stored as kinetic energy**.

- Kinetic energy is a property of the body. Since, kinetic energy is associated with the body as a whole, it is an **extensive property**.

- The quantity is the **potential energy**, of a body of mass , and elevation . The change in gravitational potential energy, , is .

Thermodynamics

- Potential energy is also an **extensive property** of the body.
- It is assumed that elevation difference () is small enough that the acceleration of gravity, , can be considered **constant**.
- Work has **units** of force times distance. In SI, the energy unit is the newton-meter, N · m, called the joule, J.
- So, for an object falling under the influence of gravity only, the potential energy would decrease as the kinetic energy increases **by an equal amount**.
- We have seen that applied forces affect their overall velocity and position. However, systems of engineering interest **interact with their surroundings in more complicated ways**.
- In thermodynamics, the **concept of energy is broadened** to account for other observed changes.

Definition of work broadened:

- The principle of conservation of energy is **extended to include** a wide variety of ways in which systems interact with their surroundings.
- Thermodynamics deals with phenomena which are not included within the scope of mechanics, so **a broader interpretation of work** is adopted.
- **Thermodynamic definition of work**: Work is done by a system on its surroundings if the sole effect on everything external to the system could have been the raising of a weight.
- The raising of a weight is, in effect, a force acting through a distance, so the **concept of work** in thermodynamics is a **natural extension** of the concept of work in mechanics.
- Work is a **means for transferring energy** (not what is transferred). **Energy is transferred** and stored when work is done.

Thermodynamics

- The **sign convention** for work is: It is positive (W>0) when **done by the system** and it is negative (W<0) when **done on the system**.

- The value of W depends on the **details of the interactions** taking place between the system and surroundings during a process and **not just the initial and final states** of the system.

- It follows that work is **not a property** of the system or the surroundings.

- The **differential** of work, , is said to be **inexact** because, the following integral **cannot be evaluated** without specifying the details of the process.

- Actually, The notion of **work at a state has no meaning**, so the value of this integral should never be indicated as ().

Thermodynamics

- On the other hand, the differential of a **property** is said to be **exact** because the change in a property between two particular states **does not depend on the details of the process**.

- For example; . The **differential of every property is exact**, written using the symbol . Inexact differential is written using the symbol .

- The rate of energy transfer by work is called **power** and is denoted by . Power is defined as, , the **product** of the force and the velocity at the point of application of the force.

- The **same sign convention** applies for as for . It is expressed in terms of J/s, called the watt, in SI.

- Next class we will see **a few examples** of work done by or on the system.

Topic: First Law of Thermodynamics
Lecture - 3

Disclaimer:

The study materials/presentations are solely meant for academic purposes and they can be reused, reproduced, modified, and distributed by others for academic purposes only with proper acknowledgements.

Thermodynamics

- On the other hand, the differential of a **property** is said to be **exact** because the change in a property between two particular states **does not depend on the details of the process**.

- For example; . The **differential of every property is exact**, written using the symbol . Inexact differential is written using the symbol .

- The rate of energy transfer by work is called **power** and is denoted by . Power is defined as, , the **product** of the force and the velocity at the point of application of the force.

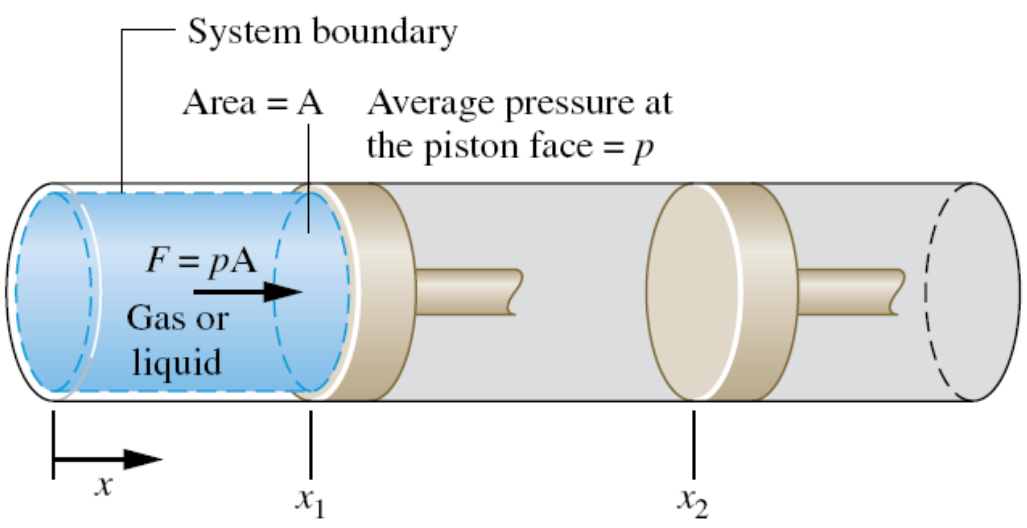
- The **same sign convention** applies for as for . It is expressed in terms of J/s, called the watt, in SI.

- Let's begin with **expansion or compression of a fluid** contained in piston-cylinder assembly.

Thermodynamics

- If denotes the pressure acting at the piston face, the **force exerted** is .

- Therefore, the **work done** by or on the system is , where is the **displacement** of the piston. Or, , where is **positive** when volume increases (expansion).



- For a change in volume from to , the work is obtained by, .

- The relation is **applicable to systems** of any shape provided the **pressure is uniform** throughout the moving boundary.

- There is **no guarantee** that a system undergoing a process **be in equilibrium** during the process.

Thermodynamics

- Typically, at a **non-equilibrium state** intensive properties vary with position at a given time. Also, at a specified position intensive properties **may vary** with time.

- For evaluating work done, **a relationship** between the gas pressure at the moving boundary and the system volume **is required**.

$$\boxed{W = \int_{V_1}^{V_2} p\, dV}$$

- However, due to non-equilibrium effects during an **actual expansion or compression process**, this relationship may be difficult, or even impossible, to obtain.

- Here comes the concept of **quasiequilibrium process**.

- Processes are sometime modeled as a quasiequilibrium (or quasistatic) process, an **idealized** process. A quasiequilibrium process is one in which the **departure from thermodynamic equilibrium** is **infinitesimally small**.

Thermodynamics

- All states through which the **system passes in a quasiequilibrium process** may be considered equilibrium states.

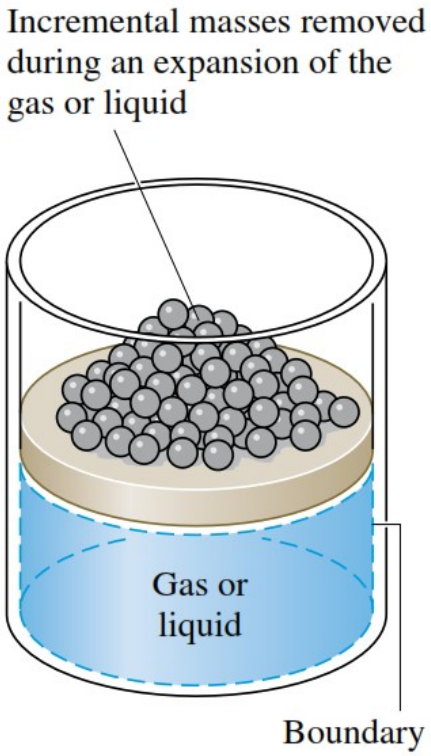
- Because nonequilibrium effects are **inevitably present** during actual processes, systems of engineering interest can **at best approach, but never realize**, a quasiequilibrium process.

- As shown in the figure, the gas pressure is **maintained uniform** throughout by a **number of small masses**.

- If one of the masses is removed, the state of the gas would **depart only slightly from equilibrium**.

- If several of the masses were removed **one after another**, the gas would pass through **a sequence of such equilibrium states**.

- In the limit, the gas would undergo a quasiequilibrium expansion process.



Thermodynamics

- **Why do we need this quasiequilibrium idealization**?

- The thermodynamic models which **gives at least qualitative information** about the actual systems can be developed using the quasiequilibrium process. Like: **Point mass or the frictionless pulley in mechanics**.

- The quasiequilibrium concept is **helpful in deducing relationships between the properties** of systems at equilibrium.

- In **our example** of expansion or compression of gas, the pressure in the equation is the pressure of **the entire quantity of gas**, and not just the pressure at the moving boundary.

- The relationship between the pressure and volume may **be graphically or analytically** obtained. Let us **first consider** a graphical relationship.

- A graphical relationship is shown in the **pressure–volume () diagram** next slide.

Thermodynamics

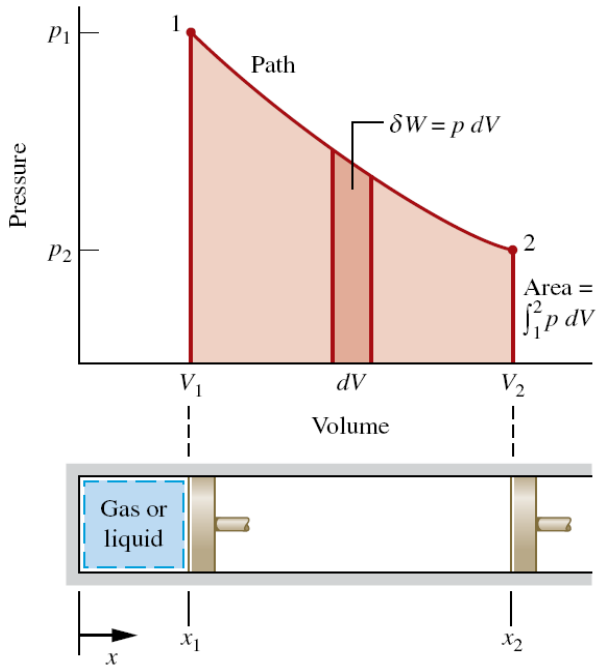
- The work done by the gas on the piston during the expansion is given by , which can be interpreted as the **area under the curve** of pressure versus volume.

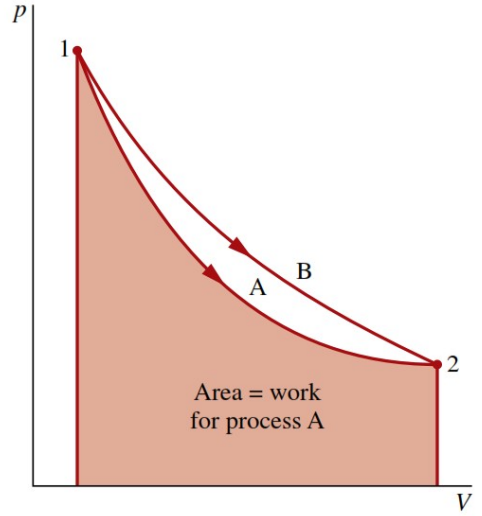
- This demonstrates that **work depends on the process** and we can conclude again that **work is not a property**.

- Suppose the gas goes from an initial equilibrium state 1 to a final equilibrium state 2 **along two different paths**.

- Since the area beneath each path represents the work for that process, the **work depends on the details of the process**.

- The relation between pressure and volume, or pressure and specific volume, also **can be described analytically**.





- A quasi-equilibrium process described by , or , where is a constant, is called **a polytropic process**.

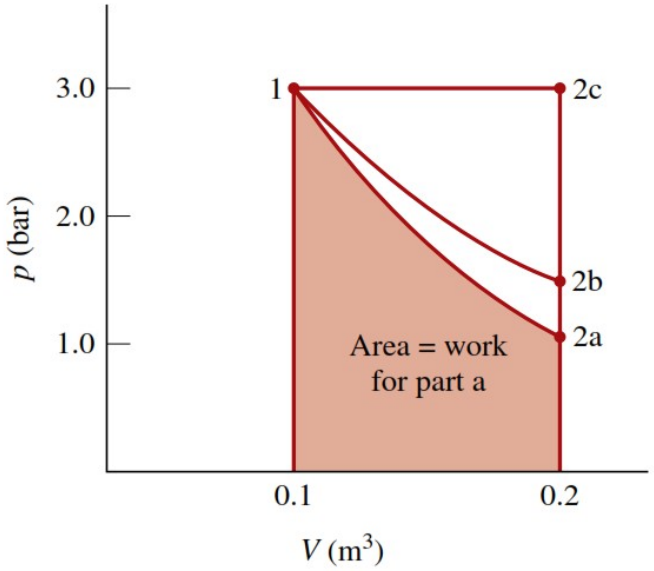
- **Additional analytical forms** for the pressure–volume relationship also may be considered.

Problem: A gas in a piston–cylinder assembly undergoes an expansion process for which the relationship between pressure and volume is given by . The initial pressure is 3 bar, the initial volume is 0.1 m^3, and the final volume is 0.2 m^3. Determine the work for the process, in kJ, if (a) = 1.5, (b) = 1.0, and (c) = 0.

$$W = \int_{V_1}^{V_2} p\,dV = \int_{V_1}^{V_2} \frac{constant}{V^n}\,dV$$

$$= \frac{(constant)V_2^{1-n} - (constant)V_1^{1-n}}{1-n}$$

$$W = \frac{(p_2V_2^n)V_2^{1-n} - (p_1V_1^n)V_1^{1-n}}{1-n} = \frac{p_2V_2 - p_1V_1}{1-n}$$



- To evaluate , the pressure at state 2 is required.

$$p_2 = p_1\left(\frac{V_1}{V_2}\right)^n = (3\text{ bar})\left(\frac{0.1}{0.2}\right)^{1.5} = 1.06\text{ bar}$$

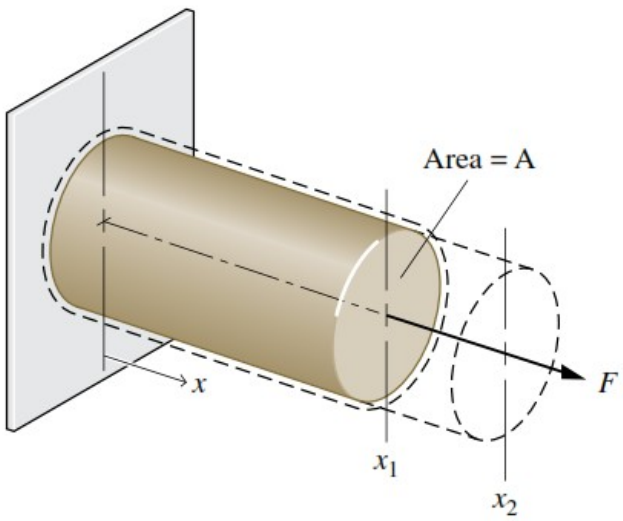
- This expression is valid for all values of n except = 1.0.

$$W = constant\int_{V_1}^{V_2}\frac{dV}{V} = (constant)\ln\frac{V_2}{V_1} = (p_1V_1)\ln\frac{V_2}{V_1}$$

- For = 0, the pressure–volume relation reduces to = constant, and the integral becomes .

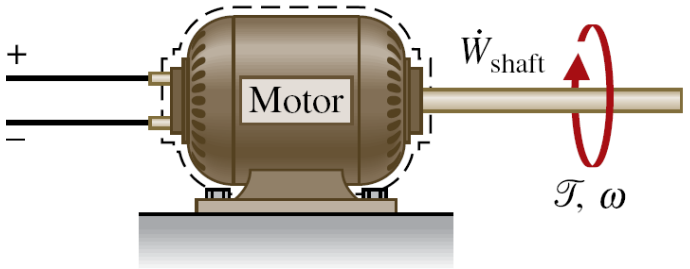
- **Extension of a solid bar**: A bar is fixed at one end and a force is applied at the other end. Let the force be represented as , where is the cross-sectional area of the bar and is the normal stress acting at the end of the bar.

- The work done as the end of the bar moves a distance is given by .



- The minus sign is required because work is done on the bar when is positive. The work for a change in length from to is found by integration $W = -\int_{x_1}^{x_2} \sigma \mathrm{A}\, dx$

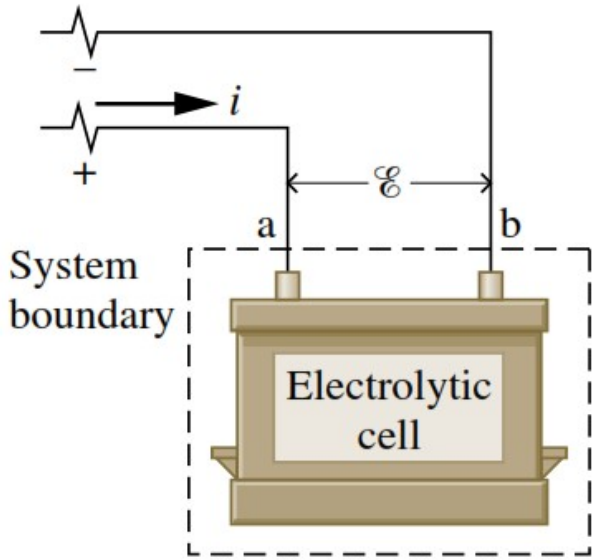
- **Power transmitted by a shaft**: Consider a shaft rotating with angular velocity and exerting a torque on its surroundings.



- Let the torque be expressed in terms of a tangential force and radius as . The velocity at the point of application of the force is , where is in radians per unit time.

- Therefore, the power transmitted from the shaft to the surroundings is: .

- **Electric Power**: A system consisting of an electrolytic cell is connected to an external circuit through which an electric current, , is flowing.



- The current is driven by the electrical potential difference existing across the terminals labeled a and b.
- The rate of energy transfer by work, or the power, is .
- Since the current equals , the work can be expressed in differential form as , where is the amount of electrical charge that flows into the system.
- Next, we turn our attention to the **understanding of energy**.
- We consider the total energy of a system, which includes kinetic energy, gravitational potential energy, and **other forms of energy**.

Thermodynamics

- Examples of such forms of energy transfer occurs (a) when a **battery is charged**, (b) when a **fluid is stirred**, (c) when a **gas is compressed**, etc.

- This other forms of energy is lumped together in the **internal energy** of the system. Internal energy is an **extensive property of the system**, as is the total energy.

- So the change in total energy has **three macroscopic contributions**: kinetic energy, potential energy and internal energy. Internal energy is represented by the symbol , and the change in internal energy in a process is .

- The specific internal energy is symbolized by u (per unit mass) or (per unit mole).

- The change in total energy of a system:

- The **microscopic interpretation of internal energy** is attributed to the **motions and configurations** of the individual molecules, atoms, and subatomic particles of the matter.

Thermodynamics

- Energy attributed to the **kinetic energy** (rotational, vibrational and translational) **of the molecules** is know as **thermal energy**.
- Energy **stored in the chemical bonds** between the atoms that make up the molecules is known as **chemical energy**.
- Energy **stored in nucleus** is know as **nuclear energy**.
- Therefore, internal energy can be broadly categorized into **thermal, chemical and nuclear** energy.
- So far, we discussed the **energy transfer by work**. We now move our attention to **energy transfer by heat**.

Thermodynamics

- The symbol denotes an amount of **energy transferred in a heat interaction** between system and surroundings.

- If a system undergoes a process involving **no heat transfer** with its surroundings, that process is called an **adiabatic process**.

- Heat transfer **into** a system is taken to be **positive** (), and heat transfer **from** a system is taken as **negative** (). The sign convention for heat transfer is just the **reverse** of the one adopted for work.

- The value of a heat transfer **depends on the details of a process** and not just the end states. Thus, like work, **heat is not a property**.

- Therefore, the **differential of heat transferred** is written as . The amount of energy transfer by heat **for a process** is given by the integral, (from state 1 to state 2).

Thermodynamics

- The net **rate of heat transfer** is denoted by . In some cases it is convenient to use the **heat flux**, , which is the **heat transfer rate per unit of surface area**.

- The **units** for heat transfer and heat transfer rate are J and J/s or W, respectively. The unit for the heat flux is W/m^2 or kW/m^2.

- Based on the experimental evidence, three mechanisms of heat transfer are recognized: **Conduction, Convection and Radiation**.

- **Conduction**: Transfer of energy occurs from the more energetic particles of a substance to adjacent particles that are less energetic due to interactions between particles, governed by **Fourier's law**.

- By Fourier's law, the rate of heat transfer **across any plane normal to the** direction, , is **proportional to** the wall area, , and the temperature gradient in the direction, as,

- where the proportionality constant is a property called the **thermal conductivity**. The **minus sign** is a consequence of energy transfer in the direction of decreasing temperature.

- **Convection**: Energy transfer occurs between a surface (solid or fluid, real or imaginary) at a temperature and an adjacent gas or liquid at another temperature by the mode of convection.

- Energy is transferred due to the combined effects of **conduction within the fluid and the bulk motion of the fluid**.

- The rate of energy transfer between the surface and the fluid can be quantified by the an **empirical expression**, , known as **Newton's law of cooling**.

Thermodynamics

- is the **surface area** and the proportionality factor (not a thermodynamic property) is called the **heat transfer coefficient**.

- **Radiation**: Thermal radiation is emitted by matter as a result of **changes in the electronic configurations** of the atoms or molecules within it.

- The energy is **transported by electromagnetic waves** (or photons). Unlike conduction and convection, thermal radiation **requires no intervening medium** to propagate and can even take place in a vacuum.

- The rate at which energy is emitted, , from a surface of area of temperature is **quantified macroscopically** by a modified form of the **Stefan–Boltzmann law** as, .

- The emissivity, indicates **how effectively the surface radiates** (), and is the **Stefan–Boltzmann constant**, .

- The **net rate of radiant exchange** between a smaller surface (), whose area is and emissivity is , and the larger surroundings of temperature is .

- When is provided it is assumed that the value has been determined by the methods introduced above. If is the unknown, its value is usually found by using the **energy balance**, discussed next.

- We have seen that **the only ways** the energy of a closed system can be exchanged are **through transfer of energy by work or by heat**.

- Now, a **fundamental aspect** of the energy concept is that **energy is conserved**; we call this the **first law of thermodynamics**, summarized in words as,

$$\begin{bmatrix} \textbf{Change in the amount of energy} \\ \textit{contained within a system during some time interval} \end{bmatrix} = \begin{bmatrix} \textbf{Net amount of energy} \\ \textit{transferred } \textbf{in} \textit{ across the system boundary by } \textbf{heat transfer} \\ \textit{during the time interval} \end{bmatrix} + \begin{bmatrix} \textbf{Net amout of energy} \\ \textit{transferred } \textbf{out} \textit{ accorss the system boundary } \textbf{by work} \\ \textit{during the time interval} \end{bmatrix}$$

Topic: First Law of Thermodynamics
Lecture – 4

Disclaimer:

The study materials/presentations are solely meant for academic purposes and they can be reused, reproduced, modified, and distributed by others for academic purposes only with proper acknowledgements.

- The **net rate of radiant exchange** between a smaller surface (), whose area is and emissivity is , and the larger surroundings of temperature is .

- When is provided it is assumed that the value has been determined by the methods introduced above. If is the unknown, its value is usually found by using the **energy balance**, discussed next.

- We have seen that **the only ways** the energy of a closed system can be exchanged are **through transfer of energy by work or by heat**.

- Now, a **fundamental aspect** of the energy concept is that **energy is conserved**; we call this the **first law of thermodynamics**, summarized in words as,

$$\begin{bmatrix} \textbf{Change in the amount of energy} \\ \textit{contained within a system during some time interval} \end{bmatrix} = \begin{bmatrix} \textbf{Net amount of energy} \\ \textit{transferred } \textbf{in} \textit{ across the system boundary by } \textbf{heat transfer} \\ \textit{during the time interval} \end{bmatrix} - \begin{bmatrix} \textbf{Net amout of energy} \\ \textit{transferred } \textbf{out} \textit{ accorss the system boundary } \textbf{by work} \\ \textit{during the time interval} \end{bmatrix}$$

Thermodynamics

- Therefore, in any process of a **closed system**, the energy of the system increases or decreases **by an amount equal to the net amount of energy transferred** across its boundary.

- This **energy balance** can be expressed in symbols as, . Dividing the total energy into its macroscopic contributions, an alternative form of energy equation is .

- **Special forms of the energy balance**:

  1. Energy balance in differential form .

  2. Time rate form of energy balance , or .

- These **alternative forms of the energy balance** are the **starting points** when applying the principle of conservation of energy to closed systems.

Thermodynamics

- **Problem 1**: 4 kg of a gas, contained in piston-cylinder assembly, undergoes a process with pressure-volume relationship is The initial pressure is 3 bar, the initial volume is 0.1 m^3, and the final volume is 0.2 m^3. The change in specific internal energy of the gas in the process is = −4.6 kJ/kg. There are no significant changes in kinetic or potential energy. Determine the net heat transfer for the process, in kJ. (-0.8 kJ)

- **Problem 2**: A silicon chip measuring 5 mm on a side and 1 mm in thickness is embedded in a ceramic substrate. At steady state, the chip has an electrical power input of 0.225 W. The top surface of the chip is exposed to a coolant whose temperature is 20°C. The heat transfer coefficient for convection between the chip and the coolant is 150 $W/m^2 \cdot K$. If heat transfer by conduction between the chip and the substrate is negligible, determine the surface temperature of the chip, in . ()

- We discussed energy balance **in a process** so far.

- Now, let us talk about **thermodynamic cycle**.

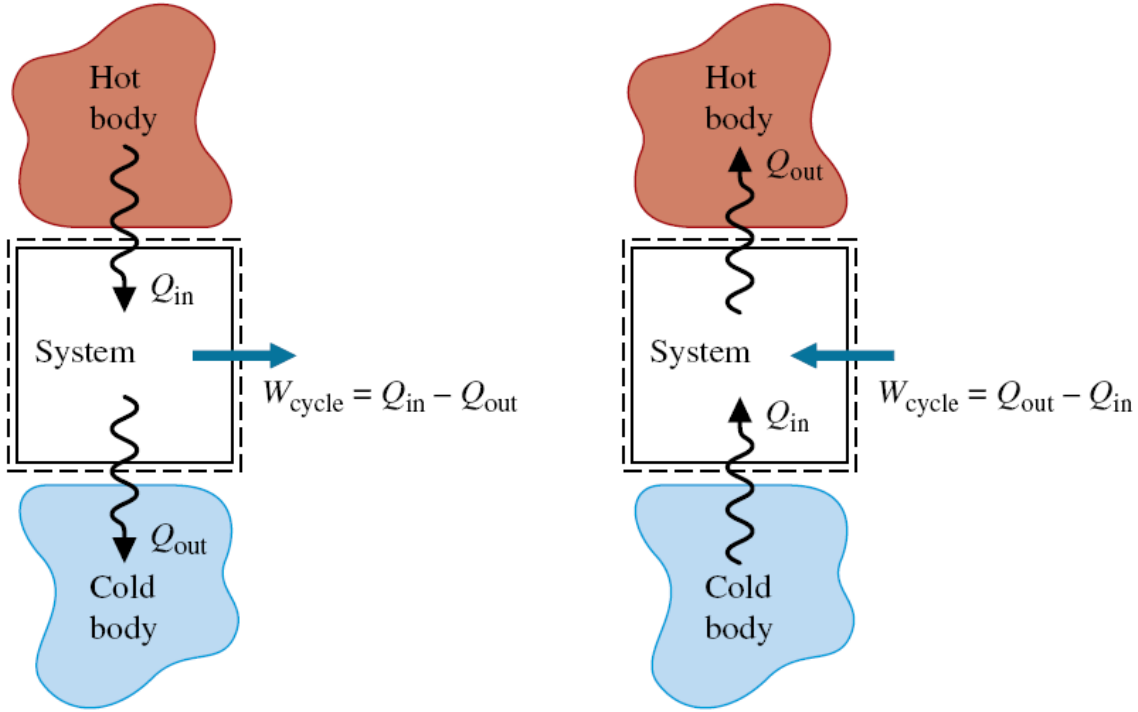
Thermodynamics

- Cycles that are repeated periodically **play prominent roles** in many areas of application.
- A thermodynamic cycle is **a sequence of processes that begins and ends at the same state**. Consequently, over the cycle the system experiences **no net change of state**.
- The **energy balance of a thermodynamic cycle**: . Since, there is no net change in its energy over the cycle, the equation reduces to .
- We deal with **two general classes of cycles** namely **power cycles** and **refrigeration and heat pump cycles**.
- In each case, a system undergoes a cycle while **communicating thermally** with **two bodies** (located in the surroundings), one hot and the other cold.
- During each cycle there is also a **net amount of energy exchanged** with the surroundings **by work**.

- Using the symbols (heat transfer **into** the system) and (heat transfer **out** of the system), we do not bother about the **sign convention** for heat transfer.

- The directions for heat and work transfer are indicated by the **arrows**.

- **Power cycles** deliver a **net work transfer** of energy to their surroundings during each cycle.



Power cycles **Refrigeration and heat pump cycles**

- Here, the net work output equals the net heat transfer to the cycle as . Therefore, **must be greater than** for a power cycle.

- is normally derived from the **combustion of fuel** or a **moderated nuclear reaction** and is generally discharged to the **surrounding atmosphere**.

Thermodynamics

- The **performance** of power cycles is expressed by a ratio called **thermal efficiency** as **or** .
- Since energy is conserved, can **never be greater than unity**. We now move on to **refrigeration and heat pump cycle**.
- Here, the energy is transferred **from a cold body** () and the energy discharged **to the hot body** ().
- To accomplish these energy transfers **requires a net work input**, . The energy balance takes the form .
- The refrigeration and heat pump cycles actually **differs in their objectives**.
- The objective of a refrigeration cycle is **to cool a refrigerated space** (Ex. in refrigerator or building) **below** that of the surroundings.

Thermodynamics

- The objective of a heat pump is **to maintain the temperature** (Ex. In building or certain industrial processes) **above** that of the surroundings.

- Accordingly, their performance parameters, called **coefficients of performance (COP)**, are defined differently.

- **COP of refrigeration cycle** is defined as . For a household refrigerator, is discharged to the space in which the refrigerator is located. is usually provided in the form of electricity.

- **COP of heat pump cycle** is defined as . So, the value of is **never less than unity**. For residential heat pumps, is normally drawn from the surrounding atmosphere and is usually provided by electricity.

- In this, we saw the **application of 1st law in closed systems**. Before discussing the same in control volume, let us discuss how to **evaluate thermodynamic properties**.

Thermodynamics

- Application of energy balance equation we developed so far **requires knowledge of the properties** of the system for solving problems.

- Before discussing how to evaluate thermodynamic properties, we introduce the concept of **phase and pure substance**.

- **Phase** refers to a quantity of matter that is **homogeneous throughout in both chemical composition and physical structure** (all gas, all liquid, etc.).

Example:

- Mixture of liquid water and water vapor contains two phases (**inhomogeneous in physical structure**)

- Mixture of alcohol and water (miscible) can form a single liquid phase (**homogeneous in chemical composition**).

- Mixture of oil and water (immiscible) form two liquid phase (**inhomogeneous in chemical composition**).

- **Pure substance** refers to a quantity of matter that is **homogeneous throughout in chemical composition**.

Example:

- Mixture of liquid water and water vapor can be considered as pure substance (**homogeneous chemical composition**)

- A uniform mixture of gases (air) can be considered as pure substance (**homogeneous chemical composition**).

- However, if air starts getting liquefied, the mixture cannot be considered as pure substance (**composition of liquefied air is different**).

Fixing the state:

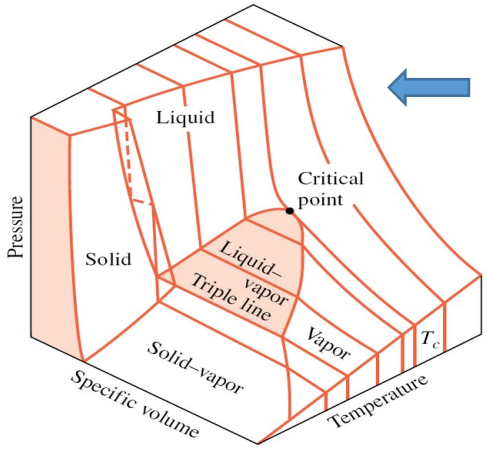
- A state of a system at equilibrium is described by the values of **a set of intensive properties**.
- All the properties are **not independent**. Therefore, a **subset** of all properties is **sufficient** to describe a state, called **state principle/state postulate**.
- The systems **in the absence of** electrical, magnetic, gravitational, motion, and surface tension effects with **pure substances**, are called **simple compressible systems**.
- For such systems, specification of the values for any **two independent intensive thermodynamic properties** will fix the values of all other properties.
- **Example**: For a gas, temperature (T) and specific volume (v) **can be** two independent properties. Therefore, pressure, $p = p(T,v)$ and specific internal energy, $u = u(T,v)$.

- We discuss the evaluation of thermodynamic properties of **simple compressible systems** consisting of a **pure substance**.

Properties of pure, simple compressible substance:

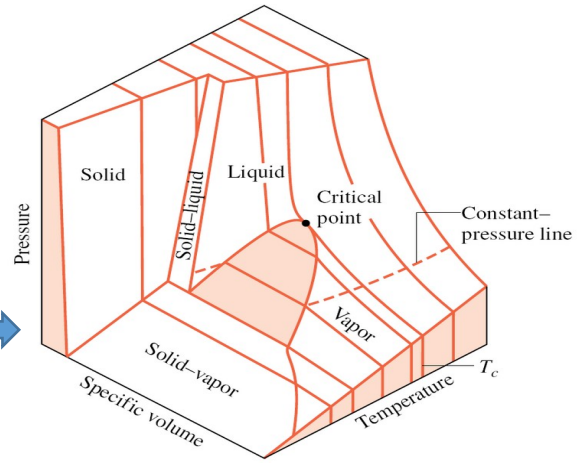
- The temperature (T) and specific volume (v) can be regarded as **independent** and pressure (p) is determined as a **function of these two** as $p = p(T,v)$.

- This is a **well known** p–v–T relation, and the graph of such function is **a surface**, known as p–v–T **surface** (shown below).



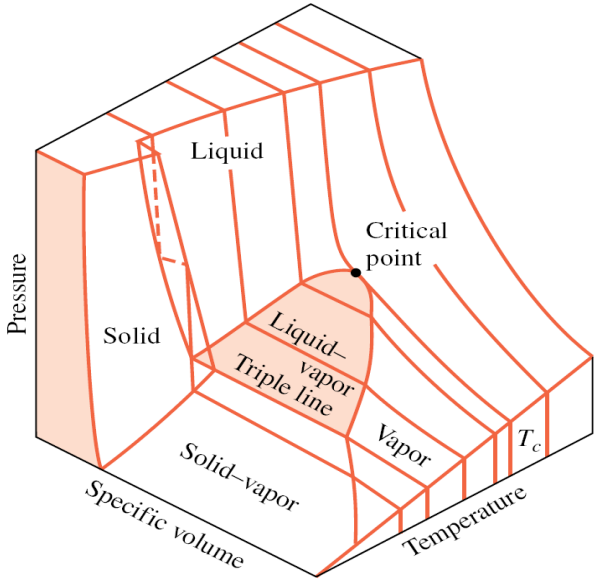
For the substance that **expands on freezing**, e.g. water

For the substance that **contracts on freezing**, e.g. most substances



Thermodynamics

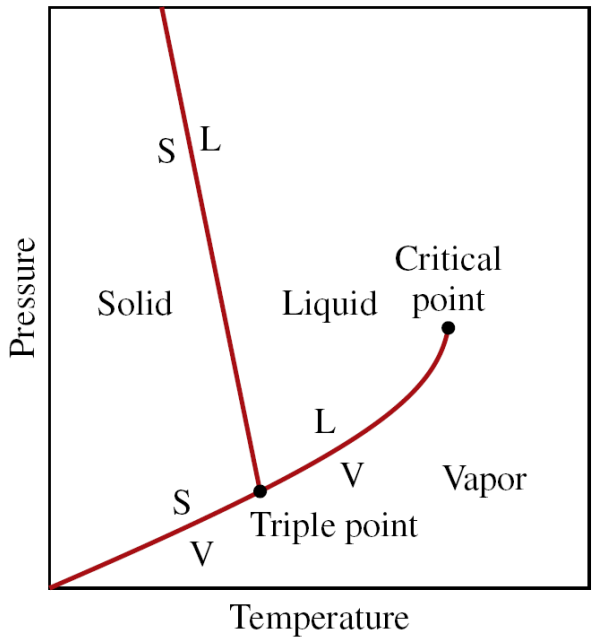
- In the single-phase regions (labelled as **solid, liquid and vapor**), the state is fixed by **any two of the properties**: p, v, and T, since all of these are **independent** when there is a single phase present.



- There are two-phase regions where two phases **exist in equilibrium**: **liquid–vapor**, **solid–liquid**, and **solid–vapor**, during changes in phase such as **vaporization**, **melting**, and **sublimation**, respectively.
- In two phase region, pressure and temperature are **not independent**. Therefore, the state can be fixed by specific volume and **either pressure or temperature**.
- All three phases can **exist in equilibrium** along the line labeled **triple line**.
- A state at which a phase change **begins or ends** is called a **saturation state**.
- The dome-shaped region composed of the liquid–vapor states is called the **vapor dome**.

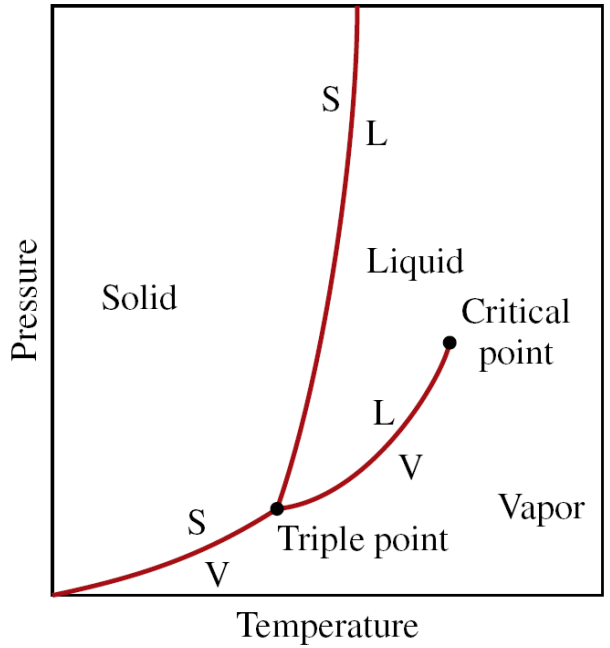
Thermodynamics

- The lines bordering the vapor dome are called **saturated liquid** and **saturated vapor lines**.
- At the top of the dome, where the saturated liquid and saturated vapor lines meet, is the **critical point**.
- The temperature, pressure and specific volume at the critical point are known as **critical temperature, critical pressure and critical specific volume**.
- It is often more convenient to work with **two-dimensional projections** of the surface.
- When the p–v–T surface is projected onto the **pressure–temperature plane**, the property diagram is known as a **phase diagram**.
- In this, the two-phase regions **reduce to lines**. Each point on these lines represents all **two-phase mixtures** at that particular temperature and pressure.



For the substance that **expands on freezing**, e.g. water

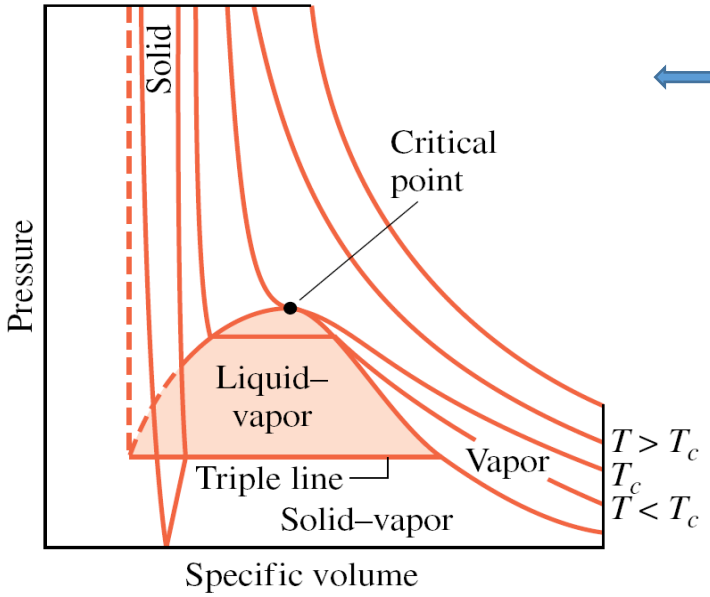
For the substance that **contracts on freezing**, e.g. most substances



- The term **saturation temperature** is the temperature at which a phase change takes place at a given pressure, and the **saturation pressure** is the pressure at which a phase change takes place at a given temperature.

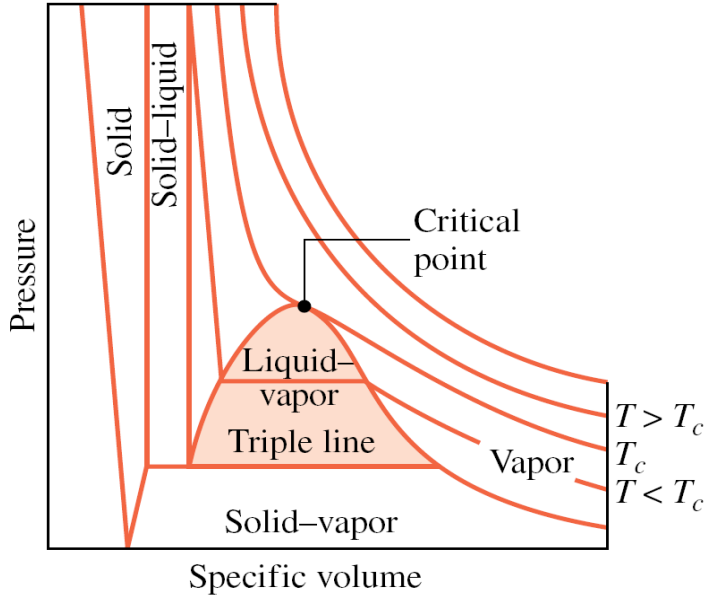
- The triple line projects onto a point, called **triple point**. For water, at the triple point is **273.16 K** and at the triple point is **0.6113 kPa**.

- Projecting the p–□–T surface onto the **pressure–specific volume plane** results in a p–□ diagram (below).



For the substance that expands on freezing, e.g. water

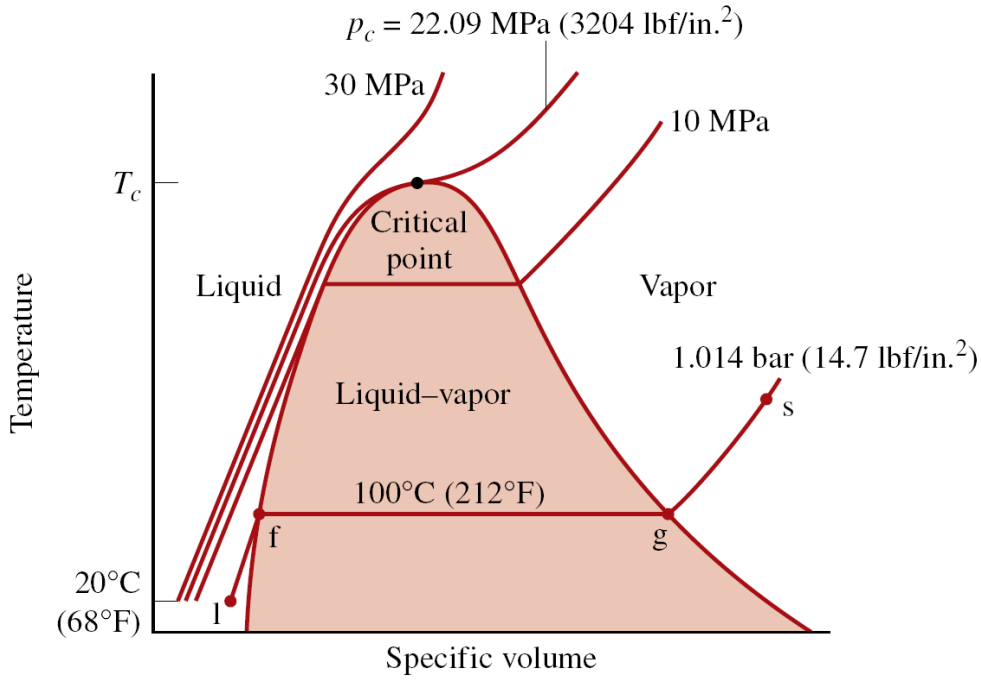
For the substance that contracts on freezing, e.g. most substances



- For solving problems, the diagram is **frequently convenient**. Note the appearance of **constant-temperature lines, called isotherms**.

- The **critical isotherm** passes through a **point of inflection** at the critical point and the slope is zero there.

- Similarly, for solving problem, a projection of surface onto plane, known as **diagram** (shown for water) is equally **convenient**.
- Note the appearance of constant-pressure lines, called **isobars.**
- For pressures less than the critical pressure, the pressure **remains constant** with temperature as the two-phase region is traversed.
- Having described the overall phase diagram, we turn our attention to **phase change of pure substance**.

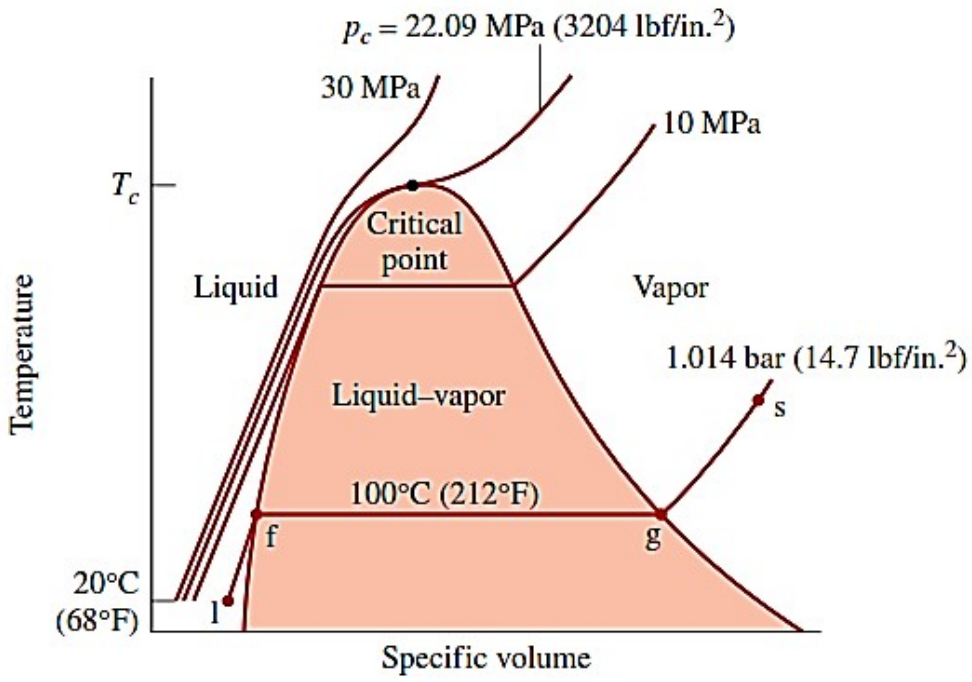


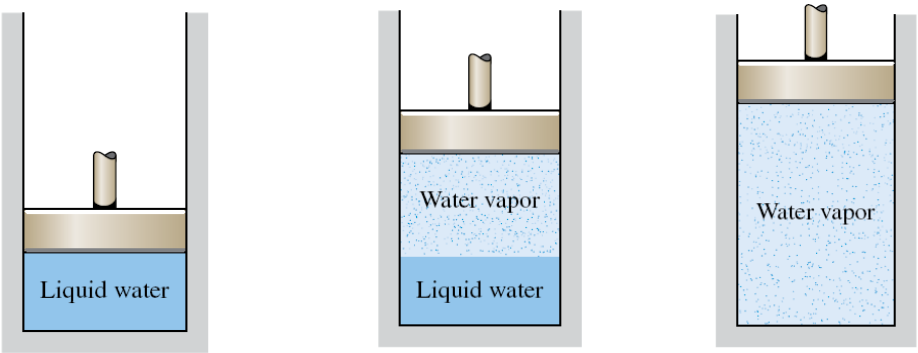
Topic: Evaluating Thermodynamic Properties
Lecture – 5

Disclaimer:

The study materials/presentations are solely meant for academic purposes and they can be reused, reproduced, modified, and distributed by others for academic purposes only with proper acknowledgements.

- Consider a closed system consisting of liquid water at 20°C contained within a piston–cylinder assembly, represented by **state 1 in the diagram**.
- As the increases (system is heated) at constant , increases slightly (**state f, saturated liquid state**).
- The liquid states along the line segment l–f are sometimes referred to as **subcooled liquid** () or **compressed liquid** ().
- An additional heat transfer at fixed p results in the **formation of vapor** without any change in T but with a considerable increase in v.



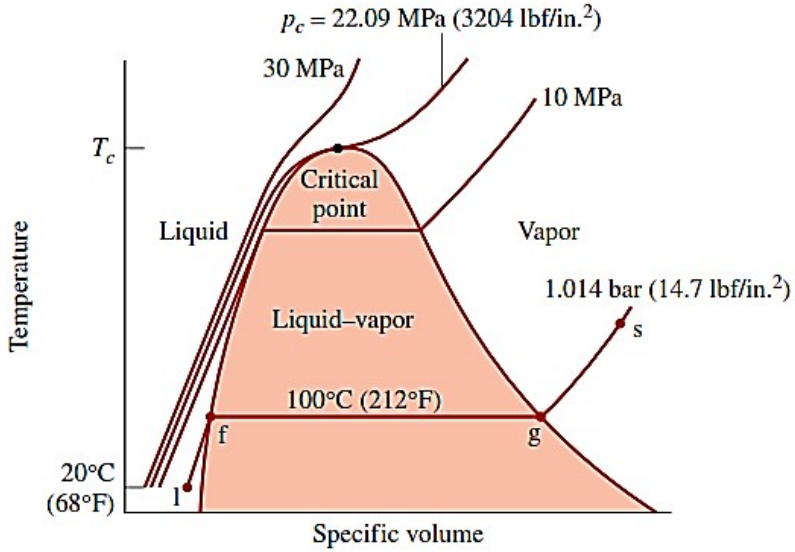


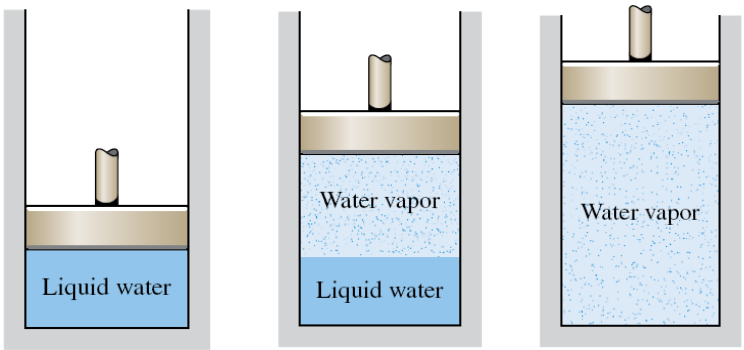
- When a mixture of liquid and vapor exists **in equilibrium**, the liquid phase is a **saturated liquid** and the vapor phase is a **saturated vapor**.

- On further heating, the last bit of liquid has vaporized (point g, **saturated vapor state**).

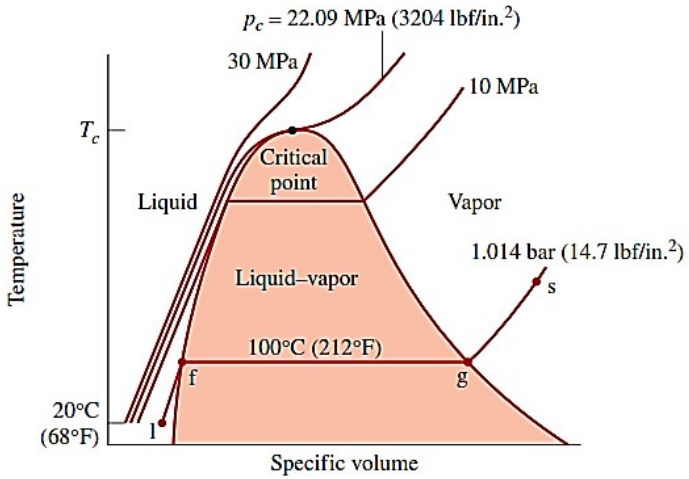
- The two-phase liquid–vapor mixture states **can be distinguished** from one another by the **quality**, an intensive property.

- The quality, x is defined as a **ratio** of the mass of vapor present to the total mass of the mixture.





- In **symbols**,



- indicates saturated liquid state, and indicates saturated vapor state.

- On further heating (beyond **state**) at constant , both and increase (**state**). A state such as is often referred to as a **superheated vapor** ().

- At states where is **greater than the critical pressure** (), the terms liquid and vapor tend to **lose their significance**.

- The phase changes from liquid to vapor (**vaporization**) and vapor to liquid (**condensation**) are of **principal interest**.

Thermodynamics

- However, the phase changes from solid to liquid (**melting**) and from solid to vapor (**sublimation**) find their application in many practical systems.

- When a solid is heated, **melting** occurs with pressure **greater than triple point pressure**, whereas **sublimation** occurs when the pressure is **less than triple point pressure**.

- Thermodynamics property data can be found in **tables** which are commonly available for pure, simple compressible substances.

- Making use of these tables is an **important skill**. The tables for the **properties of water** are referred as **steam tables**. Tables are **also available** for different refrigerants, propane, etc.

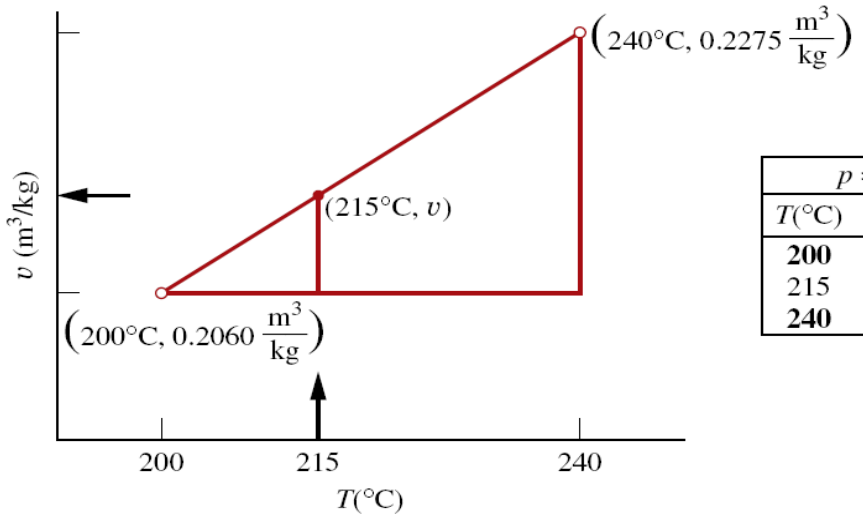
- The properties of water vapor and liquid water are listed in **superheated vapor tables** (Table A4) and **compressed liquid tables** (Table A5), respectively.

TABLE A-2 Properties of Saturated Water (Liquid–Vapor): Temperature Table

Pressure Conversions: 1 bar = 0.1 MPa = 10^2 kPa

Temp. °C	Press. bar	Specific Volume m^3/kg Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008	10
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6	0.1658	8.8765	11
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4	0.1806	8.8524	12
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3	0.1953	8.8285	13
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1	0.2099	8.8048	14
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814	15
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8	0.2390	8.7582	16
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6	0.2535	8.7351	17
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4	0.2679	8.7123	18
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2	0.2823	8.6897	19
20	0.02339	1.0018	57.791	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.6672	20
21	0.02487	1.0020	54.514	88.14	2404.3	88.14	2451.8	2539.9	0.3109	8.6450	21
22	0.02645	1.0022	51.447	92.32	2405.7	92.33	2449.4	2541.7	0.3251	8.6229	22
23	0.02810	1.0024	48.574	96.51	2407.0	96.52	2447.0	2543.5	0.3393	8.6011	23
24	0.02985	1.0027	45.883	100.70	2408.4	100.70	2444.7	2545.4	0.3534	8.5794	24

- In those tables, the values of **several properties** such as specific volume (), specific internal energy (), specific enthalpy () and specific entropy () are given as a function of and .
- While solving problems, the states often **do not match** exactly with the values given in the tables.
- Therefore, **linear interpolation** can be utilized with acceptable accuracy (see figure).
- We need **to determine** the of water vapor at a state where = 10 bar and = 215°C. Data from table are given in the box.
- Now, we can think of the **slope of a straight line** joining the adjacent table entries as



p = 10 bar	
T(°C)	v (m³/kg)
200	**0.2060**
215	v = ?
240	**0.2275**

$$slope = \frac{(0.2275 - 0.2060)\ \mathrm{m^3/kg}}{(240 - 200)°\mathrm{C}} = \frac{(v - 0.2060)\ \mathrm{m^3/kg}}{(215 - 200)°\mathrm{C}}$$

Thermodynamics

- Solving for , the result is $= 0.2141\ m^3/kg$
- The tables are given in every book (**separate pdf file will be uploaded)**.
- There are **saturation tables**, giving data for water at saturated liquid, saturated vapor, and saturated solid states.
- Saturation tables (**A-2, A-3**) consist of property data for water at saturated liquid and saturated vapor. Both tables provide saturated liquid and saturated vapor data.
- A-2 is called **temperature table** as temperatures are listed in the **first column** and the corresponding saturation pressure in the second column.
- A-3 is called **pressure table** as pressure values are listed in the **first column** and the corresponding saturation temperature in the second column.

TABLE A-2 Properties of Saturated Water (Liquid–Vapor): Temperature Table

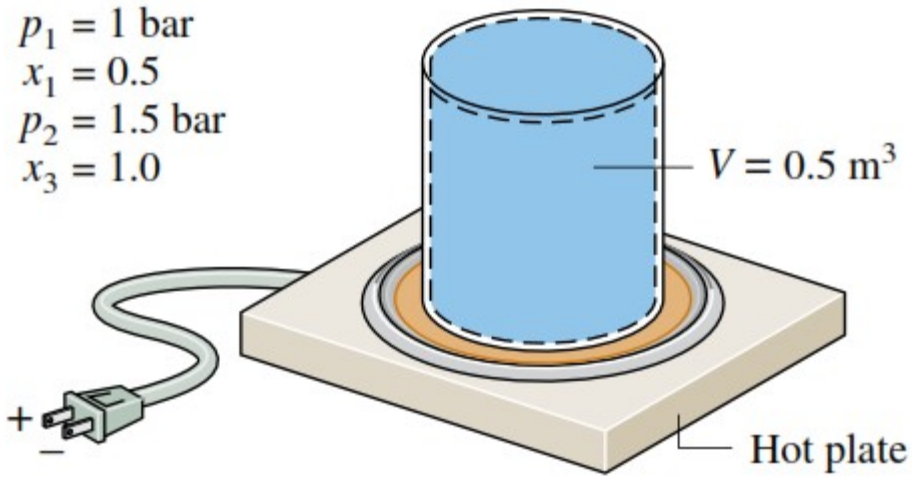
Pressure Conversions: 1 bar = 0.1 MPa = 10^2 kPa

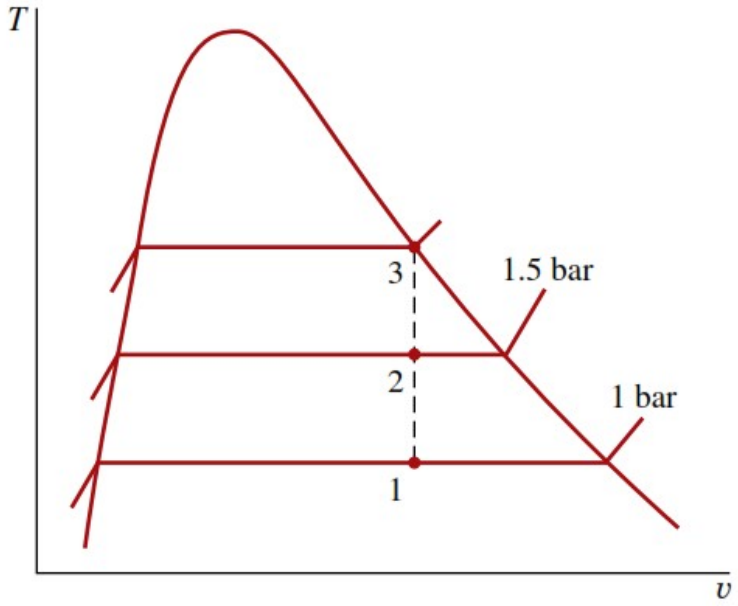
Temp. °C	Press. bar	Specific Volume m^3/kg Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008	10
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6	0.1658	8.8765	11
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4	0.1806	8.8524	12
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3	0.1953	8.8285	13
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1	0.2099	8.8048	14
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814	15
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8	0.2390	8.7582	16
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6	0.2535	8.7351	17
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4	0.2679	8.7123	18
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2	0.2823	8.6897	19
20	0.02339	1.0018	57.791	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.6672	20
21	0.02487	1.0020	54.514	88.14	2404.3	88.14	2451.8	2539.9	0.3109	8.6450	21
22	0.02645	1.0022	51.447	92.32	2405.7	92.33	2449.4	2541.7	0.3251	8.6229	22
23	0.02810	1.0024	48.574	96.51	2407.0	96.52	2447.0	2543.5	0.3393	8.6011	23
24	0.02985	1.0027	45.883	100.70	2408.4	100.70	2444.7	2545.4	0.3534	8.5794	24

Thermodynamics

- Next two columns give the specific volume of saturated liquid () and saturated vapor ().
- Now the **specific volume of two-phase liquid-vapor mixture** can be determined by using saturation tables and quality of mixture () as .
- The increase in specific volume on vaporization is also denoted as (). Therefore, .

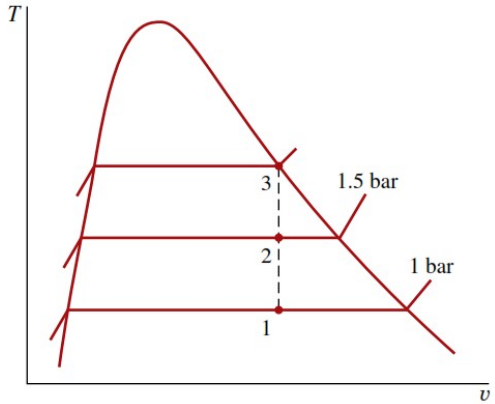
Problem 1: A closed, rigid container of volume 0.5 m^3 is placed on a hot plate. Initially, the container holds a two-phase mixture of saturated liquid water and saturated water vapor at = 1 bar with a quality of 0.5. After heating, the pressure in the container is = 1.5 bar. Indicate the initial and final states on a diagram, and determine **a)** the temperature, in °C, at states 1 and 2, **b)** the mass of vapor present at states 1 and 2, in kg, and **c)** If heating continues, determine the pressure, in bar, when the container holds only saturated vapor.





- The **specific volume** at state 1 (fixing state by **pressure** and **quality**) is found using the given quality as

$$\upsilon_1 = \upsilon_{f1} + x_1(\upsilon_{g1} - \upsilon_{f1})$$



- At state 2, the pressure is known and $\upsilon_2 = \upsilon_1 = 0.8475\ m^3/kg$
- From Table A-3 ▭ State 2 must be in the **two-phase region** as well.
- Since states 1 and 2 are in the two-phase liquid–vapor region, the **saturation temperatures** can be obtained from Table A-3 **(a)**
- Find total mass and then **mass of vapor present from quality** at state 1 and state 2. **(b)**
- From Table A-3 at $\upsilon_g = 0.8475\ m^3/kg$ we get = 2.11 bar. **(c)**

Evaluating specific internal energy (u) and specific enthalpy (h)

- In many thermodynamic analysis, the term, appear frequently. Therefore, it is given a name, **enthalpy**.

- Enthalpy is denoted by (for **specific enthalpy**). Mathematically, . Since , and are all properties, the combination, is **also a property**.

- The property tables provide the value of **, and along with , and** . Now let's see how to get internal energy () and enthalpy () data from tables.

- In saturation tables, values of and as well as and are given **as a function of both saturation temperature and pressure**.

- From these values, in similar manner, and of the **two phase liquid-vapor mixture** is calculated as and

TABLE A-2 Properties of Saturated Water (Liquid–Vapor): Temperature Table

Pressure Conversions: 1 bar = 0.1 MPa = 10^2 kPa

Temp. °C	Press. bar	Specific Volume m^3/kg Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008	10
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6	0.1658	8.8765	11
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4	0.1806	8.8524	12
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3	0.1953	8.8285	13
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1	0.2099	8.8048	14
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814	15
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8	0.2390	8.7582	16
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6	0.2535	8.7351	17
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4	0.2679	8.7123	18
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2	0.2823	8.6897	19
20	0.02339	1.0018	57.791	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.6672	20
21	0.02487	1.0020	54.514	88.14	2404.3	88.14	2451.8	2539.9	0.3109	8.6450	21
22	0.02645	1.0022	51.447	92.32	2405.7	92.33	2449.4	2541.7	0.3251	8.6229	22
23	0.02810	1.0024	48.574	96.51	2407.0	96.52	2447.0	2543.5	0.3393	8.6011	23
24	0.02985	1.0027	45.883	100.70	2408.4	100.70	2444.7	2545.4	0.3534	8.5794	24

Thermodynamics

- The **increase in specific internal energy and enthalpy** are also tabulated for convenience, and are denoted as () and (), respectively.

- and for **compressed liquid and superheated vapor** are given in **tables A-4 and A-5**, respectively.

- Table A-6 provide the properties of **saturated solid and saturated vapor**. Therefore, pressures and temperatures are **below those at the triple point**.

- The values of u, h and s listed in the tables are **not measured directly**, rather **calculated from other data easily obtained** from experiments.

- In this context, we need to understand **reference states and reference values**.

- While applying the energy balance, **the differences** in kinetic, potential and internal energy between two states are **what matter and not the absolute value** of them at each state.

Thermodynamics

- Similarly, the values of u, h and s are **assigned relative to arbitrary reference values** at arbitrary reference states.

- For water, the **reference state** is saturated liquid at 0.01°C (32.02°F). At this state, the specific internal energy is **set to zero**.

- Values of the **specific enthalpy are calculated** from $h = u + pv$, using the tabulated values for p, □, and u.

- The values assigned to particular states change if the reference state or reference values change, but the **differences remain the same**.

- Let us consider the energy balance for a closed system, **neglecting** the changes in KE and PE.

- 1st law of thermodynamics reduces to

- **Case 1**: If the system consists of a **single phase of water** (**liquid or vapor**), energy equation takes the form of , where is the system mass.

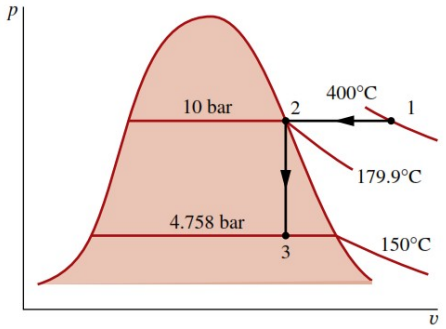
- Now, if initial and final temperatures, and , and pressures, and are known, for instance, internal energies, and can be **found from tables**.

- **Case 2**: If the system consists of **water vapor initially and water-vapor mixture at final state**, and . If quality is known, can be evaluated directly.

- **Case 3**: If the system consists of two **separated masses of water vapor** (at and at) initially, which mix to form **total mass of water vapor** (at) in the final state. In this case, the following equations are used.

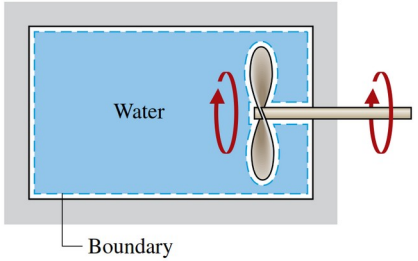
$$U_1 = m'u(T', p') + m''u(T'', p'')$$
$$U_2 = (m' + m'')u(T_2, p_2)$$
$$= mu(T_2, p_2)$$

- **Problem 2**: Water contained in a piston–cylinder assembly undergoes two processes in series from an initial state where the pressure is 10 bar and the temperature is 400°C. Process 1–2 The water is cooled as it is compressed at a constant pressure of 10 bar to the saturated vapor state. Process 2–3 The water is cooled at constant volume to 150°C.



a. Sketch both processes on and diagrams.
b. For the overall process determine the work, in kJ/kg.
c. For the overall process determine the heat transfer, in kJ/kg.

- **Problem 3**: A well-insulated rigid tank having a volume of 10 ft^3 contains saturated water vapor at 212°F. The water is rapidly stirred until the pressure is 20 lbf/in^2. Determine the temperature at the final state, in °F, and the work during the process, in Btu. (**Use tables A-xE**)



Topic: Control Volume analysis of 1st Law
Lecture – 6

Disclaimer:

The study materials/presentations are solely meant for academic purposes and they can be reused, reproduced, modified, and distributed by others for academic purposes only with proper acknowledgements.

- Devices such as **turbines, pumps, and compressors** through which mass flows are thought of a region in space through which mass flows (**a control volume**).

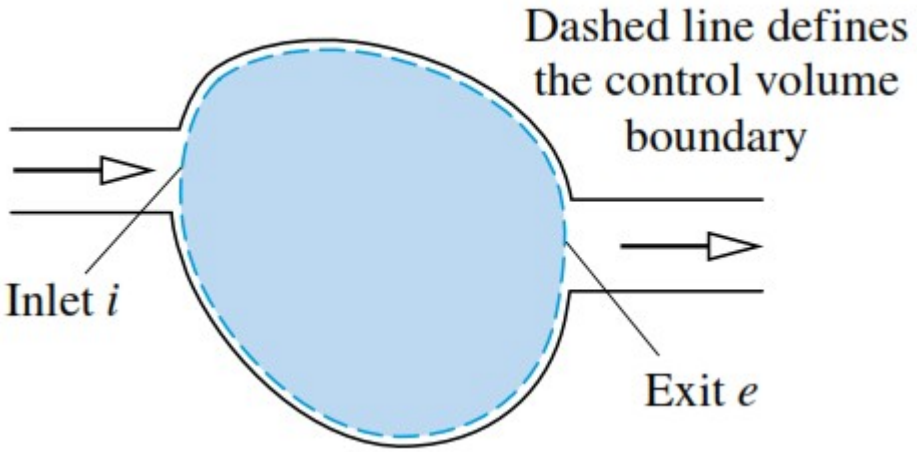
- Like closed system, **energy transfer** across the boundary of a control volume can occur **by means of heat and work**.

- In addition, **another type of energy transfer** must be accounted for, the **energy accompanying mass** as it enters or exits.

Conservation of mass for a control volume:

- A **control volume** with mass flowing in at and flowing out at , respectively.

- Application of **conservation of mass** states that:

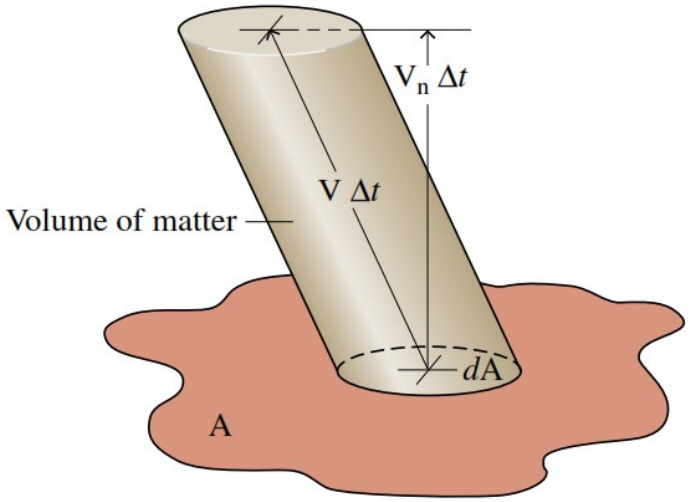


- This statement can be **expressed in symbols** as

$$\frac{dm_{cv}}{dt} = \dot{m}_i - \dot{m}_e$$

- In SI, all terms in above essed in **kg/s**.
- There may be **several locations on the boundary** through which mass enters or exits.
- Now, mass flow rate can be $\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$ **f local properties**.

- Let us considering a small quantity of matter flowing with velocity across an **incremental area** in a **time interval** , as shown in figure.



- denotes the component of the **relative velocity normal to** in the direction of flow.
- The volume of the matter (contained in the oblique cylinder) is the product of the area of its base and its altitude .
- Amount of mass that crosses in time interval is
- The instantaneous mass flow rate is then
- When this is integrated over the area A, mass flow rate is obtained a $\dot{m} = \int_A \rho V_n \, dA$

One-Dimensional Flow Form of the Mass rate Balance:

- The flow is **normal to the boundary** at locations where mass enters or exits the CV.
- All intensive properties, including velocity and density, are uniform with position **over each inlet or exit area** through which matter flows.
- Once these two idealizations are satisfied, the flow is said to be **one-dimensional**.
- Mass flow rate becomes $\dot{m} = \rho AV$ or $\dot{m} = \dfrac{AV}{\upsilon}$
- The product AV is the **volumetric flow rate** (m^3/s).
- Substituting this expression of mass flow rate in conservation of mass principle for control volumes gives $$\frac{dm_{cv}}{dt} = \sum_i \frac{A_i V_i}{\upsilon_i} - \sum_e \frac{A_e V_e}{\upsilon_e}$$

Steady-State Form of the Mass rate Balance:

- Many systems can be idealized as being at **steady state**, meaning that all properties are **unchanging in time**.
- The **identity of the matter** within the control volume **changes**, but the total amount present at any instant remains constant, therefore:
- When a control volume is at steady state, **every property is independent of time**.

Unsteady-State Form of the Mass rate Balance:

- The total mass contained within CV at an instant can be related to the **local density**.

$$m_{cv}(t) = \int_V \rho \, dV$$

- Now, the mass rate balance can be written as

$$\frac{d}{dt}\int_V \rho \, dV = \sum_i \left(\int_A \rho V_n \, dA\right)_i - \sum_e \left(\int_A \rho V_n \, dA\right)_e$$

- The product appearing in this equation, known as the **mass flux**, gives the time rate of mass flow per unit of area.

Conservation of Energy for a Control Volume:

- Like mass, energy is an **extensive property**, so it too can be transferred into or out of a control volume as a result of **mass crossing the boundary**.

- This is the **principal difference** between the **closed system and control volume** forms.

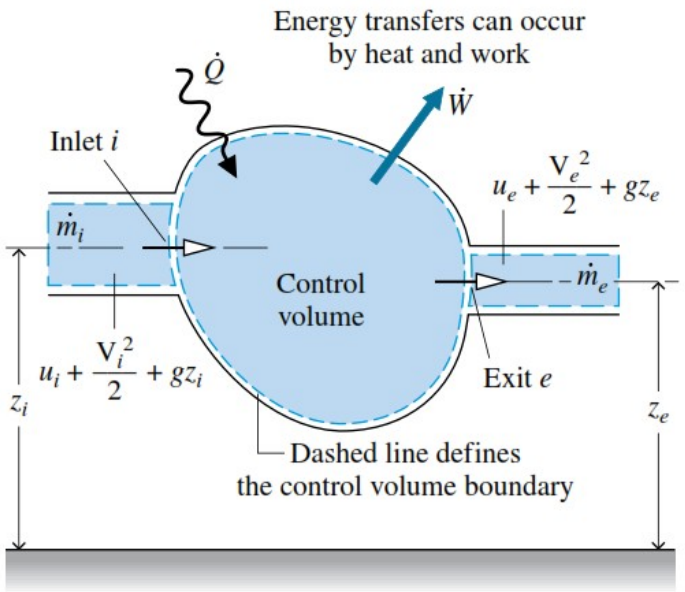
- Accordingly, the **conservation of energy principle applied to a control volume** states

$$\begin{bmatrix}\text{time } \textit{rate of change} \\ \text{of the energy} \\ \text{contained within} \\ \text{the control volume} \\ \textit{at time } t\end{bmatrix} = \begin{bmatrix}\textit{net rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred in} \\ \text{by heat } \textit{at} \\ \textit{time } t\end{bmatrix} - \begin{bmatrix}\textit{net rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred out} \\ \text{by work } \textit{at} \\ \textit{time } t\end{bmatrix} + \begin{bmatrix}\textit{net rate} \text{ of energy} \\ \text{transfer } \textit{into} \text{ the} \\ \text{control volume} \\ \text{accompanying} \\ \text{mass flow}\end{bmatrix}$$

- For the **one-inlet, one-exit** control volume with one-dimensional flow the energy rate balance is

$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \underline{\dot{m}_i\left(u_i + \frac{V_i^2}{2} + gz_i\right)} - \underline{\dot{m}_e\left(u_e + \frac{V_e^2}{2} + gz_e\right)}$$

- The underlined terms account for the rates of transfer of **internal, kinetic, and potential energy** of the entering and exiting streams.



Thermodynamics

- Because work is involved **where matter flows across the boundary**, it is convenient to separate the work term into **two contributions**.

- One contribution is the **work associated with the fluid pressure** as mass is introduced at inlets and removed at exits.

- The other contribution, denoted by , includes **all other work effects** (those associated with rotating shafts, displacement of the boundary, and electrical effects, etc.).

- As energy transfer by work can be expressed as the **product of a force and the velocity at the point of application of the force**, the time rate of energy transfer by work to/from the control volume is the **product of normal force () and fluid velocity ()**.

- At **inlet**, and at **exit**,

- The work term of the energy equation can be written as $\dot{W} = \dot{W}_{cv} + (p_e A_e)V_e - (p_i A_i)V_i$

- With , the above expression for work can be written as

$$\dot{W} = \dot{W}_{cv} + \dot{m}_e(p_e \upsilon_e) - \dot{m}_i(p_i \upsilon_i)$$

- The **work associated with the pressure** at the inlet and exit is commonly referred to as **flow work**.

One-Dimensional Flow Form of the Control Volume Energy rate Balance:

- Collecting all terms referring to the inlet and the exit into separate expressions, we have

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i\left(u_i + p_i\upsilon_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(u_e + p_e\upsilon_e + \frac{V_e^2}{2} + gz_e\right)$$

- With , the energy rate balance becomes

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

- The **appearance** of the sum in the control volume energy equation is the principal reason for **introducing enthalpy** previously.

- Considering **several locations** on the boundary through which mass enters or exits, the **energy rate balance** is

$$\boxed{\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)}$$

Integral Form of the Control Volume Energy rate Balance:

- Similar to mass rate balance, the energy rate balance can be expressed **in terms of local properties** to obtain forms that are more generally applicable.

- The **total energy associated with the control volume** at time (), can be written as a volume integral.

$$E_{cv}(t) = \int_V \rho e \, dV = \int_V \rho \left(u + \frac{V^2}{2} + gz \right) dV$$

- The energy rate balance becomes

$$\frac{d}{dt}\int_V \rho e \, dV = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \left[\int_A \left(h + \frac{V^2}{2} + gz \right) \rho V_n \, dA \right]_i - \sum_e \left[\int_A \left(h + \frac{V^2}{2} + gz \right) \rho V_n \, dA \right]_e$$

Steady-State Forms of the Mass and Energy rate Balances:

- The **mass rate balance** takes the form

- Furthermore, at steady state , so the energy balance equation becomes

- It **can also be w** $0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$

$$\underbrace{\dot{Q}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right)}_{\text{(energy rate in)}} = \underbrace{\dot{W}_{cv} + \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)}_{\text{(energy rate out)}}$$

- The total rate at which **mass/energy** is transferred into the control volume equals the total rate at which **mass/energy** is transferred out.

- Many important applications involve **one-inlet, one-exit control volumes** at steady state.

- The **mass rate balance reduces** simply to .

- Next, applying the energy rate balance and factoring the mass flow rate gives:

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)\right]$$

- Or,

$$0 = \frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)$$

Thermodynamics

- The enthalpy, kinetic energy, and potential energy terms all **appear as differences** between their values at the inlet and exit.

- This steady-state forms of the energy rate balance **relate only energy transfer** quantities evaluated at the boundary of the control volume.

- When the mass and energy rate balances are **applied to a control volume**, simplifications are normally needed to **make the analysis manageable**.

- That is, the control volume of interest is modeled by **making assumptions**.

- Next, we present **examples illustrating the analysis** of **several devices of interest in engineering**,

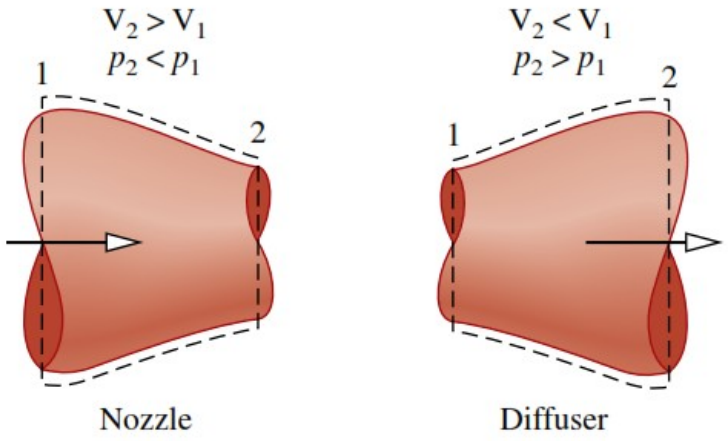
- These include nozzles and diffusers, turbines, compressors and pumps, heat exchangers, and throttling devices.

Nozzles and Diffusers:

- A **nozzle** is a flow passage of varying cross-sectional area in which the **velocity of a gas or liquid increases** in the direction of flow.

- In a **diffuser**, the gas or liquid **decelerates** in the direction of flow.

- In a nozzle, the **cross-sectional area decreases** in the direction of flow and in a diffuser, the **walls of the flow passage diverge** (Figure).

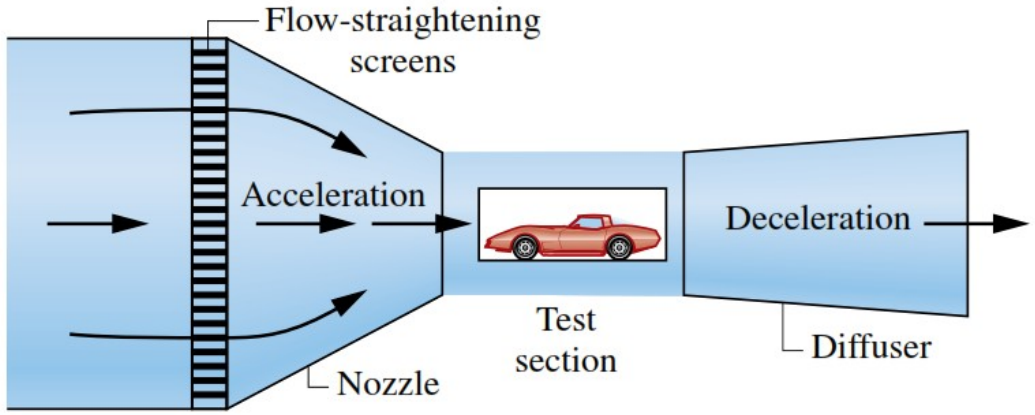


- Nozzles and diffusers have **several important engineering** applications.

- A nozzle and diffuser are combined in a **wind-tunnel test facility**. Ducts with converging and diverging passages are commonly used in **building air-conditioning systems**.

- Nozzles and diffusers also are key components of **turbojet engines**.

- Nozzles and diffusers also are key components of **turbojet engines**.



- For a control volume enclosing a nozzle or diffuser, the **only work is flow work**.
- The **change in potential energy** from inlet to exit is **negligible** under most conditions.
- Therefore, $0 = \dot{Q}_{cv} + \dot{m}\left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2}\right]$
- The **heat transfer with the surroundings is often small** enough relative to the enthalpy and kinetic energy terms that it also **can be neglected**.

$$0 = (h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2}\right)$$

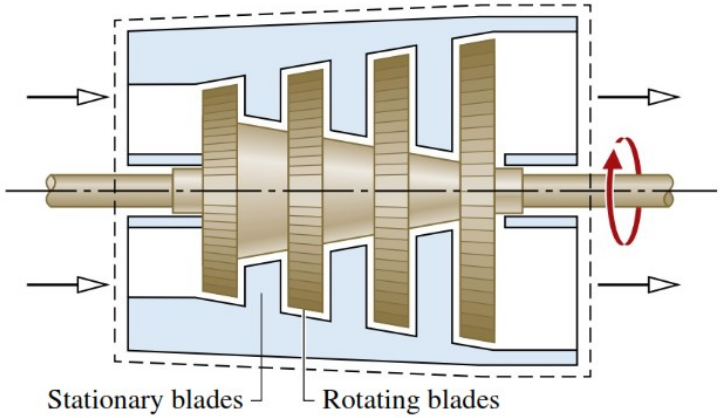
Topic: Control Volume analysis of 1st Law
Lecture – 7

Disclaimer:

The study materials/presentations are solely meant for academic purposes and they can be reused, reproduced, modified, and distributed by others for academic purposes only with proper acknowledgements.

Turbines:

- A turbine is a device in which **power is developed** as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate.



- Turbines are **widely used** for power generation in vapor **power plants, gas turbine power plants, and aircraft engines**.

- Turbines are also key components of **wind-turbine power plants** that, are renewable means for **generating electricity**.

- For a steam or gas turbine, the **net kinetic and potential energy** of the matter flowing across the boundary is usually **small enough to be neglected**. Therefore,

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}(h_1 - h_2)$$

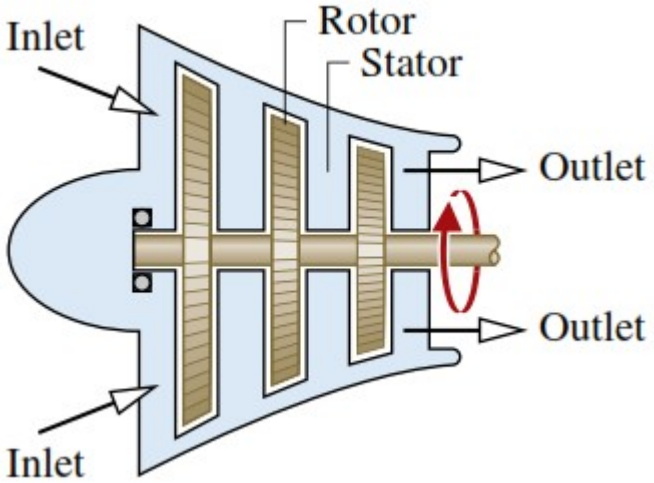
- Again, the heat transfer between the turbine and surroundings is **often small enough** relative to the power and enthalpy terms that it also **can be negl**

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$

Compressors and Pumps:

- Compressors and pumps are devices in which **work is done on the substance** flowing through them in order to typically **increase the pressure and/or elevation** of the substance.

- The term compressor is used **when the substance is a gas** (vapor) and the term pump is used **when the substance is a liquid**.
- The **axial-flow compressor** shown in figure is a key component of **turbojet engines**. Other types are reciprocating, centrifugal compressor, etc.



- The mass and energy rate balances reduce at steady state **as for the case of turbines**.

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$

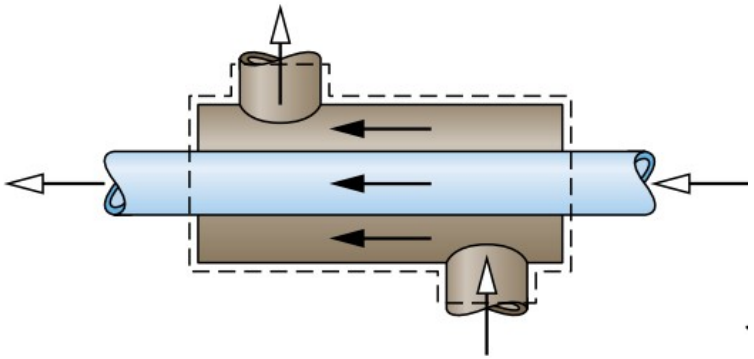
- Next we will discuss **heat exchangers**.

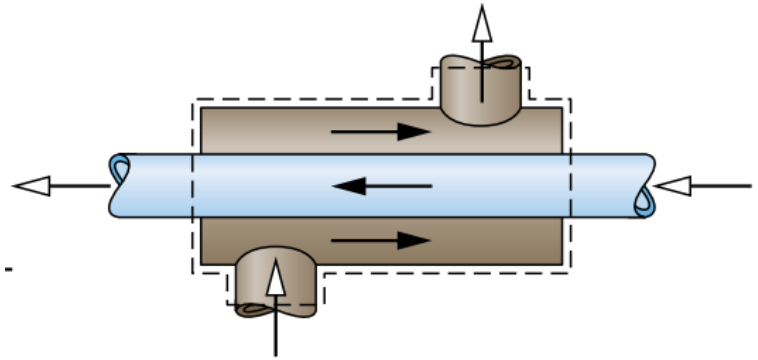
Heat exchanger:

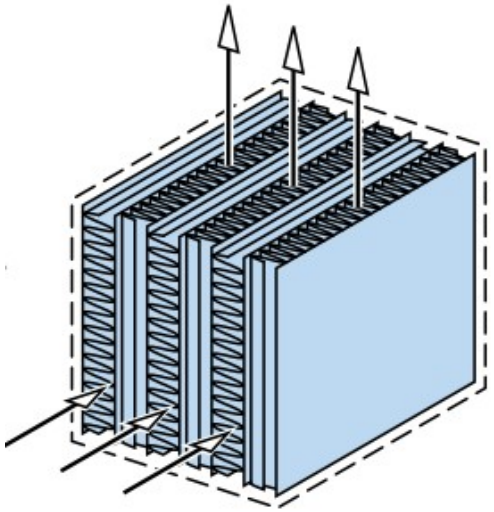
- Heat exchangers **are used in** home heating and cooling systems, automotive systems, electrical power generation, and chemical processing.

- A common type of heat exchanger is one in which a **gas or liquid is separated** from another gas or liquid by **a wall through which energy is conducted**.

- These heat exchangers take **many different forms**. **Counterflow**, **parallel flow** (having tube-within-a-tube) or **cross flow** configurations.







- Heat exchangers can involve **multiple inlets and exits**.

- For a control volume enclosing a heat exchanger, the **only work is flow work** at the places where matter enters and exits, so the term drops out of the energy rate balance.

- In addition, the **kinetic and potential energies** of the flowing streams usually **can be ignored** at the inlets and exits.

- Therefore, the energy rate balance reduces to

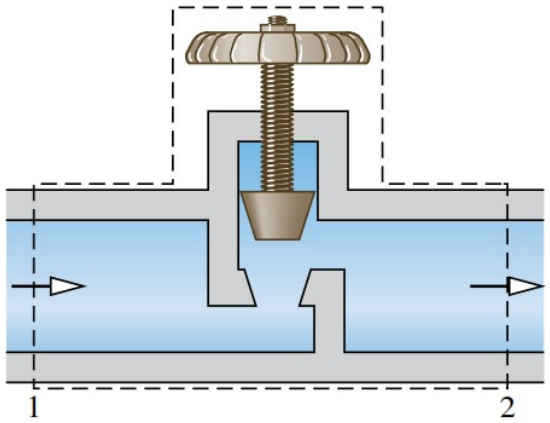
$$0 = \dot{Q}_{cv} + \sum_i \dot{m}_i h_i - \sum_e \dot{m}_e h_e$$

- Although high rates of energy transfer within the heat exchanger occur, **heat transfer with the surroundings is often small** enough to be neglected.

- Thus, the term of equation above would drop out.

Throttling device:

- A significant **reduction in pressure** can be achieved simply by **introducing a restriction** into a line through which a gas or liquid flows. This is commonly done by means of a **partially opened valve**, know as **throttling device**.
- An **application** of throttling occurs in **vapor-compression refrigeration** systems.



- For a control volume enclosing a throttling device, the **only work is flow work** at the places where matter enters and exits, so the term drops out of the energy rate balance.
- There is usually **no significant heat transfer** with the surroundings, and the **change in potential energy** from inlet to exit **is negligible**.
- Therefore, the energy rate balance reduces to:

$$0 = (h_1 - h_2) + \frac{V_1^2 - V_2^2}{2}$$

- Although velocities may be **relatively high** in the vicinity of the restriction, the **change in the specific kinetic energy** at upstream and downstream of the reduced flow area **can be neglected**.

- With this further simplification, $h_2 = h_1 \qquad (p_2 < p_1)$

- When the **flow through the valve or other restriction** is idealized in this way, the process is called a **throttling process**.

Transient analysis:

- Many devices undergo **periods of transient operation** during which the **state changes with time**. **Examples** include the startup or shutdown of turbines, compressors, and motors. **Additional examples** include vessels being filled or emptied.

- **The Mass Balance**: We begin by **integrating the mass rate balance** from time 0 to a final time t.

$$\int_0^t \left(\frac{dm_{cv}}{dt} \right) dt = \int_0^t \left(\sum_i \dot{m}_i \right) dt - \int_0^t \left(\sum_e \dot{m}_e \right) dt$$

- This **takes the form**

$$m_{cv}(t) - m_{cv}(0) = \sum_i \left(\underline{\int_0^t \dot{m}_i \, dt} \right) - \sum_e \left(\underline{\int_0^t \dot{m}_e \, dt} \right)$$

- Introducing the **symbols** for the underlined terms

$$m_i = \int_0^t \dot{m}_i \, dt \qquad m_e = \int_0^t \dot{m}_e \, dt$$

- the **mass balance** becomes,

$$m_{cv}(t) - m_{cv}(0) = \sum_i m_i - \sum_e m_e$$

- **The Energy Balance**: We integrate the energy rate balance, ignoring the effects of kinetic and potential energy.

$$U_{cv}(t) - U_{cv}(0) = Q_{cv} - W_{cv} + \sum_i \left(\underline{\int_0^t \dot{m}_i h_i \, dt} \right) - \sum_e \left(\underline{\int_0^t \dot{m}_e h_e \, dt} \right)$$

- For the **special case** where the states at the inlets and exits are constant with time

$$\int_0^t \dot{m}_i h_i \, dt = h_i \int_0^t \dot{m}_i \, dt = h_i m_i$$

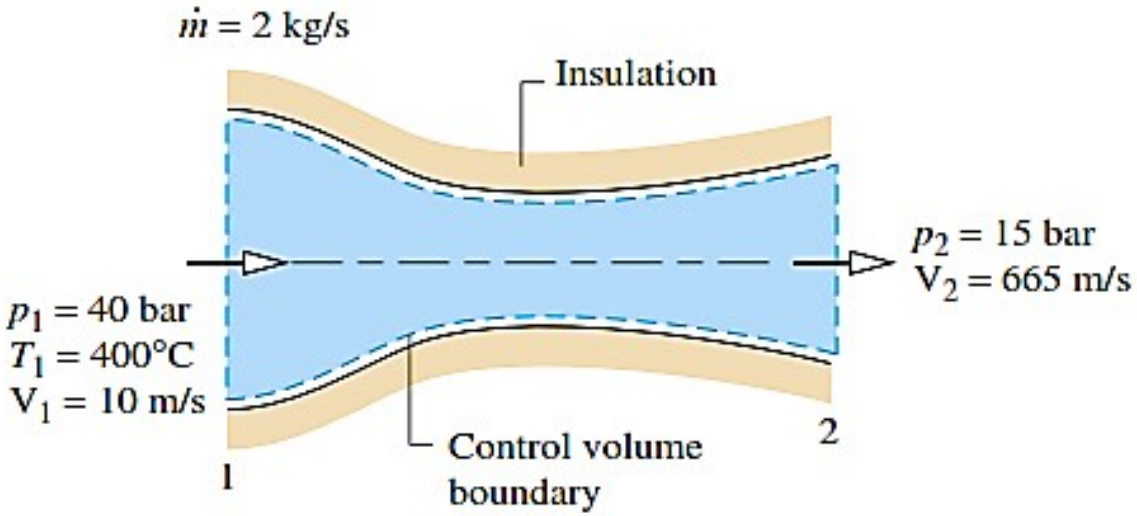
$$\int_0^t \dot{m}_e h_e \, dt = h_e \int_0^t \dot{m}_e \, dt = h_e m_e$$

- Energy balance equation takes the following **special form**,

$$U_{cv}(t) - U_{cv}(0) = Q_{cv} - W_{cv} + \sum_i m_i h_i - \sum_e m_e h_e$$

Numerical problems

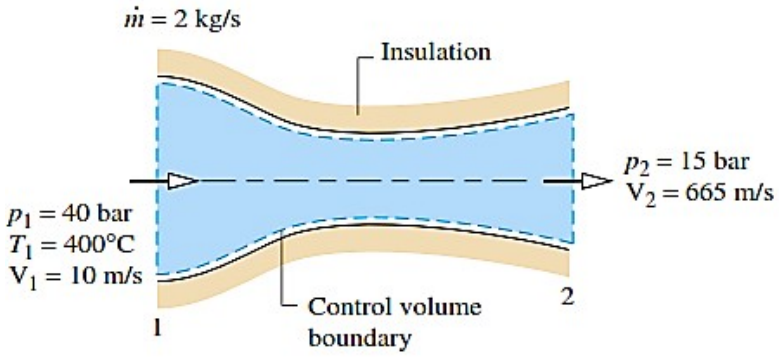
Problem: Steam enters a converging–diverging nozzle operating at steady state with = 40 bar, = 400°C, and a velocity of 10 m/s. The steam flows through the nozzle with negligible heat transfer and no significant change in potential energy. At the exit, = 15 bar, and the velocity is 665 m/s. The mass flow rate is 2 kg/s. Determine the exit area of the nozzle, in .



The **exit area** can be determined from $A_2 = \dfrac{\dot{m}v_2}{V_2}$

This requires the **specific volume** at the exit.

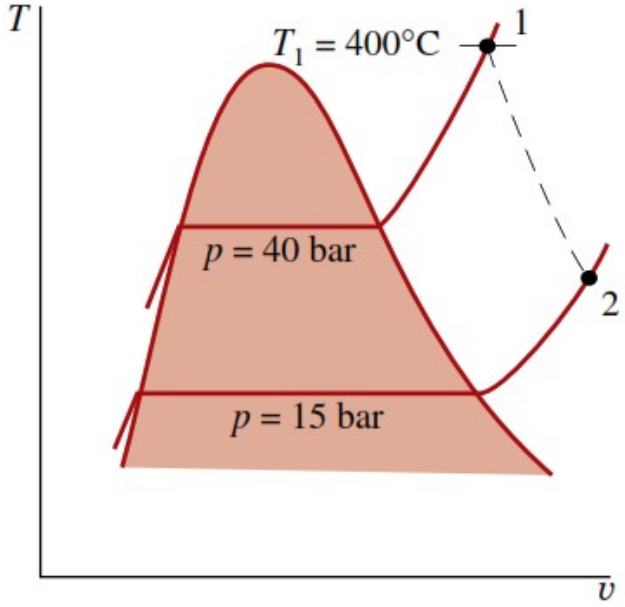
Now, the state at the exit is **fixed by the values of two independent intensive properties**.



Pressure (given) and specific enthalpy (**need to be evaluated**).

From the **steady-state energy rate balance**

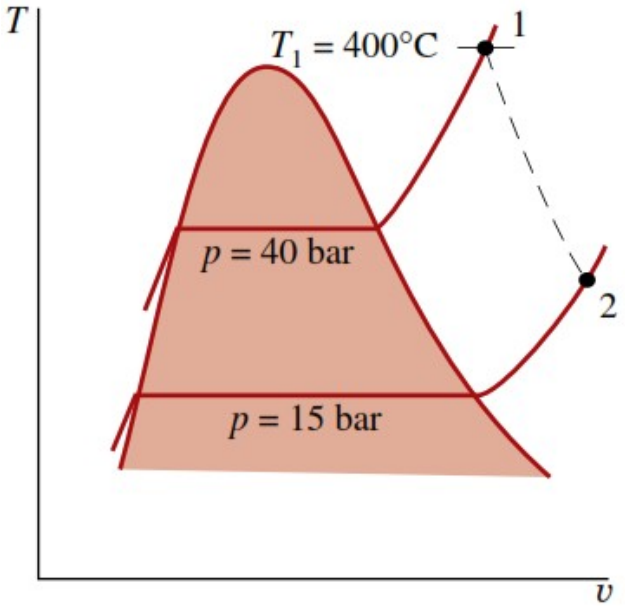
$$0 = \cancel{\dot{Q}}^{0}_{cv} - \cancel{\dot{W}}^{0}_{cv} + \dot{m}\left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)\right]$$



With **assumption**

$$0 = (h_1 - h_2) + \left(\frac{V_1^2 - V_2^2}{2}\right)$$

From **Table A-4**, = 3213.6 kJ/kg, = 2992.5 k J/ kg

From the Table $\upsilon_2 = 0.1627\ \text{m}^3/\text{kg}$

Therefore, the **exit area** is $A_2 = \dfrac{(2\ \text{kg/s})(0.1627\ \text{m}^3/\text{kg})}{665\ \text{m/s}} = 4.89 \times 10^{-4}\ \text{m}^2$