Heat & Mass Flow Processes

Week_01

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Mechanical Engineering Department

Course Outline

MT-364 Heat and Mass Flow Processes

Basic Concepts; Fourier's law; heat conduction equation; conduction through geometrical configurations, variable thermal conductivity, overall heat transfer coefficient, extended surfaces, heat flow in an infinitely thick plates; Convection: continuity equation; Forced Convection, boiling & condensation heat transfer; Thermal Radiations, surface emission properties, radiation properties of real surface, radiation heat exchange b/w surfaces, radiation shields; Heat Exchangers, Heat Exchanger Calculations; Modes of mass transfer, mass diffusion coefficient, convective mass transfer.

Course Outline

Recommended Books:

1. Heat and Mass Transfer by G. Kamaraj & P. Raveendiran (Text Book)
2. Heat Transfer, A Practical Approach by Y.A. Cengel (Reference Book)

Prerequisite: MT 234: Thermodynamics for Technologists

Introduction & Basic Concepts of Heat Transfer

What is Heat Transfer?

Difference between Heat and Temperature:

- *Temperature* is a measure of the amount of energy possessed by the molecules of a substance. It manifests itself as a degree of hotness, and can be used to predict the direction of heat transfer. The usual symbol for temperature is *T*. The scales for measuring temperature in SI units are the Celsius and Kelvin temperature scales.

- *Heat*, on the other hand, is energy in transit. The form of energy that can be transferred from one system to another as a result of temperature difference. Spontaneously, heat flows from a hotter body to a colder one. The usual symbol for heat is Q. In the SI system, common units for measuring heat are the Joule and calorie.

Introduction & Basic Concepts of Heat Transfer

Difference between Thermodynamics and Heat Transfer

Thermodynamics is concerned with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another.

Thermodynamics tells us:

- how much heat is transferred (dQ)
- how much work is done (dW)
- final state of the system

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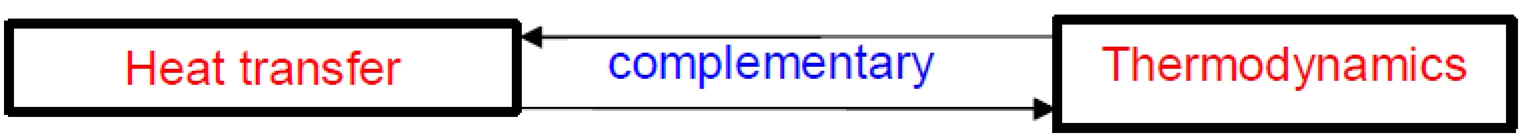
Difference between Thermodynamics and Heat Transfer

Heat Transfer deals with the determination of the *rates* of such energy transfers as well as variation of temperature.

Heat Transfer tells us:

- how (with what **modes**) dQ is transferred
- at what **rate** dQ is transferred
- temperature distribution inside the body



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Modern Theory of Heat:

The kinetic energy of each molecule of the substance is proportional to its absolute temperature

Molecules do have

- Vibrational Energy
- Rotational Energy
- Translational Energy

Kinetic energy of a molecule is the sum of these three energies

Heat Transfer in Engineering

- Transmission of energy from one region to another
- Due to this change in temperature, temperature gradient exists

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Purpose of Heat Transfer

- To calculate the rate of flow of energy as heat under both steady and transient conditions.
- To calculate the temperature field.

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Application Areas of Heat Transfer

The human body
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Air conditioning systems
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Heating systems
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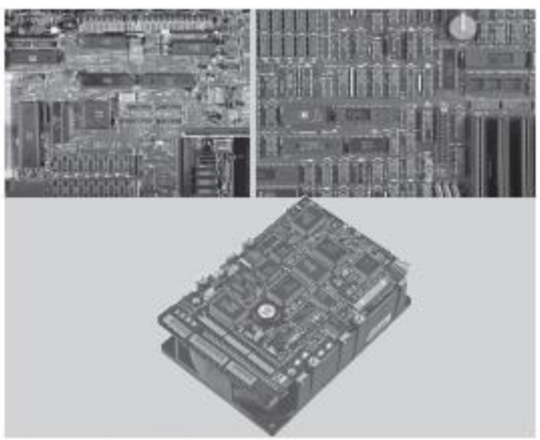

Electronic equipment

Power plants

Refrigeration systems

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ENGINEERING HEAT TRANSFER

Heat transfer equipment such as heat exchangers, boilers, condensers, radiators, heaters, furnaces, refrigerators, and solar collectors are designed primarily on the basis of heat transfer analysis.

The heat transfer problems encountered in practice can be considered in two groups: (1) *rating* and (2) *sizing* problems.

The rating problems deal with the determination of the heat transfer rate for an existing system at a specified temperature difference.

The sizing problems deal with the determination of the size of a system in order to transfer heat at a specified rate for a specified temperature difference.

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ENGINEERING HEAT TRANSFER

An engineering device or process can be studied either *experimentally* (testing and taking measurements) or *analytically* (by analysis or calculations).

The experimental approach has the advantage that we deal with the actual physical system, and the desired quantity is determined by measurement, within the limits of experimental error. However, this approach is expensive, time consuming, and often impractical.

The analytical approach (including the numerical approach) has the advantage that it is fast and inexpensive, but the results obtained are subject to the accuracy of the assumptions, approximations, and idealizations made in the analysis.

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Thermodynamic Properties:

The most of general sense of thermodynamics is the study of energy and its relationship to the properties of matter. All activities in nature involve some interaction between energy and matter. Thermodynamics is a science that governs the following:

- Energy and its transformation
- Feasibility of a process involving transformation of energy
- Feasibility of a process involving transfer of energy
- Equilibrium processes

More specifically, thermodynamics deals with energy conversion, energy exchange and the direction of exchange.

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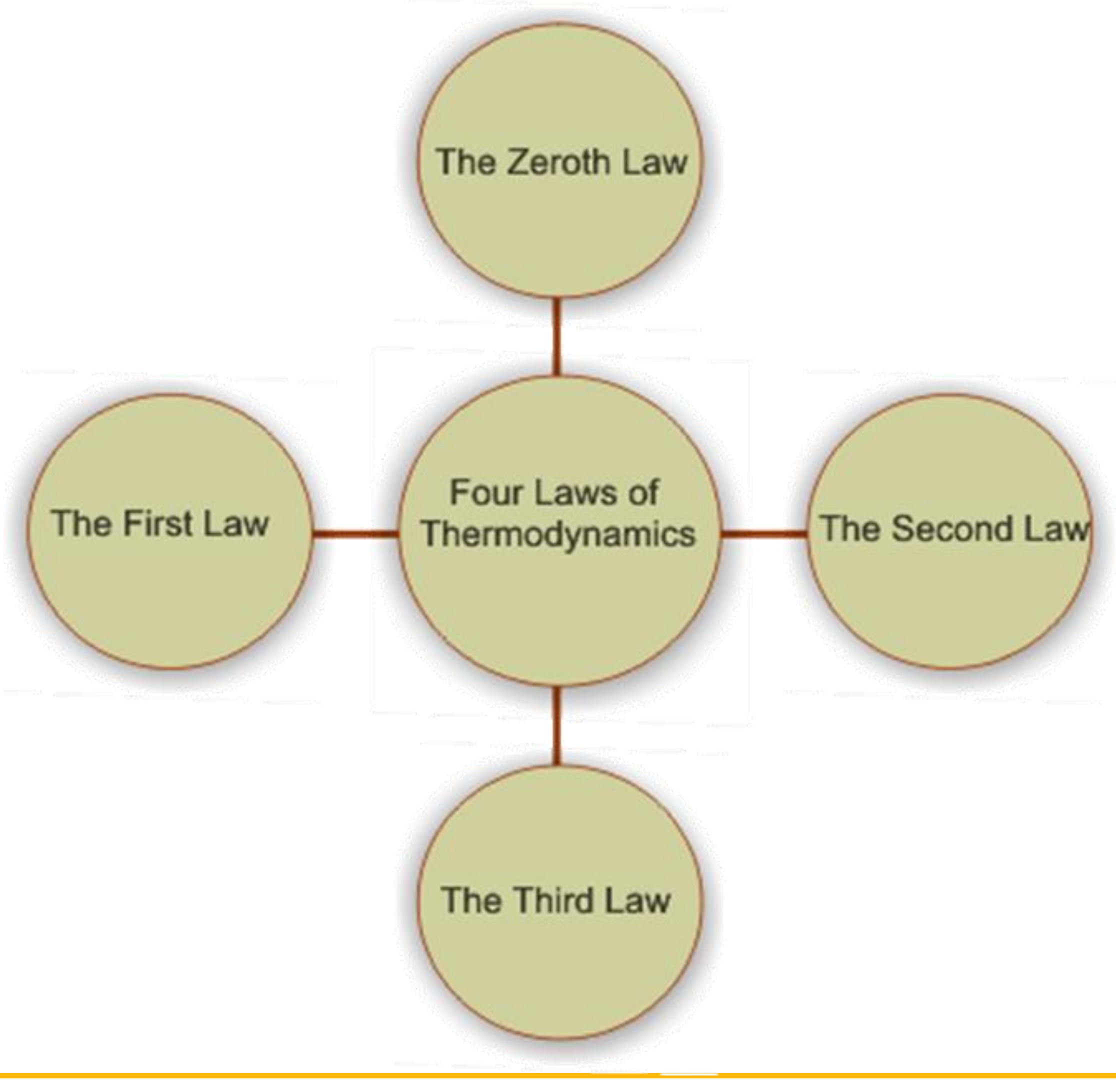
Basic Laws of Thermodynamics:



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- **The Zeroth Law** deals with thermal equilibrium and provides a means for measuring temperatures.
- **The First Law** deals with the conservation of energy and introduces the concept of internal energy.
- **The Second Law** of thermodynamics provides with the guidelines on the conversion of internal energy of matter into work. It also introduces the concept of entropy.
- **The Third Law** of thermodynamics defines the absolute zero of entropy. The entropy of a pure crystalline substance at absolute zero temperature is zero.

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Thermodynamic Systems:

System: A thermodynamic system is defined as a definite quantity of matter or a region in space upon which attention is focussed in the analysis of a problem. We may want to study a quantity of matter contained with in a closed rigid walled chambers, or we may want to consider something such as gas pipeline through which the matter flows. The composition of the matter inside the system may be fixed or may change through chemical and nuclear reactions. A system may be arbitrarily defined. It becomes important when exchange of energy between the system and the everything else outside the system is considered. The judgment on the energetics of this exchange is very important.

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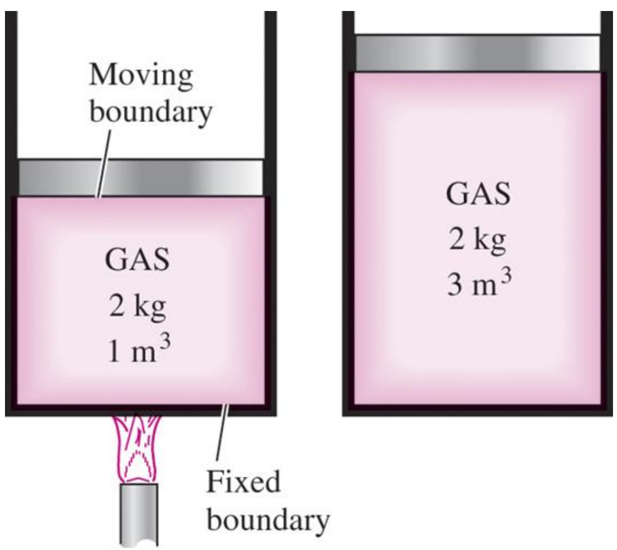
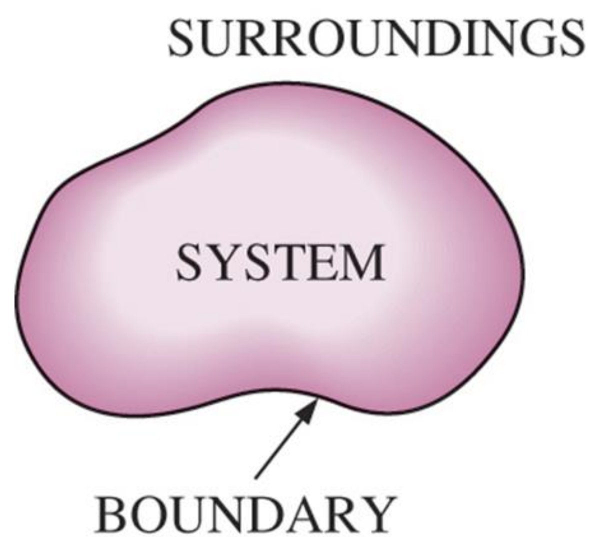
Surroundings:

Everything external to the system is surroundings. The system is distinguished from its surroundings by a specified boundary which may be at rest or in motion. The interactions between a system and its surroundings, which take place across the boundary, play an important role in thermodynamics. A system and its surroundings together comprise a universe.





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Types of systems:

Two types of systems can be distinguished. These are referred to, respectively, as closed systems and open systems or control volumes. A closed system or a control mass refers to a fixed quantity of matter, whereas a control volume is a region in space through which mass may flow. A special type of closed system that does not interact with its surroundings is called an Isolated system .

Two types of exchange can occur between the system and its surroundings:

- energy exchange (heat or work) and
- exchange of matter (movement of molecules across the boundary of the system and surroundings).

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Types of systems:

Based on the types of exchange, one can define

- **isolated systems:** no exchange of matter and energy
- **closed systems:** no exchange of matter but some exchange of energy
- **open systems:** exchange of both matter and energy

If the boundary does not allow heat (energy) exchange to take place it is called adiabatic boundary otherwise it is diathermal boundary.

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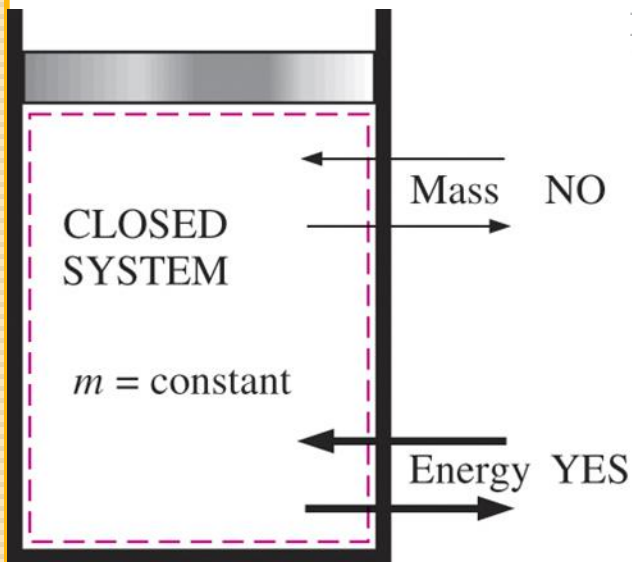
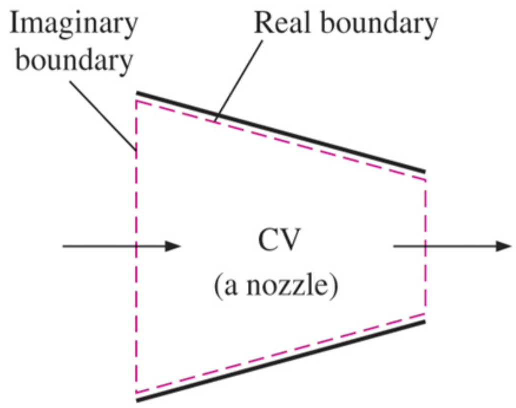
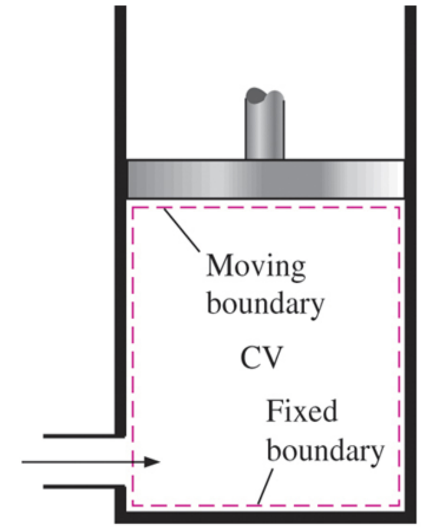
Types of systems:





(*a*) A control volume with real and imaginary boundaries



(*b*) A control volume with fixed and moving boundaries

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Thermodynamic Approach:

Thermodynamics can be studied through two different approaches:

(a) Macroscopic Approach and

(b) Microscopic Approach

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Macroscopic Approach:

Consider a certain amount of gas in a cylindrical container. The volume (V) can be measured by measuring the diameter and the height of the cylinder. The pressure (P) of the gas can be measured by a pressure gauge. The temperature (T) of the gas can be measured using a thermometer. The state of the gas can be specified by the measured P, V and T . The values of these variables are space averaged characteristics of the properties of the gas under consideration. In classical thermodynamics, we often use this macroscopic approach.

The macroscopic approach has the following features.

- The structure of the matter is not considered.
- A few variables are used to describe the state of the matter under consideration.
- The values of these variables are measurable following the available techniques of experimental physics.

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Microscopic Approach:

On the other hand, the gas can be considered as assemblage of a large number of particles each of which moves randomly with independent velocity. The state of each particle can be specified in terms of position coordinates (x_i , y_i , z_i) and the momentum components (p_{xi} , p_{yi} , p_{zi}). If we consider a gas occupying a volume of 1 cm^3 at ambient temperature and pressure, the number of particles present in it is of the order of 10^{20} . The same number of position coordinates and momentum components are needed to specify the state of the gas. The microscopic approach can be summarized as:

- A knowledge of the molecular structure of matter under consideration is essential.
- A large number of variables are needed for a complete specification of the state of the matter.

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Thermodynamic Equilibrium:

- A system is said to be in an equilibrium state if its properties will not change without some perceivable effect in the surroundings.
- Equilibrium generally requires all properties to be uniform throughout the system.
- There are mechanical, thermal, phase, and chemical equilibrium.

Nature has a preferred way of directing changes.eg:

- water flows from a higher to a lower level
- Electricity flows from a higher potential to a lower one
- Heat flows from a body at higher temperature to the one at a lower temperature
- Momentum transfer occurs from a point of higher pressure to a lower one.
- Mass transfer occurs from higher concentration to a lower one

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Types of Equilibrium

Between the system and surroundings, if there is no difference in

- Pressure → Mechanical equilibrium
- Potential → Electrical equilibrium
- Concentration of species → Species equilibrium
- Temperature → Thermal equilibrium

No interactions between them occur. They are said to be in equilibrium. Thermodynamic equilibrium implies all those together. A system in thermodynamic equilibrium does not deliver anything.

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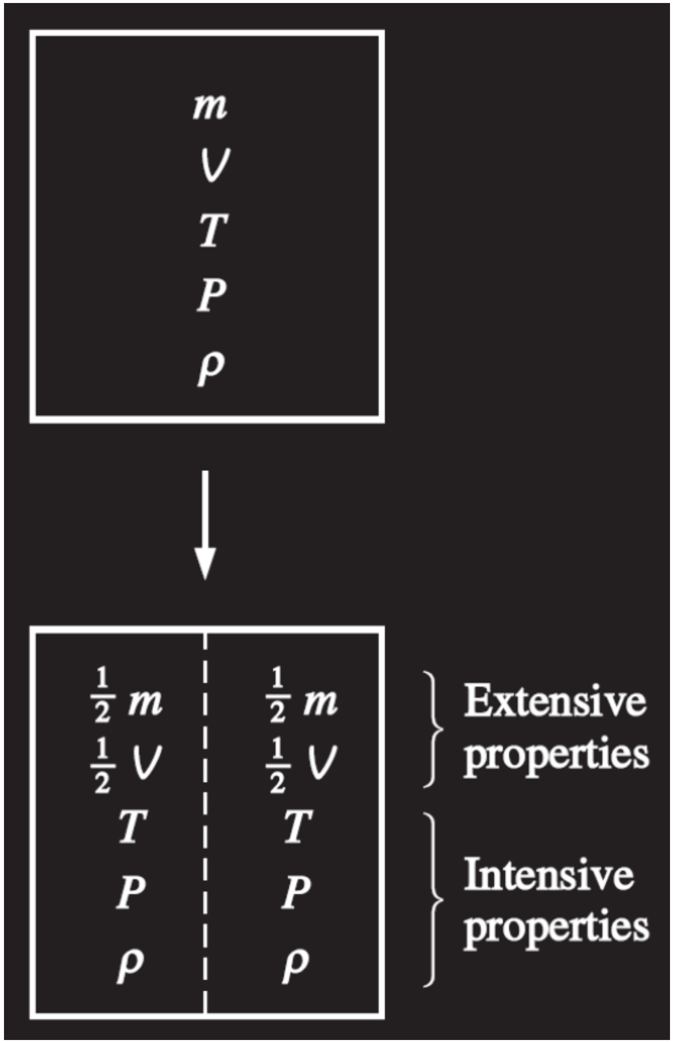
Property: Any characteristic of a system. Some familiar properties are pressure P, temperature T, volume V, and mass m. Properties are considered to be either intensive or extensive.

Intensive properties: Those that are independent of the mass of a system, such as temperature, pressure, and density.

Extensive properties: Those whose values depend on the size—or extent—of the system.

Specific properties: Extensive properties per unit mass.



Criterion to differentiate intensive and extensive properties.

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The ratio of the extensive property to the mass is called the specific value of that property .

specific volume, $v = V/m = 1/\rho$ (ρ is the density)

specific internal energy, $u = U/m$

Similarly, the molar properties are defined as the ratios of the properties to the mole number (N) of the substance

Molar volume $= v = V/N$

Molar internal energy $= u = U/N$

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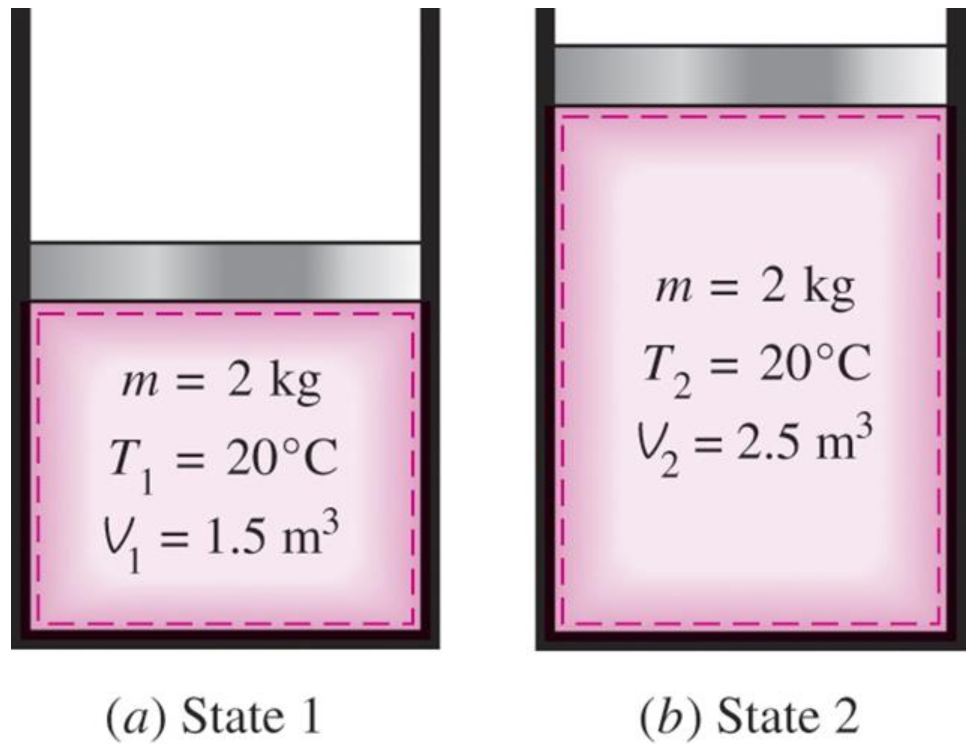
State:

It is the condition of a system as defined by the values of all its properties. It gives a complete description of the system. Any operation in which one or more properties of a system change is called a change of state.



A system at two different states.

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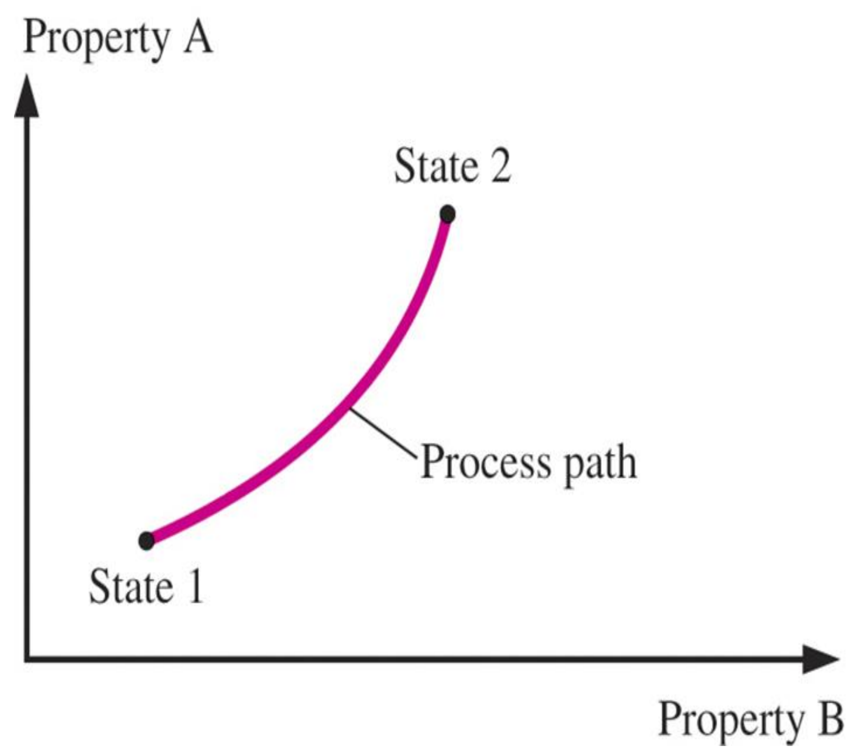
PROCESSES AND CYCLES

Process: Any change that a system undergoes from one equilibrium state to another.

Path: The series of states through which a system passes during a process.

To describe a process completely, one should specify the initial and final states, as well as the path it follows, and the interactions with the surroundings.



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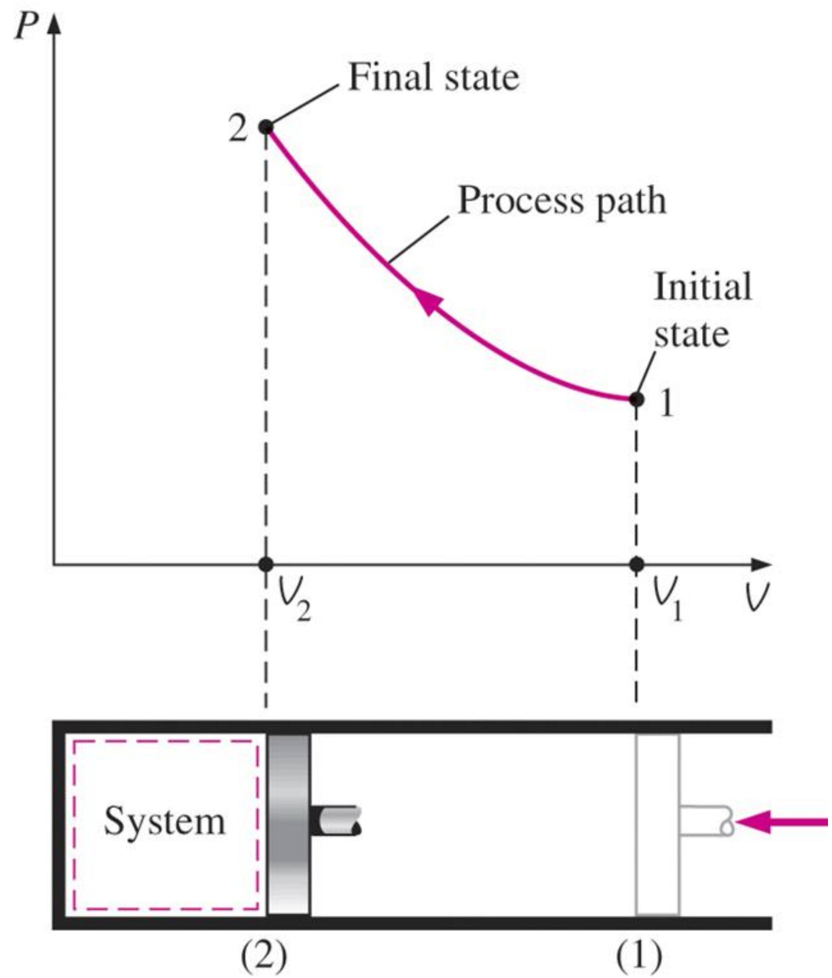
- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature *T*, pressure *P*, and volume *V* (or specific volume *v*).
- The prefix iso- is often used to designate a process for which a particular property remains constant.



The *P*-*V* diagram of a compression process.

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Types of Processes

- As a matter of rule we allow one of the properties to remain a constant during a process.
- Construe as many processes as we can (with a different property kept constant during each of them)
- Complete the cycle by regaining the initial state

(1)Isothermal (T)
(2) Isobaric (p)
(3) Isochoric (v)
(4) Isentropic (s)
(5) Isenthalpic (h)
(6) Isosteric (concentration)
(7) Adiabatic (no heat addition or removal

Cycle: A process during which the initial and final states are identical.

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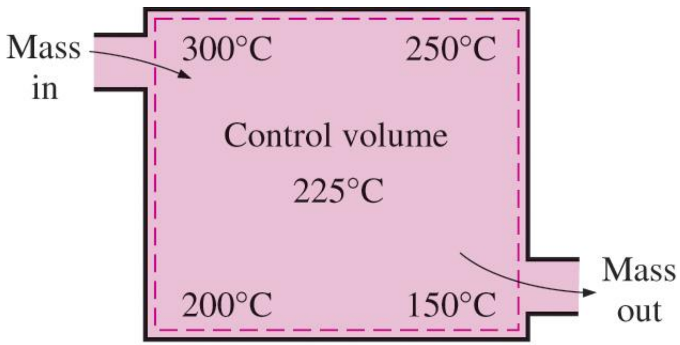
The Steady-Flow Process:

- The term steady implies no change with time. The opposite of steady is unsteady, or transient.

- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as steady-flow devices.



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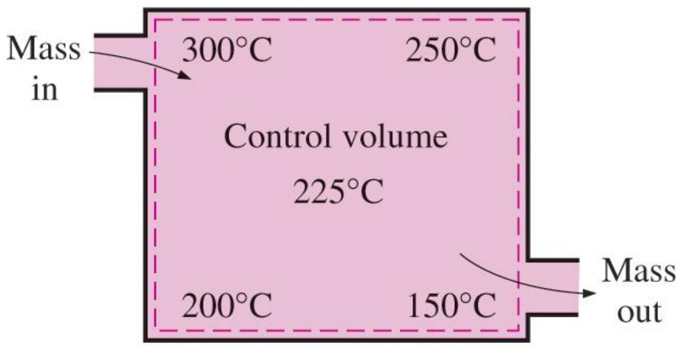

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During a steady-flow process, fluid properties within the control volume may change with position but not with time.

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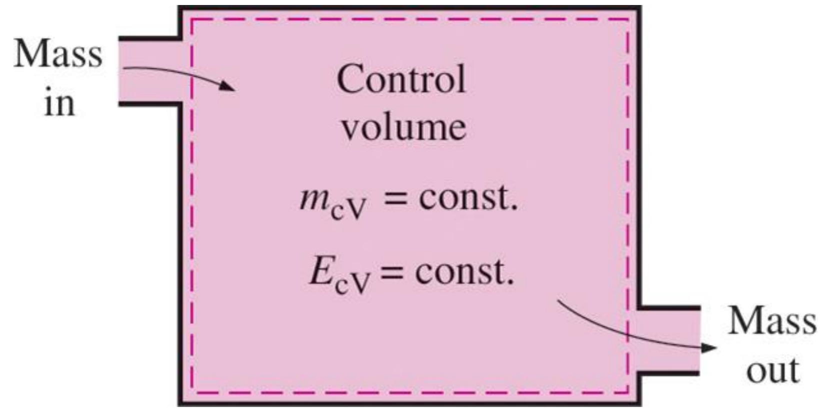
➢ **Steady-flow process**: A process during which a fluid flows through a control volume steadily.



Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

➢ Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

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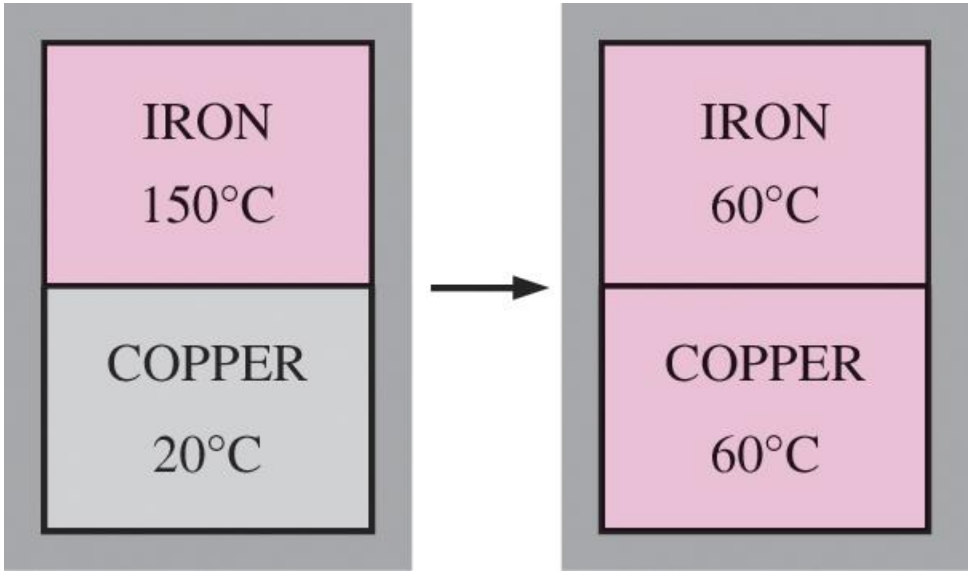
TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

- The zeroth law of thermodynamics: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.



Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

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Temperature Scales:

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point.*
- Ice point: A mixture of ice and water that is in equilibrium with air saturated with vapor at 1 atm pressure (0°C or 32°F).
- Steam point: A mixture of liquid water and water vapor (with no air) in equilibrium at 1 atm pressure (100°C or 212°F).
- Celsius scale: in SI unit system
- Fahrenheit scale: in English unit system
- **Thermodynamic temperature scale**: A temperature scale that is independent of the properties of any substance.
- Kelvin scale (SI) Rankine scale (E)

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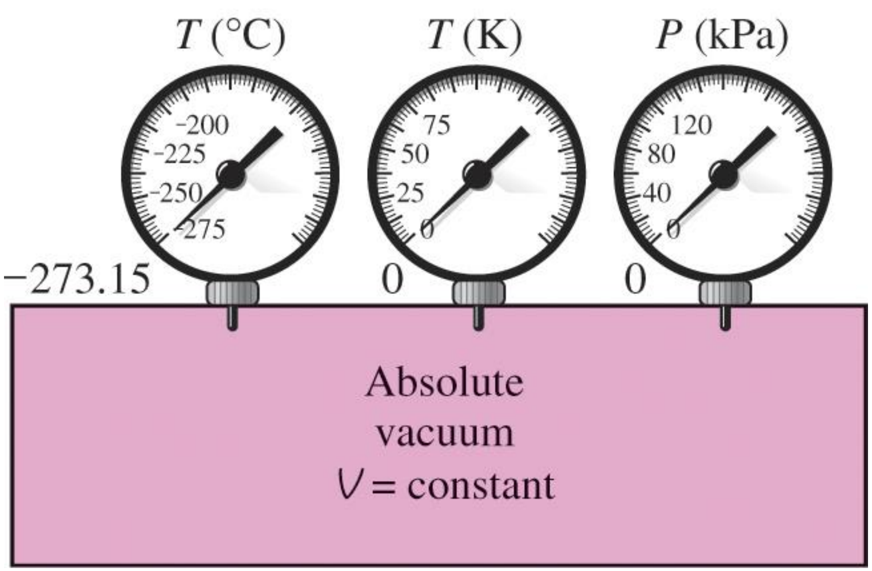
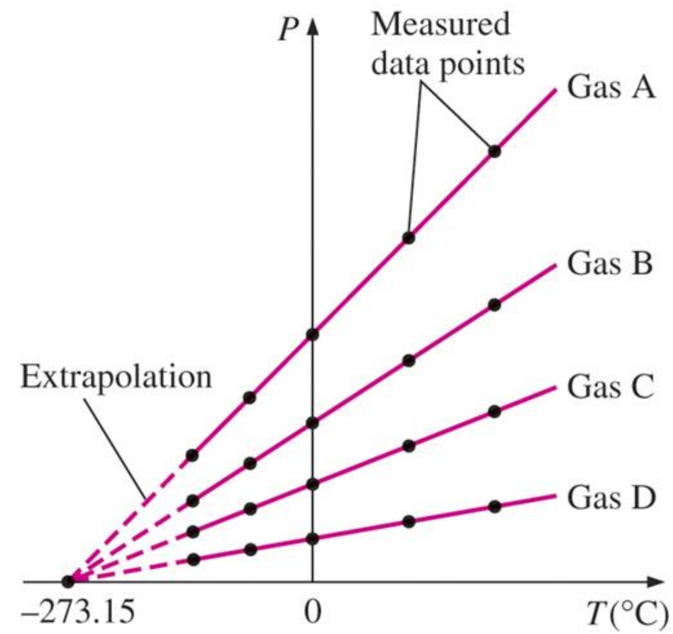
Temperature Scales:

- A temperature scale nearly identical to the Kelvin scale is the ideal-gas temperature scale. The temperatures on this scale are measured using a constant-volume gas thermometer.



A constant-volume gas thermometer would read -273.15°C at absolute zero pressure.



P versus *T* plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.

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$$T(\text{K}) = T(°\text{C}) + 273.15$$

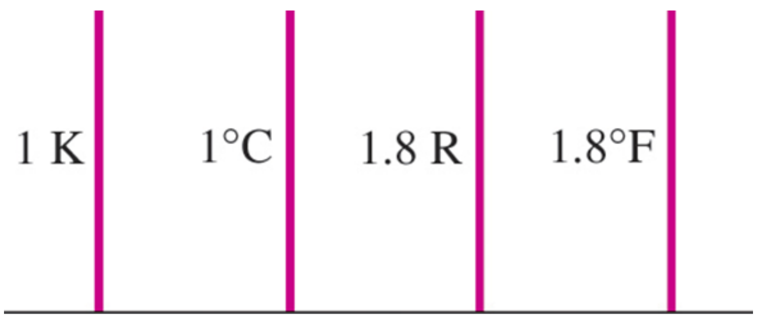
$$T(\text{R}) = T(°\text{F}) + 459.67$$

$$T(\text{R}) = 1.8T(\text{K})$$

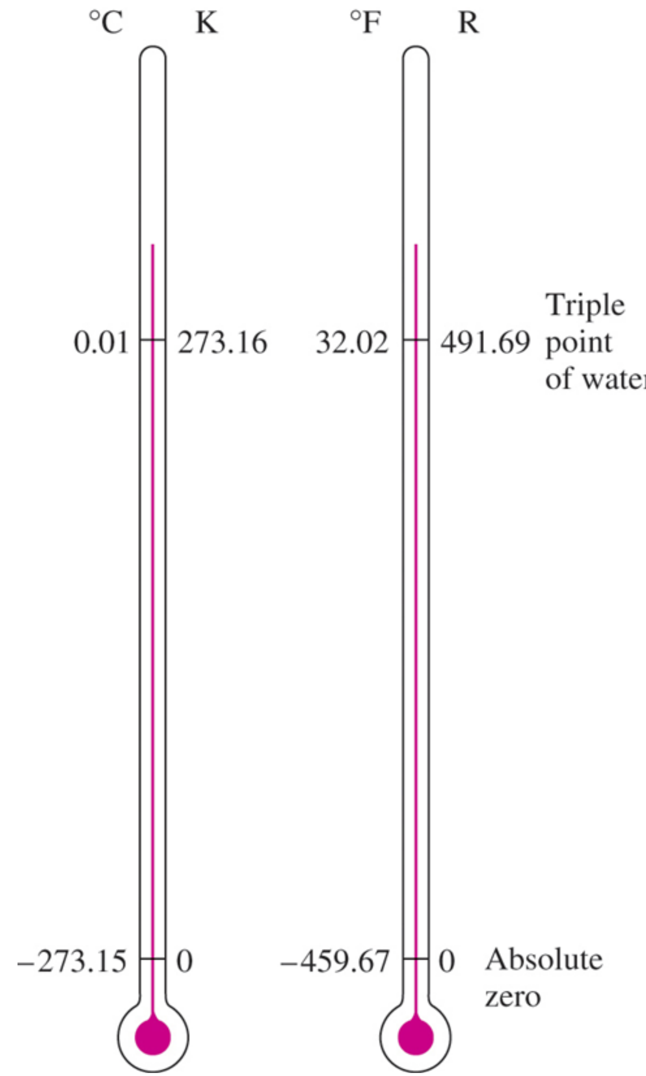
$$T(°\text{F}) = 1.8T(°\text{C}) + 32$$

$$\Delta T(\text{K}) = \Delta T(°\text{C})$$

$$\Delta T(\text{R}) = \Delta T(°\text{F})$$



Comparison of magnitudes of various temperature units.



Comparison of temperature scales.

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- The reference temperature in the original Kelvin scale was the **ice point**, 273.15 K, which is the temperature at which water freezes (or ice melts).
- The reference point was changed to a much more precisely reproducible point, the **triple point** of water (the state at which all three phases of water coexist in equilibrium), which is assigned the value 273.16 K.

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PRESSURE:

Pressure is defined as a normal force exerted by a fluid per unit area. We speak of pressure only when we deal with a gas or a liquid. The counterpart of pressure in solids is normal stress. Since pressure is defined as force per unit area, it has the unit of newton per square meter (N/m^2), which is called a Pascal (Pa). That is,

$$1 \text{ Pa} = 1 \text{ N/m}^2$$

The pressure unit Pascal is too small for pressures encountered in practice. Therefore, its multiples kilopascal ($1 \text{ kPa} = 10^3 \text{ Pa}$) and mega Pascal ($1 \text{ MPa} = 10^6 \text{ Pa}$) are commonly used. Three other pressure units commonly used in practice, especially in Europe, are bar, standard atmosphere, and kilogram-force per square centimeter:

$$1 \text{ bar} = 10^5 \text{ pa} = 0.1 \text{ MPa} = 100\text{kPa} : 1 \text{ atm} = 101{,}325 \text{ pa} = 101.325\text{kPa} = 1.01325\text{bars}$$

$$1\text{kgf/cm}^3 = 9.807\text{N/cm}^3 = 9.807 \times 10^4\text{N/m}^2 = 9.807 \times 10^4\text{Pa} = 0.9807\text{bar} = 0.9679\text{atm}$$

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- **Absolute pressure**: The actual pressure at a given position. It is measured relative to absolute vacuum (i.e., absolute zero pressure).
- **Gage pressure**: The difference between the absolute pressure and the local atmospheric pressure. Most pressure-measuring devices are calibrated to read zero in the atmosphere, and so they indicate gage pressure.
- **Vacuum pressures**: Pressures below atmospheric pressure.

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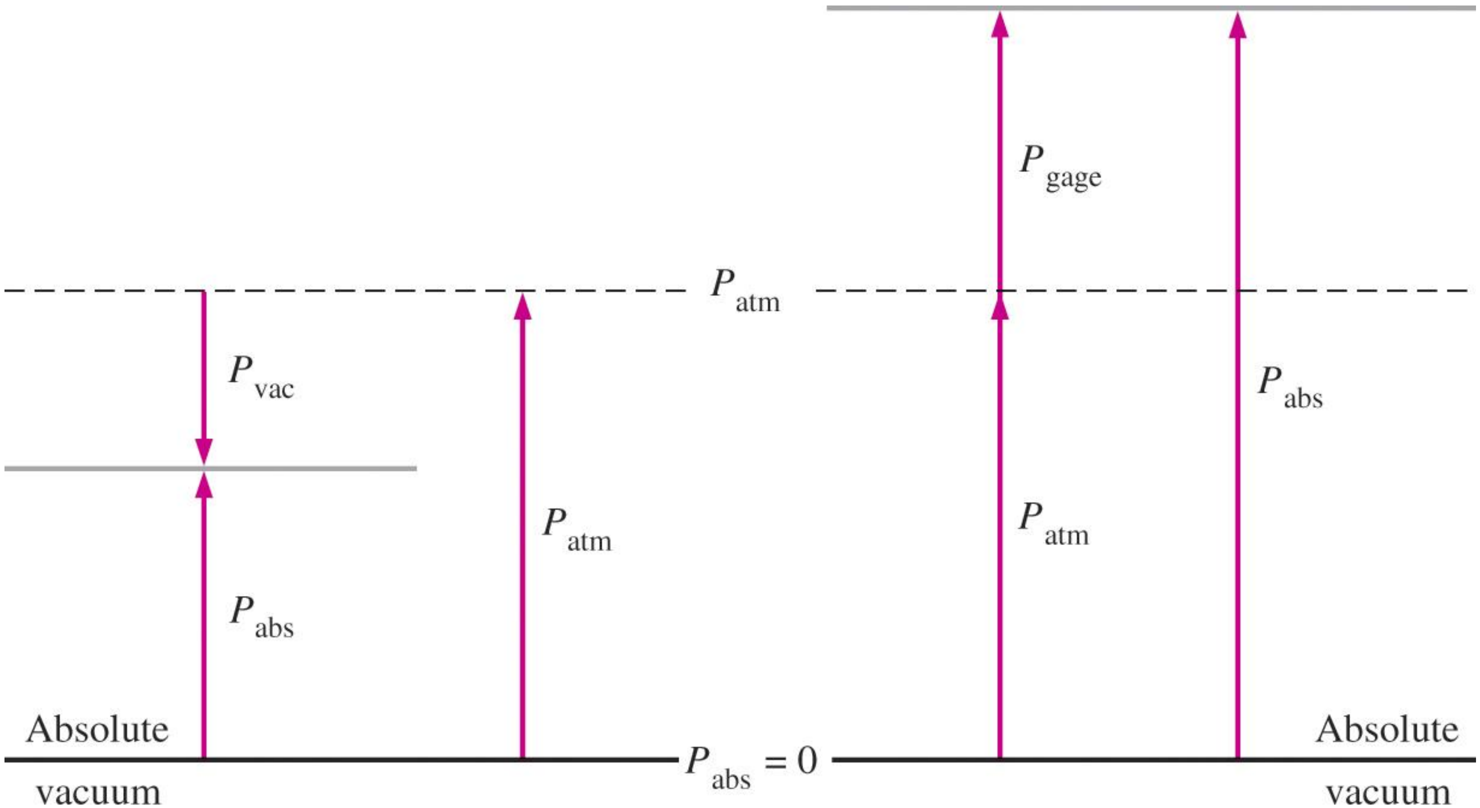

$$P_{gage} = P_{abs} - P_{atm}$$

$$P_{vac} = P_{atm} - P_{abs}$$

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Variation of Pressure with Depth:

- Pressure in a fluid at rest does not change in the horizontal direction. This can be shown easily by considering a thin horizontal layer of fluid and doing a force balance in any horizontal direction. However, this is not the case in the vertical direction in a gravity field.
- Pressure in a fluid increases with depth because more fluid rests on deeper layers, and the effect of this “extra weight” on a deeper layer is balanced by an increase in pressure.

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Energy:

- Energy is the ability to do work and work is the transfer of energy from one form to another.
- In practical terms, energy is what we use to manipulate the world around us, whether by exciting our muscles, by using electricity, or by using mechanical devices such as automobiles.
- Energy comes in different forms - heat (thermal), light (radiant), mechanical, electrical, chemical, and nuclear energy.. In SI, the unit of energy is Newton-meter, N m or Joule, J.

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Forms of Energy

Energy is found in different forms, such as light, heat, sound, and motion. There are many forms of energy, but they can all be put into two categories: potential and kinetic.

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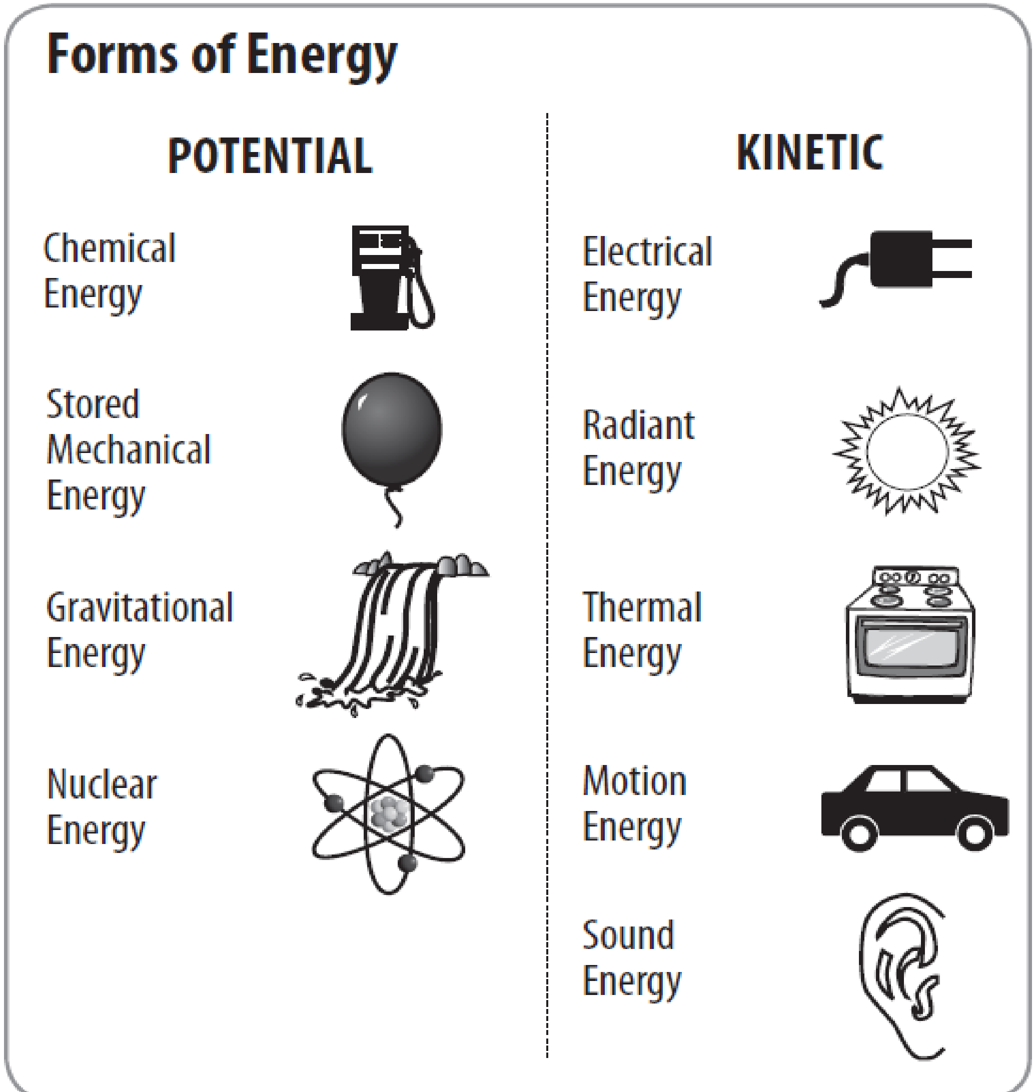

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Potential Energy

- **Potential energy** is stored energy and the energy of position, or gravitational energy. There are several forms of potential energy.
- **Chemical energy** is energy stored in the bonds of atoms and molecules. It is the energy that holds these particles together. Biomass, petroleum, natural gas, and propane are examples of stored chemical energy.
- **Stored mechanical energy** is energy stored in objects by the application of a force. Compressed springs and stretched rubber bands are examples of stored mechanical energy.

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- **Nuclear energy** is energy stored in the nucleus of an atom; it is the energy that holds the nucleus together. The energy can be released when the nuclei are combined or split apart. Nuclear power plants split the nuclei of uranium atoms in a process called **fission**. The sun combines the nuclei of hydrogen atoms in a process called **fusion**.
- **Gravitational energy** is the energy of position or place. A rock resting at the top of a hill contains gravitational potential energy. Hydropower, such as water in a reservoir behind a dam, is an example of gravitational potential energy.

Kinetic Energy

- **Kinetic energy** is motion; it is the motion of waves, electrons, atoms, molecules, substances, and objects.

- **Electrical energy** is the movement of electrons. Everything is made of tiny particles called atoms. Atoms are made of even smaller particles called electrons, protons, and neutrons. Applying a force can make some of the electrons move. Electrons moving through a wire is called circuit electricity. Lightning is another example of electrical energy.

- **Radiant energy** is electromagnetic energy that travels in transverse waves. Radiant energy includes visible light, x-rays, gamma rays, and radio waves. Solar energy is an example of radiant energy.

Introduction & Basic Concepts of Heat Transfer

- **Thermal energy**, or heat, is the internal energy in substances; it is the vibration and movement of the atoms and molecules within substances. The more thermal energy in a substance, the faster the atoms and molecules vibrate and move. Geothermal energy is an example of thermal energy.

- **Motion energy** is the movement of objects and substances from one place to another. Objects and substances move when a force is applied according to Newton's Laws of Motion. Wind is an example of motion energy.

- **Sound energy** is the movement of energy through substances in longitudinal (compression/rarefaction) waves. Sound is produced when a force causes an object or substance to vibrate; the energy is transferred through the substance in a longitudinal wave.

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Heat: Heat is an energy which appears at boundary when the system changes its state due to difference in temperature.

Work: Work, appears at boundary when the system changes its state due to movement of a part under the action of force.

Basic Laws Governing Heat Transfer

1. First Law of Thermodynamics
2. Second Law of Thermodynamics
3. Law of Conservation of Mass
4. Newton's Law of Motion
5. The rate Equation

Introduction & Basic Concepts of Heat Transfer

1. First Law of Thermodynamics: It is based on " Law of Conservation of Energy".

- Energy can neither be created nor be destroyed.
- When a system undergoes a thermodynamic cycle, then the net heat supplied to the system from the surroundings is equal to the net work done by the system on its surroundings.

$$\oint \delta Q = \oint \delta W$$

- It is for both reversible and irreversible transformations

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Closed System:

Net heat across the system boundary + Heat generated in the system = Change in internal energy.

Open System:

Net energy through the volume + Energy generated in the volume = Change in internal energy in the control volume.

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2. Second Law of Thermodynamics:

- Heat will flow naturally from one to another reservoir which is at lower temperature.
- It states that heat flows in the direction of lower temperature, i.e. hot body to cold body (Source to Sink).

3. Law of Conservation of Mass:

- It is used to determine the flow parameters.

5. Newton’s law of motion:

- It is used to determine the fluid flow parameters.

6. Rate Equations:

- These equations are used for application purposes depending upon the heat transfer mode.

Introduction & Basic Concepts of Heat Transfer

Modes of Heat Transfer

Conduction: An energy transfer across a system boundary due to a temperature difference by the mechanism of intermolecular interactions. Conduction needs matter and does not require any bulk motion of matter. OR

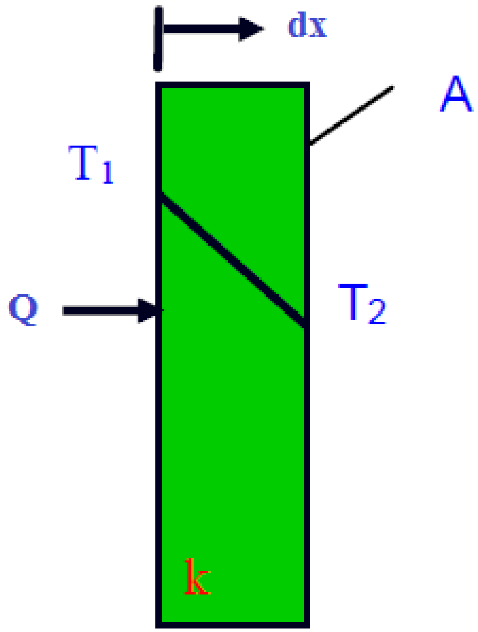
The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.

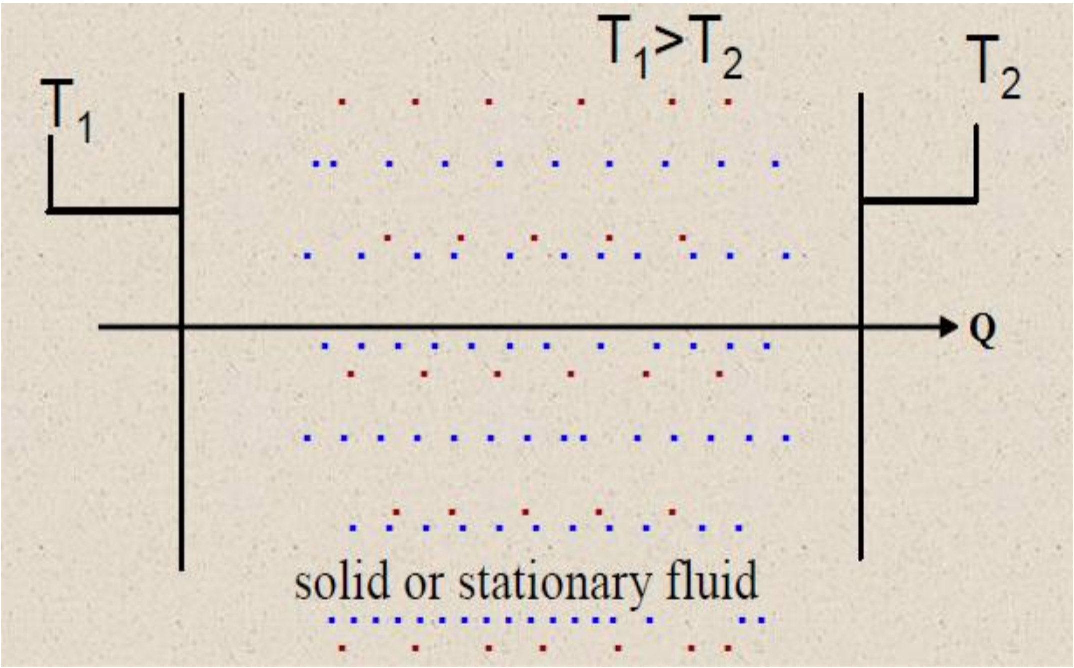
In gases and liquids, conduction is due to the *collisions* and *diffusion* of the molecules during their random motion.

In solids, it is due to the combination of *vibrations* of the molecules in a lattice and the energy transport by *free electrons*.

The rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer.

Modes of Heat Transfer





Introduction & Basic Concepts of Heat Transfer

Fourier's Law of Heat Conduction:

It states that" Rate of flow of heat through a homogeneous solid is directly proportional to the area of the solid at right angles to the direction of heat flow and to change the temperature with respect to the length of the heat flow.

$$Q \alpha A(T_2 - T_1) / dx$$

$$Q = -KA \frac{dT}{dx} = -\frac{dT}{R_{cond}}$$

Where,

Q = Rate of Heat Transfer

A = Surface Area of wall

dT = Temp Gradiant (Final Temp - Initial Temp)

dx = Thickness of the wall

K = Thermal conductivity of the material

R_{cond} = Conductive Resistance

Introduction & Basic Concepts of Heat Transfer

Assumptions of Fourier's Law;

- Heat flow is unidirectional
- Conduction of heat under steady state condition.
- No internal heat generation
- Material is homogeneous and isotropic (K is constant at all directions)

Thermal Conductivity(k):

It is defined as the amount of energy conducted through a body of unit area and unit thickness in unit time, when the difference in temperature is unity. i.e

$$k = \frac{Q.dx}{A.dT}$$

UNITS OF "K": The units of "k" are W/mK or W/m°C.

Introduction & Basic Concepts of Heat Transfer

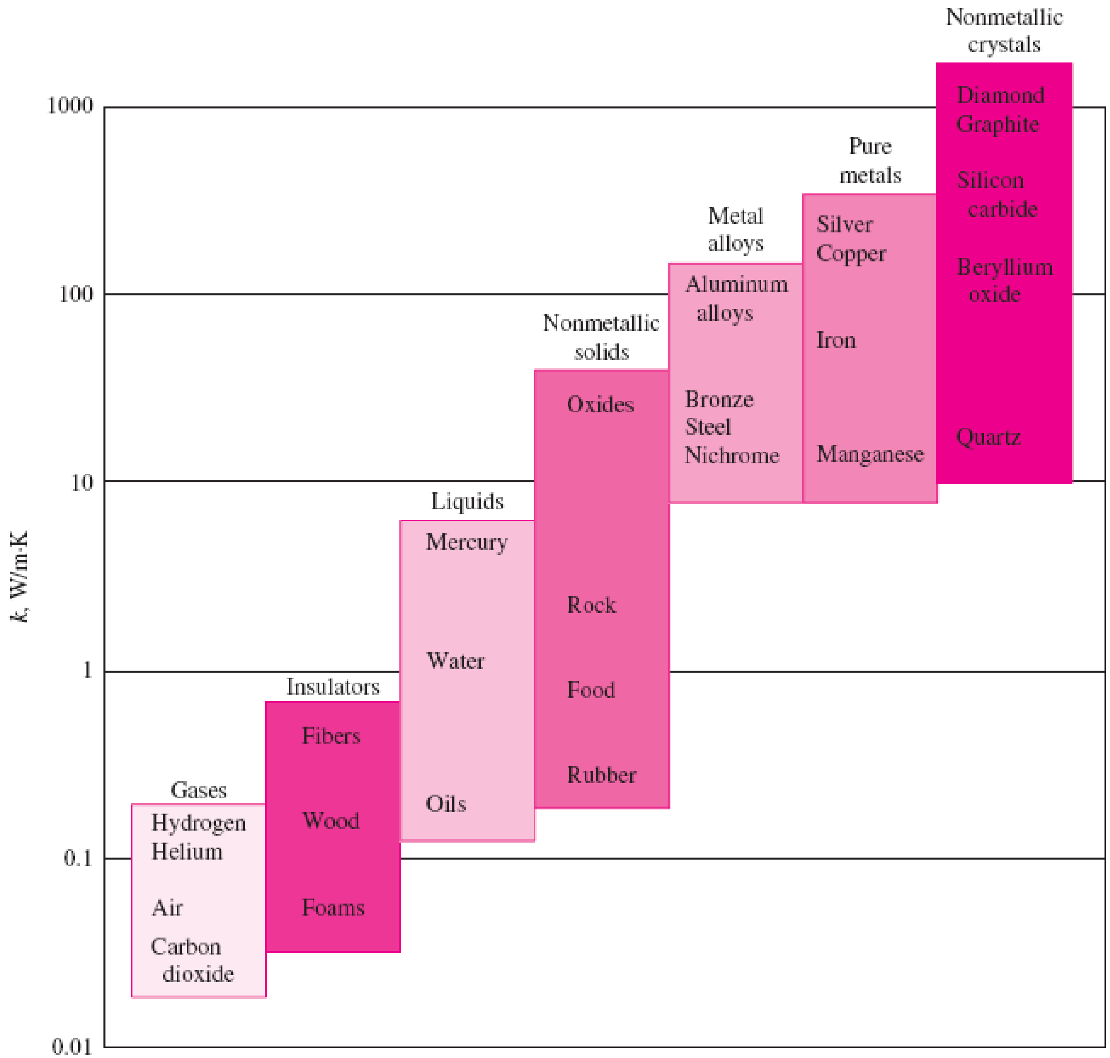
Thermal conductivity depends on, or the factors affecting thermal conductivity are:

1. Material Structure
2. Moisture
3. Density
4. Pressure and temperature

The thermal conductivity of a material is a measure of the ability of the material to conduct heat.

A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or *insulator*.

Introduction & Basic Concepts of Heat Transfer



The range of thermal conductivity of various materials at room temperature

Thermal Diffusivity

c_p Specific heat, J/kg · °C: Heat capacity per unit mass

ρc_p Heat capacity, J/m³·°C: Heat capacity per unit volume

α Thermal diffusivity, m²/s: Represents how fast heat diffuses through a material

$$\alpha = \frac{\text{Heat conduction}}{\text{Heat storage}} = \frac{k}{\rho c_p} \qquad (\text{m}^2/\text{s})$$

A material that has a high thermal conductivity or a low heat capacity will obviously have a large thermal diffusivity.

The larger the thermal diffusivity, the faster the propagation of heat into the medium.

A small value of thermal diffusivity means that heat is mostly absorbed by the material and a small amount of heat is conducted further.

The thermal diffusivities of some materials at room temperature

Material	α, m²/s*
Silver	149×10^{-6}
Gold	127×10^{-6}
Copper	113×10^{-6}
Aluminum	97.5×10^{-6}
Iron	22.8×10^{-6}
Mercury (l)	4.7×10^{-6}
Marble	1.2×10^{-6}
Ice	1.2×10^{-6}
Concrete	0.75×10^{-6}
Brick	0.52×10^{-6}
Heavy soil (dry)	0.52×10^{-6}
Glass	0.34×10^{-6}
Glass wool	0.23×10^{-6}
Water (l)	0.14×10^{-6}
Beef	0.14×10^{-6}
Wood (oak)	0.13×10^{-6}

Introduction & Basic Concepts of Heat Transfer

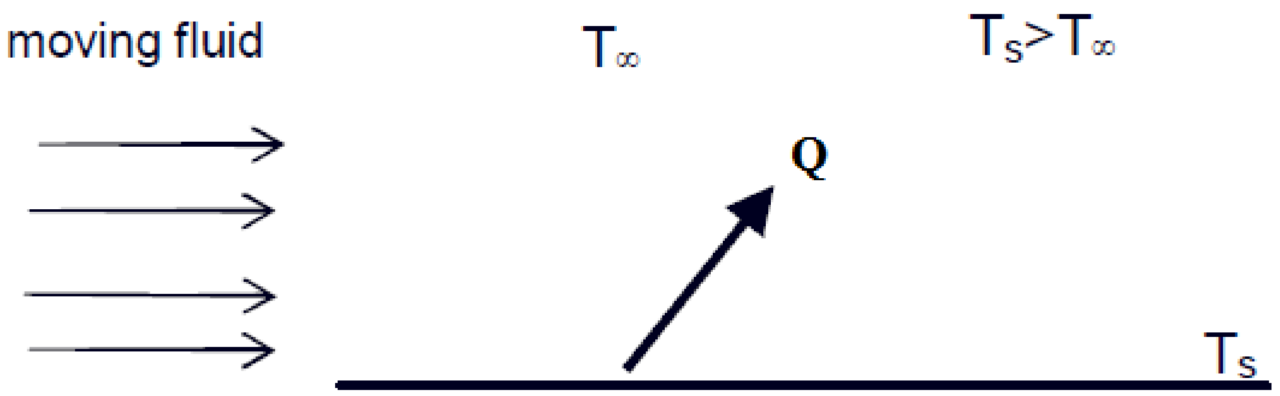
Convection: An energy transfer across a system boundary due to a temperature difference by the combined mechanisms of intermolecular interactions and bulk transport. Convection needs fluid matter. OR

The mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of *conduction* and *fluid motion*.

The faster the fluid motion, the greater the convection heat transfer.

In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction.

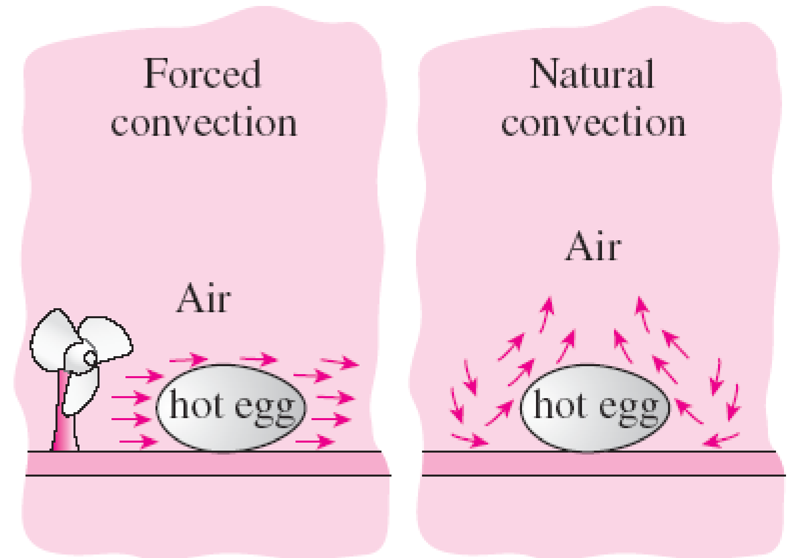
Introduction & Basic Concepts of Heat Transfer



Introduction & Basic Concepts of Heat Transfer

Forced convection: If the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind.

Natural (or free) convection: If the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid.



The cooling of a boiled egg by forced and natural convection.

Heat transfer processes that involve *change of phase* of a fluid are also considered to be convection because of the fluid motion induced during the process, such as the rise of the vapor bubbles during boiling or the fall of the liquid droplets during condensation.

Introduction & Basic Concepts of Heat Transfer

NEWTON'S LAW OF COOLING: It states that; The rate of heat Transfer is directly proportional to the Temperature Gradient and the convective resistance of the fluid medium.

$$Q \alpha A(T\infty - Ts)$$

$$Q = h\ A\ dT$$

$$Q = dT/(1/hA) = dT/R_{conv}$$

Here:

Q = Rate of Heat Transfer

A = Surface Area of conducting surface

dT = Temperature Gradiant.

h = convection Heat Transfer co-efficient.

R_{conv} = convective Resistance

UNITS OF" h": The units of "h" are $\frac{W}{m^2K}$ or $\frac{W}{m^2{}^\circ C}$

Introduction & Basic Concepts of Heat Transfer

The convection heat transfer coefficient *h* is not a property of the fluid.

It is an experimentally determined parameter whose value depends on all the variables influencing convection such as

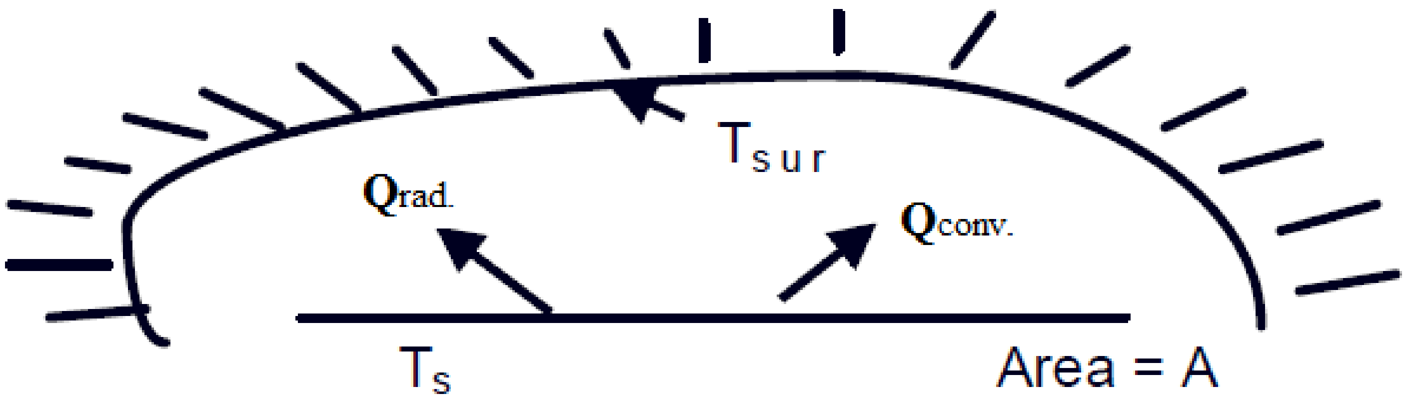
- the surface geometry
- the nature of fluid motion
- the properties of the fluid
- the bulk fluid velocity

Typical values of convection heat transfer coefficient

Type of convection	h, W/m^2 · °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

Introduction & Basic Concepts of Heat Transfer

Radiation: Radiation heat transfer involves the transfer of heat by electromagnetic radiation that arises due to the temperature of the body. Radiation does not need matter.



Introduction & Basic Concepts of Heat Transfer

- Radiation: The energy emitted by matter in the form of *electromagnetic waves* (or *photons*) as a result of the changes in the electronic configurations of the atoms or molecules.
- Unlike conduction and convection, the transfer of heat by radiation does not require the presence of an *intervening medium*.
- In fact, heat transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.
- In heat transfer studies we are interested in *thermal radiation*, which is the form of radiation emitted by bodies because of their temperature.
- All bodies at a temperature above absolute zero emit thermal radiation.
- Radiation is a *volumetric phenomenon*, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees.
- However, radiation is usually considered to be a *surface phenomenon* for solids.

Stefan-Boltzmann Law: This law states that the emissive power of a black body is directly proportional to the fourth power of its absolute temperature. i.e.

$$Q \propto \varepsilon A F_{1-2}(T_s^4 - T_{sur}^4)$$

$$Q = \sigma \varepsilon A F_{1-2}(T_s^4 - T_{sur}^4)$$

$$Q = \frac{(T_s^4 - T_{sur}^4)}{1/\sigma \varepsilon A F_{1-2}} = \frac{(T_s^4 - T_{sur}^4)}{R_{rad}}$$

Here

F_{1-2} = view factor or shape factor or configuration factor.

σ = Stephen Boltzmann constant.

$\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$

ε = Surface emissivity

R_{rad} = Radiative Resistance.

Introduction & Basic Concepts of Heat Transfer

Blackbody: The idealized surface that emits radiation at the maximum rate.

Emissivity ε: A measure of how closely a surface approximates a blackbody for which $\varepsilon = 1$ of the surface. $0 \leq \varepsilon \leq 1$.

Radiation emitted by real surfaces

Emissivities of some materials at 300 K

Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Blackbody radiation represents the *maximum amount of radiation that can be emitted from a surface at a specified temperature.*

Introduction & Basic Concepts of Heat Transfer

Net radiation heat transfer: The difference between the rates of radiation emitted by the surface and the radiation absorbed.

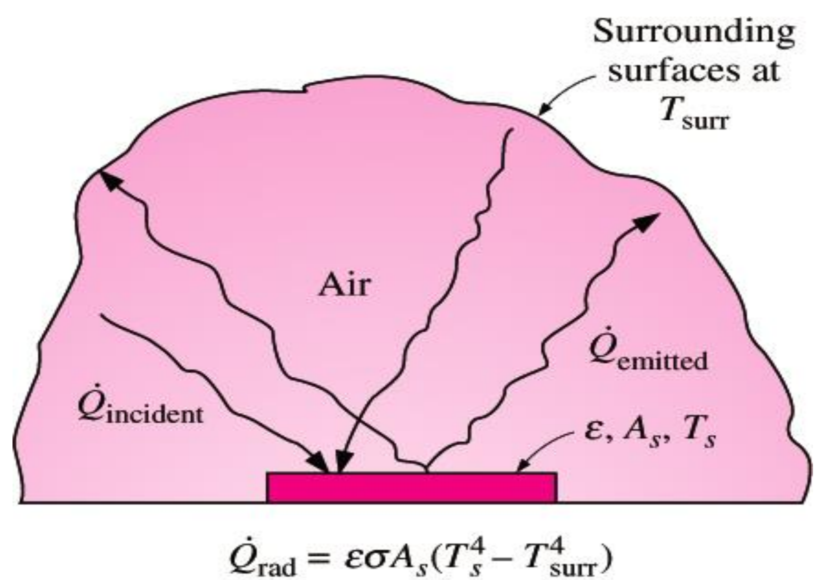
The determination of the net rate of heat transfer by radiation between two surfaces is a complicated matter since it depends on

- the properties of the surfaces
- their orientation relative to each other
- the interaction of the medium between the surfaces with radiation

Radiation is usually significant relative to conduction or natural convection, but negligible relative to forced convection.

When a surface is *completely enclosed* by a much larger (or black) surface at temperature T_{surr} separated by a gas (such as air) that does not intervene with radiation, the net rate of radiation heat transfer between these two surfaces is given by

$$\dot{Q}_{rad} = \varepsilon \sigma A_s (T_s^4 - T_{surr}^4) \qquad \text{(W)}$$



Radiation heat transfer between a surface and the surfaces surrounding it.

Introduction & Basic Concepts of Heat Transfer

SIMULTANEOUS HEAT TRANSFER MECHANISMS

Heat transfer is only by conduction in *opaque solids*, but by conduction and radiation in *semitransparent solids.*

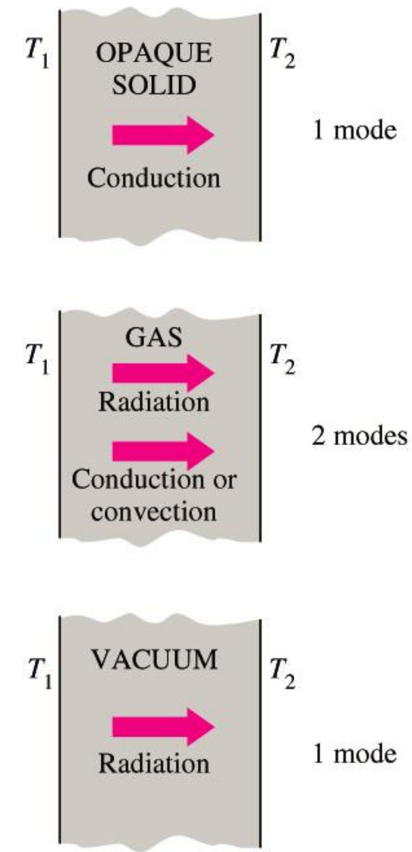
A solid may involve conduction and radiation but not convection. A solid may involve convection and/or radiation on its surfaces exposed to a fluid or other surfaces.

Heat transfer is by conduction and possibly by radiation in a *still fluid* (no bulk fluid motion) and by convection and radiation in a *flowing fluid.*

In the absence of radiation, heat transfer through a fluid is either by conduction or convection, depending on the presence of any bulk fluid motion.

Convection = Conduction + Fluid motion

Heat transfer through a *vacuum* is by radiation.



Most gases between two solid surfaces do not interfere with radiation.

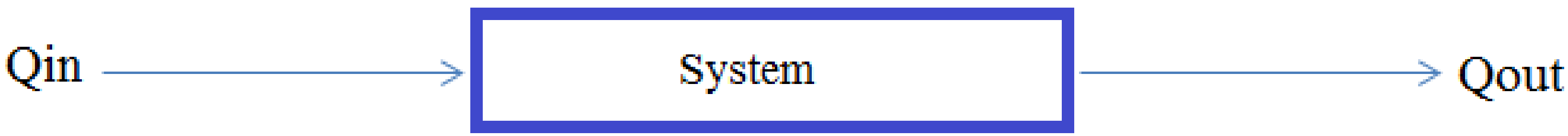
Liquids are usually strong absorbers of radiation.

Although there are three mechanisms of heat transfer, a medium may involve only two of them simultaneously.

Introduction & Basic Concepts of Heat Transfer

STEADY STATE SYSTEM:

If the properties of system are not changing w.r.t time then the system is said to be in steady state.



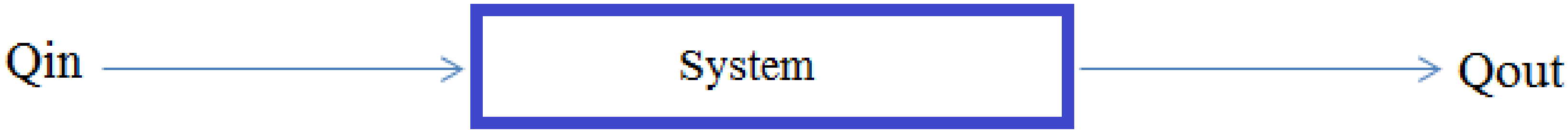
$$Q_{in} - Q_{out} = 0$$

$$Q_{in} = Q_{out}$$

Introduction & Basic Concepts of Heat Transfer

UNSTEADY STATE SYSTEM:

If the properties of the system are changing w.r.t time, then the system is said to be in unsteady state.



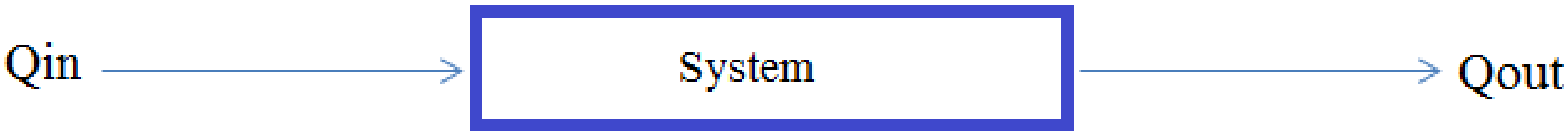
$$Q_{in} - Q_{out} \neq 0$$

$$Q_{in} \neq Q_{out}$$

Introduction & Basic Concepts of Heat Transfer

COOLING PROCESS:

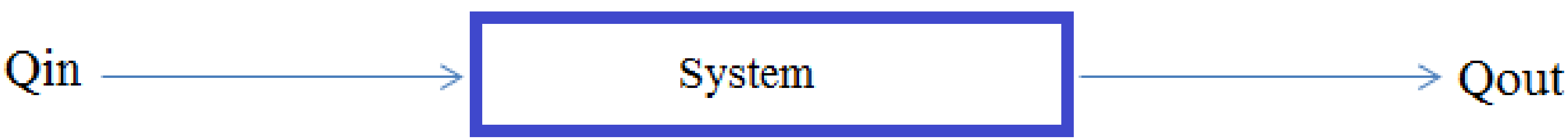
If "Q_{in}"is less than "Q_{out}" Then there will be a cooling process. i.e.



$$Q_{in} < Q_{out}$$

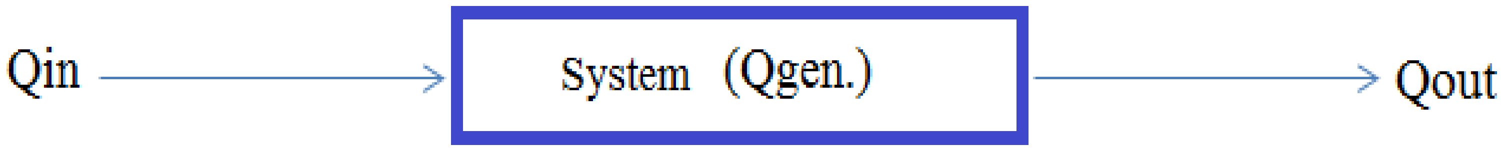
HEATING PROCESS:

IF "Q_{in}"is greater than "Q_{out}" then there will be a heating process. i.e.



$$Q_{in} > Q_{out}$$

THERMODYNAMIC SYSTEMS WITH INTERNAL GENRATION



$$Qin + Qgen. - Qout = 0 \rightarrow (S.S)$$

$$Qin + Qgen. = Qout \rightarrow (S.S)$$

$$Qin + Qgen. - Qout \neq 0 \rightarrow (U.S.S)$$

$$Qin + Qgen. \neq Qout \rightarrow (U.S.S)$$

$$Qin + Qgen. < Qout \rightarrow (cooling)$$

$$Qin + Qgen. > Qout \rightarrow (heating)$$

Introduction & Basic Concepts of Heat Transfer

→ Heat flows in all direction like light; we have,

$$q' = \frac{Q}{L} = Rate\ of\ heat\ transfer\ per\ unit\ length.$$

$$q'' = \frac{Q}{A} = Rate\ of\ heat\ transfer\ per\ unit\ Area.$$

$$q''' = \frac{Q}{V} = Rate\ of\ heat\ transfer\ per\ unit\ Volume.$$

Example 1.1:

A stainless steel plate of 2cm thick is maintained at a temperature of $550°C$ at one face and $50°C$ on the other. The thermal conductivity of stainless steel at $300°C$ is $19.1\,W/mK$. Calculate the heat transferred through the material per unit area.

Given:

Stainless steel plate

$$L = 2cm = 2 \times 10^{-2} m$$

$$T_1 = 550°C$$

$$T_2 = 50°C$$

$$k = 19.1 W/mK$$

Find

$$\frac{Q}{A} \quad \text{or} \quad q = ?$$

Solution

Fourier's equation

$$Q = -kA.\frac{dT}{dx} = -\frac{kA(T_2 - T_1)}{L}$$

$$q = \frac{Q}{A} = \frac{k(T_1 - T_2)}{L}$$

$$= \frac{19.1(550 - 50)}{2 \times 10^{-2}}$$

$$\boxed{q = 477.5\ kW/m^2}$$

Example 1.2:

A plane wall is $150mm$ thick and its wall area is $4.5m^2$. Its conductivity is $9.35W/m\ K$ and temperatures are steady at $150°C$ and $45°C$ on both sides. Determine the temperature gradient in the flow direction.

Given: Plane wall

$$L = 150mm = 150 \times 10^{-3}m$$

$$k = 9.35W/m\ K$$

$$T_1 = 150°C$$

$$T_2 = 45°C$$

$$A = 4.5m^2$$

Find

Temperature gradient $\left(\frac{dT}{dx}\right) = ?$

Introduction & Basic Concepts of Heat Transfer

We know that Fourier's equation

$$Q = -kA.\frac{dT}{dx}$$

$$\therefore \boxed{\frac{dT}{dx} = -\frac{Q}{kA}}$$

$$Q = -\frac{kAdT}{dx} = \frac{kA(T_1 - T_2)}{L}$$

$$= \frac{9.35 \times 4.5(150 - 45)}{150 \times 10^{-3}}$$

Introduction & Basic Concepts of Heat Transfer

$$\boxed{Q = 29452.5W}$$

$$\therefore \qquad \text{Temperature gradient} \left(\frac{dT}{dx}\right) = -\frac{Q}{kA}$$

$$= -\frac{29452.5}{9.35 \times 4.5}$$

$$\boxed{\frac{dT}{dx} = -700K/m}$$

Example 1.3:

A hot plate $1m \times 1.5m$ is maintained at $300°C$ Air at $20°C$ flows over the plate. If the convective heat transfer co-efficient is $20W/m^2K$, calculate the rate of heat transfer.

Solution

Given

$$\text{Area of the plate} = 1 \times 1.5 = 1.5m^2$$
$$\text{Plate surface temperature} = T_s = 300°C$$
$$\text{Temperature of air} = T_f = 20°C$$
$$\text{Convective heat transfer coefficient } h = 20W/m^2K$$

Find

Rate of heat transfer (Q)

$$\therefore \quad Q = hA(T_s - T_f)$$
$$= 20 \times 1.5(300 - 20)$$

$$\boxed{Q = 8400W}$$

Example 1.4:

A surface having an area of $1.5 m^2$ and maintained at $300°C$ exchanges heat by radiation with another surface at $40°C$. Geometric factor is 0.52. Determine heat lost by radiation.

Solution

$$Q_{rad} = F_{1-2}\sigma A(T_1^4 - T_2^4)$$

$$= 0.52 \times 1.5 \times 5.67 \left[\left(\frac{573}{100}\right)^4 - \left(\frac{313}{100}\right) \right.$$

Introduction & Basic Concepts of Heat Transfer

Exercise Problems:

1. A wire of $1.5mm$ in diameter and $100mm$ long is submerged in water at atmospheric pressure. The temperature of the water is $100°C$. Heat transfer coefficient is $4500W/m^2K$. Find how much heat is transferred to maintain the wire surface at $120°C$?

2. Calculate the rate of heat transfer per unit area through a copper plate $45mm$ thick whose one face is maintained at $350°C$ and other face at $50°C$. Take thermal conductivity of copper as $370W/mK$.

3. Air at $300°C$ flows over a flat plate of area $0.125m^2$, and the convective heat transfer coefficient is $250W/m^2K$. Calculate the heat transfer from air to one side of the plate when the plate is maintained at $40°C$.

4. Two large parallel plates at a uniform temperature of $500K$ and $1000K$ are separated by non participating gas. Assuming plates are black bodies, calculate the radiant heat transfer between them (Here $F_{1-2} = 1$).

Links for Video Lectures

Part A:

https://pern.sharepoint.com/sites/HMFP-MECH-TECH-2018/Shared%20Documents/General/Recordings/HMFP%20THEORY-20210405_101945-Meeting%20Recording.mp4?web=1

Part B:

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Lab Session_01:

https://pern.sharepoint.com/sites/HMFP-MECH-TECH-2018/Shared%20Documents/General/Recordings/HMFP%20LAB-20210412_140514-Meeting%20Recording.mp4?web=1


Thank You!