1

Basic Concepts

Contents

1.1 Introduction to Engineering Thermodynamics

Thermodynamics is the branch of science that deals with energy (heat & work both) transfer and its effect on the state or condition of the system.

Thermodynamics basically involves four laws (explained later) known as Zeroth, First, Second and Third law of thermodynamics.

- ***Zeroth law*** deals with thermal equilibrium and relates to the concept of equality of temperature.
- ***First law*** relates to the conservation of energy and introduces the concept of internal energy.
- ***Second law*** relates the direction of flow of heat, dictates limits on the conversion of heat into work and introduces the principle of increase of entropy.
- ***Third law*** defines the absolute zero of entropy.

These laws are based on experimental observations and have ***No Mathematical Proof***.

1.1.1 Application Areas of Engineering Thermodynamics

All activities in nature involve some interaction between energy and matter; thus, ***it is hard to imagine an area that does not relate to thermodynamics*** in some manner.

Thermodynamics is commonly encountered in many engineering systems and other aspects of life, and one does not need to go very far to see some application areas of it. In fact, one does not need to go anywhere. The heart is constantly pumping blood to all parts of the human body, various energy conversions occur in trillions of body cells, and the heat generated by human body is constantly rejected to the environment. Human comfort is closely tied to the rate of this metabolic heat rejection. We try to control this heat transfer rate by selecting our clothing to environmental conditions.

Some of the selected areas of application of engineering thermodynamics are:

- Automobile Engines
- Turbines, Compressors & Pumps
- The propulsion system for Aircraft and Rockets
- Combustion Systems
- HVAC Systems: Vapor Compression & Absorption Refrigeration, Heat Pumps
- Cooling of Electronic Equipment
- Power Stations: Nuclear, Thermal, etc.
- Alternative Energy Systems: Geothermal, Wind, Solar, etc.
- Cryogenic Systems
- Energy-efficient Home
- Biomedical Applications: Life-support Systems, Artificial Organs

1.2 Macroscopic and Microscopic Point of View

Every substance is composed of a large number of molecules. The properties of the substance depending on the behavior of these molecules.

The behavior of a system may be investigated from either a microscopic (Micro means small) or macroscopic (Macro means big) point of view.

For applications involving lasers, plasmas, high-speed gas flows, chemical kinetics, very low temperatures (cryogenics), and others, the methods of statistical thermodynamics are essential.

*Table **1.1** - Difference between macroscopic & microscopic approach*

Sr. No.	Macroscopic Approach	Microscopic Approach
1	In this approach, a certain quantity of matter is considered without taking into account the events occurring at the molecular level.	The matter is considered to be comprised of a large number of tiny particles known as molecules, which moves randomly in a disordered fashion. The effect of molecular motion is considered.
2	An analysis is concerned with the overall behavior of the system.	The Knowledge of the structure of matter is essential in analyzing the behavior of the system.
3	This approach is used in the study of classical thermodynamics.	This approach is used in the study of statistical thermodynamics.
4	A few properties are required to describe the system.	Large numbers of variables are required to describe the system.
5	The properties like pressure, temperature, etc. needed to describe the system, can be easily measured.	The properties like velocity, momentum, kinetic energy, etc. needed to describe the system, cannot be measured easily.
6	The properties of the system are their average values.	The properties are defined for each molecule individually.
7	This approach requires simple mathematical formulas for analyzing the system.	No. of molecules are very large so it requires an advanced statistical and mathematical method to explain any change in the system.

1.3 Thermodynamic System and Control Volume

Thermodynamic System

"It is defined as a quantity of matter or a region in the space upon which attention is concentrated for the investigation or analysis of the thermodynamic problems i.e. heat transfer, work transfer, etc."

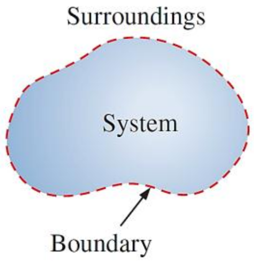


Fig.1.1 – System, Surroundings & Boundary

Surroundings or Environment

"It is the matter or region outside the system"

Boundary

"The system and surroundings are separated by an envelope called boundary of the system"

Types of boundary

- Fixed or moving boundary
- Real or imaginary boundary

Mathematically, the boundary has zero thickness, and thus it neither contain any mass nor occupy any volume in space.

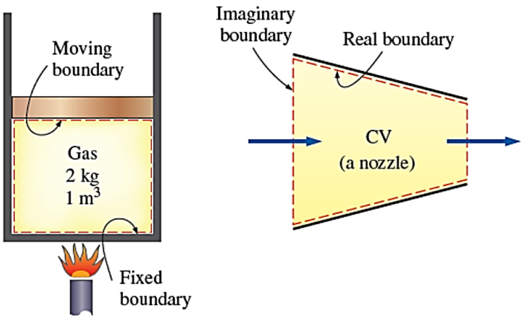


Fig.1.2 – Types of Boundary

1.3.1 Types of Thermodynamic System

a) Open System

In an open system **mass and energy** (in the form of heat and work) **both can transfer** across the boundary. Most of the engineering devices are open systems.

Examples: Boiler, Turbine, Compressor, Pump, I.C. Engine, etc.

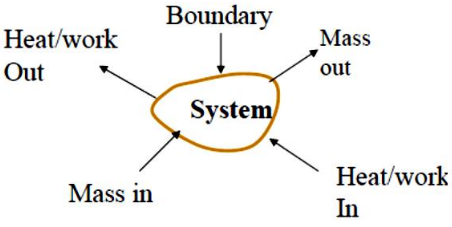


Fig.1.3 – An Open System

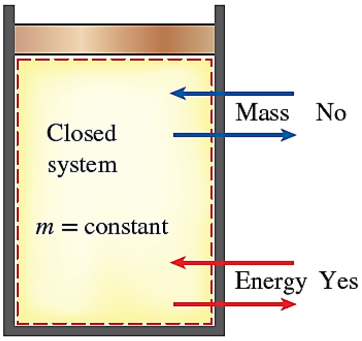


Fig.1.4 – A Closed System

b) Closed System

A closed system ***can exchange energy in the form of heat and work*** with its surroundings but there is ***no mass transfer*** across the system boundary.

The mass within the system remains constant however its volume can change against a flexible boundary. Further, the physical nature and chemical composition of the mass may change.

Examples: Cylinder bounded by a piston with a certain quantity of fluid, Pressure cooker and Bomb calorimeter, etc.

c) Isolated System

There is no interaction between the system and surroundings.

It is of fixed mass and energy, and hence there is ***no mass and energy transfer*** across the system boundary.

Examples:

The Universe and Perfectly insulated closed vessel (Thermo flask).

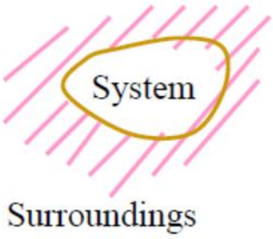


Fig.1.5 – An Isolated System

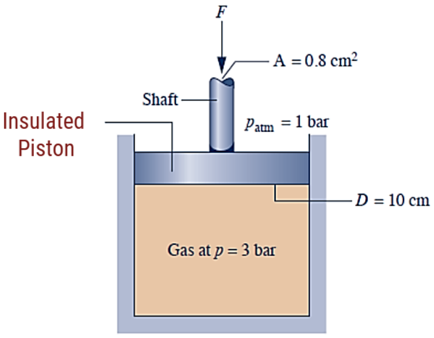


Fig.1.6 – An Adiabatic System

d) Adiabatic System

Boundaries ***do not allow heat transfer*** to take place across them.

An adiabatic system is thermally insulated from its environment. It can exchange energy in the form of work only. If it does not, it becomes isolated.

Example: A perfectly insulated piston-cylinder arrangement.

e) Homogeneous & Heterogeneous System

*Table **1.2** - Homogeneous & Heterogeneous System*

Homogeneous System	Heterogeneous System
"A system which consists of a single-phase is termed as a homogeneous system." **Examples:** ▶ A mixture of air and water vapor ▶ Water + Nitric acid	"A system which consists of two or more phases is called a heterogeneous system." **Examples:** ▶ Water + Steam ▶ Ice + Water

1.3.2 Control Volume Concept

For thermodynamic analysis of an open system, such as an air compressor, turbine, etc. attention is focused on a certain volume in space surrounding the system, known as **control volume**.

The control volume bounded by the surface is called "**Control Surface**".

Both mass and energy can cross the control surface. It may be physical or imaginary.

__**Example of Control Volume:**__

Consider an air compressor (open system) as shown in *Fig.1.7*. Since compressed air will leave the compressor and be replaced by fresh air, it is not convenient to choose a fixed mass as our system for the analysis. Instead, we can concentrate our attention on the volume formed by compressor surfaces and consider the compressed air and fresh air streams as mass leaving and entering the control volume.

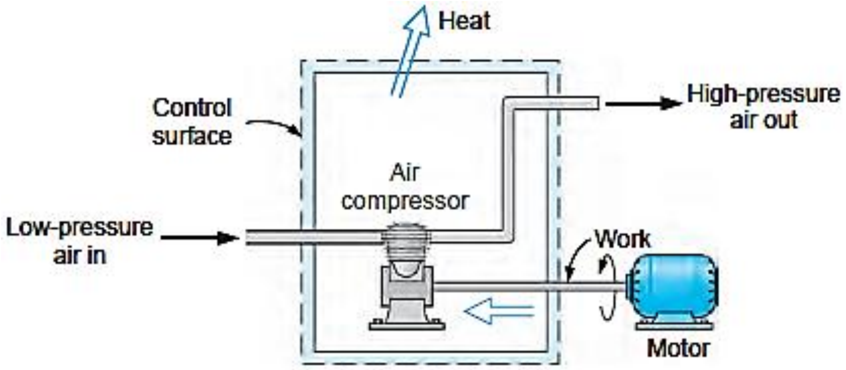


Fig.1.7 – An example of a control volume

1.3.3 Difference between System & Control Volume

*Table **1.3** - Difference between system & control volume*

Sr. No.	System	Control Volume
1	A system is a defined quantity of matter which is considered to analyze the problem.	A control volume is a certain volume which is considered to analyze the problem.
2	The system is separated from its surrounding by a boundary which may be real or imaginary and may change shape, volume and position relative to an observer.	The C.V. is separated from its surrounding by a control surface which may be real or imaginary and normally fixed in shape & position relative to an observer.

1.4 Thermodynamic Properties, Processes and Cycles

1.4.1 Thermodynamic Properties

"A thermodynamic property refers to the characteristics which can be used to describe the physical condition or state of a system."

Examples of thermodynamic properties are: Temperature, Pressure, Volume, Energy, Mass, Velocity, Viscosity, Thermal Conductivity, Modulus of Elasticity, Co-efficient of Thermal Expansion, etc.

1.4.1.1 Salient Aspects of a Thermodynamic Property

- It is a macroscopic characteristic of the system.
- It has a unique value when the system is in a particular state, and this value does not depend on the previous states that the system passed through; that is, it is not a *path function but it is a point function*.
- Since the property is not dependent on the path, any change depends only on the initial and final states of the system. *Hence its differential is exact*.

1.4.1.2 Types of Thermodynamic Properties

1. **Intensive Property**
   Intensive property is **I**ndependent of the mass of the system. Its value remains the same whether one considers the whole system or only a part of it.

   Examples: Pressure, Temperature, Density, Viscosity, Thermal Conductivity, Electrical Potential, etc.
2. **Extensive Property**
   Extensive property depends on the mass of the system.

   Examples: Mass, Energy, Enthalpy, Volume, Entropy, etc.
3. **Specific Property**
   Extensive properties per unit mass are called specific properties.
   Examples: Specific volume $\left(v = \frac{V}{m}\right)$ and specific total energy $\left(e = \frac{E}{m}\right)$.

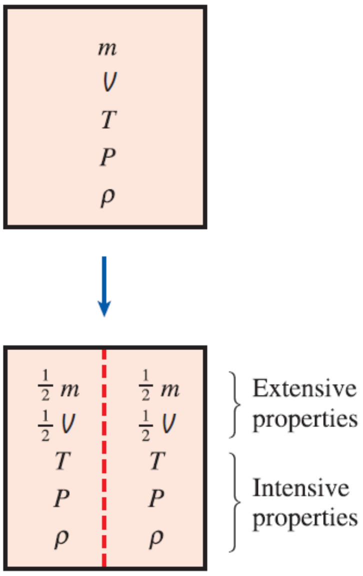


Fig.1.8 - Criterion to differentiate intensive and extensive properties

Note: An easy way to determine whether a property is intensive or extensive is to divide the system into two equal parts with an imaginary partition, as shown in *Fig.1.8*. The value of intensive properties remains the same as the original system, whereas extensive properties became half.

1.4.2 State

*"**State** refers to the condition of a system as described by its properties."*

It gives a complete description of the system. At a given state, all the properties of a system have fixed values.

If the value of even one property changes, the state will change to a different one, any such kind of operation is called ***Change of state***.

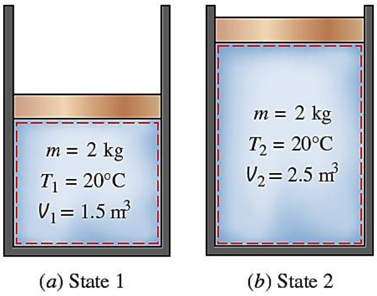


Fig.1.9 – System at different states

1.4.3 Process and Path

Any change that a system undergoes from one equilibrium state to another is called a ***process***, and the series of states through which a system passes during a process is called the ***path*** of the process.

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

There are infinite ways for a system to change from one state to another state.

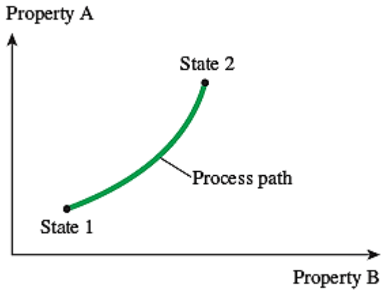


Fig.1.10 – Process & Path

1.4.4 Cycle

When a system in a given initial state goes through a number of different changes of state or processes and finally returns to its initial state, the system has undergone a **cycle**. Thus for a cycle, the initial and final states are identical.

Example: Steam (water) that circulates through a steam power plant undergoes a cycle.

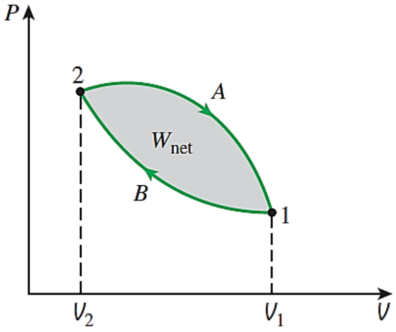


Fig.1.11 - Cycle

1.4.5 Point Function

When two properties locate a point on the graph (Co-ordinate axis) then those properties are called as Point Function.

Examples: Pressure, Volume, Temperature, etc. It can be represented by an exact differential. i.e. $\int_1^2 dV = V_2 - V_1$

1.4.6 Path Function

There are certain quantities which cannot be located on a graph (Co-ordinate axis) by a point but are given by the area or so, on that graph.

In that case, the area on the graph, relating to the particular process, is a function of the path of the process, such quantities are called Path Functions.

Examples: Heat, Work, etc.

Heat (Q) and Work (W) can be represented by an inexact differential. Their change can not be written as a difference between their end states.

Thus,

$$\int_1^2 \delta W \neq W_2 - W_1 \text{ and is shown as } W_{1-2}$$

$$\int_1^2 \delta Q \neq Q_2 - Q_1 \text{ and is shown as } Q_{1-2}$$

<u>**Note:**</u> The operator δ is used to denote inexact differentials and d is used to denote exact differentials.

1.5 Thermodynamic Equilibrium

A system is said to be in a state of thermodynamic equilibrium if the conditions for the following three types of equilibrium are satisfied simultaneously:

- **Mechanical Equilibrium:** There are no unbalanced forces within the system or between the surroundings. The pressure in the system is the same at all points and does not change with respect to time.
- **Thermal Equilibrium:** The temperature of the system does not change with time and has the same value at all points of the system.
- **Chemical Equilibrium:** No chemical reaction takes place in the system and the chemical composition which is same throughout the system does not vary with time.

A system in thermodynamic equilibrium does not deliver anything.

1.6 The Concept of Continuum

The matter is made up of atoms. Atoms are widely spaced in the gas phase and matter may also have some voids as shown in *Fig.1.12*.

Yet it is very convenient to ignore the atomic nature of a substance and view it as a continuous, homogeneous matter with no voids (holes), that is, a **Continuum**.

The continuum idealization allows us to treat properties as point functions and allow us to apply a macroscopic approach when the smallest unit of the matter is large enough compared to the mean free path of the atoms.

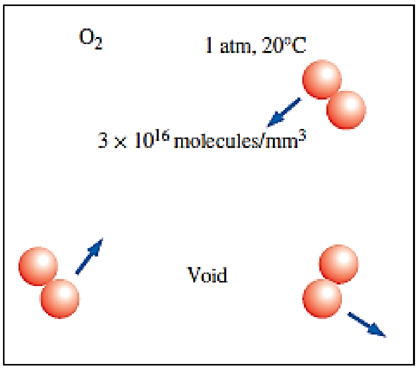


Fig.1.12 – Atoms in Gas Phase

For example, consider a container filled with oxygen at atmospheric conditions. The diameter of the oxygen molecule is about $3 \times 10^{-10}\ m$ and its mass is $5.3 \times 10^{-26}\ kg$. Also, the mean free path of oxygen at 1 atm pressure and 20°C is $6.3 \times 10^{-8}\ m$ That is, an oxygen molecule travels, on average, a distance of $6.3 \times 10^{-8}\ m$ (about 200 times its diameter) before it collides with another molecule. Also, there are about 3×10^{16} molecules of oxygen in the tiny volume of $1\ mm^3$ at 1 atm pressure and 20°C as shown in *Fig.1.12*.

At very high vacuums or very high elevations, the mean free path may become large (for example, it is about 0.1 m for atmospheric air at an elevation of 100 km). For such cases, the **rarefied gas flow theory** should be used, and the impact of individual molecules should be considered.

1.7 Quasi-Static Process

"Quasi" means almost slow or infinitely slow.

Consider a system of gas contained in a cylinder fitted with a piston upon which many very small pieces of weights are placed as shown in *Fig.1.13*.

The upward force exerted by the gas just balances the weights on the piston and the system is initially in equilibrium state identified by pressure P_1, volume V_1 and temperature T_1.

When these weights are removed slowly, one at a time, the unbalanced potential is infinitesimally small. The piston will slowly move upwards and at any particular instant of piston travel, the system would be almost close to the state of equilibrium.

Every state passed by the system will be an equilibrium state. The locus of a series of such equilibrium states is called a ***"Quasi-Static or Quasi-Equilibrium process."***

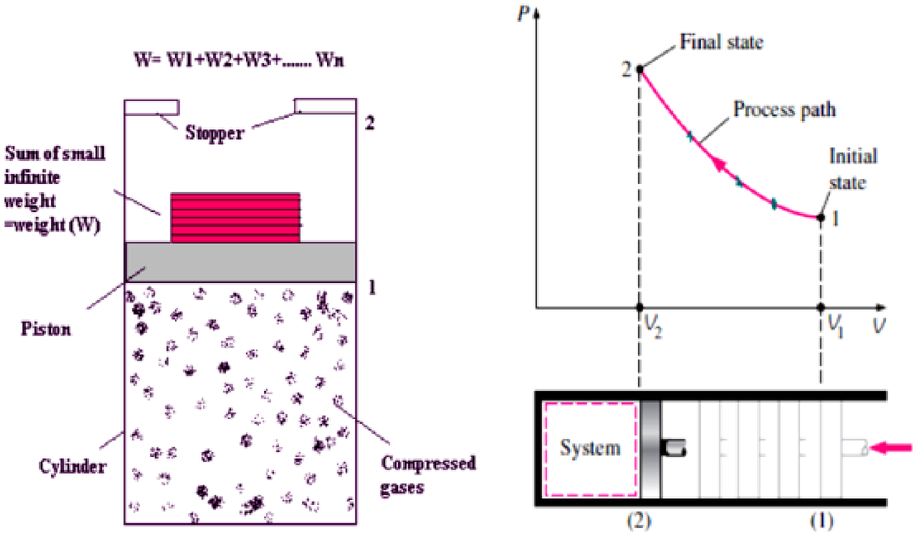


Fig.1.13 – Quasi-static process with p-v diagram of the compression process

It should be pointed out that a quasi-equilibrium process is an idealized process and is not a true representation of an actual process. But many actual processes closely approximate it, and they can be modeled as quasi-equilibrium with negligible error.

Engineers are interested in quasi-equilibrium processes for two reasons. First, they are easy to analyze; second, work-producing devices deliver the most work when they operate on quasi-equilibrium processes. Therefore, quasi-equilibrium processes serve as standards to which actual processes can be compared.

Fig.1.13 shows the p-v diagram of a compression process of gas. A quasi-static process is also called a reversible process. This process is a succession of equilibrium states and ***infinite slowness*** is its characteristic feature.

1.8 The Zeroth Law of Thermodynamics

"It states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other."

The Zeroth law serves as a basis for the validity of temperature measurement, by replacing the 3rd system by a thermometer. If we want to know if two objects are at the same temperature, it is not necessary to bring them into contact. If they are individually in thermal equilibrium with a third object (thermometer) then we can say that two objects are at the same temperature.

The Zeroth law was first formulated and labeled by R. H. Fowler in 1931.

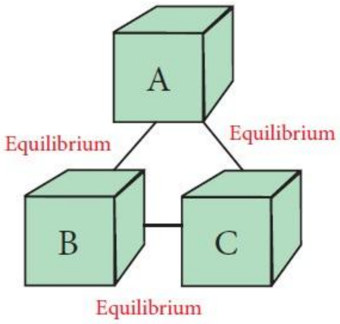


Fig.1.14 – Systems in equilibrium

1.9 Temperature & Temperature Scales

1.9.1 Temperature:

It can be defined as a measure of hotness or coldness, but it is not the exact definition. Temperature is a basic property such as mass, length and time thus cannot be defined precisely.

For example, a metal chair will feel much colder than a wooden one, even when both are at the same temperature.

1.9.2 Temperature Scale

Temperature scales enable us to use a common basis for temperature measurements and several temperature scales have been introduced so far.

All temperature scales are based on some easily reproducible states such as freezing and boiling point temperatures of water i.e. ice point and steam point respectively.

The temperature scale used in **SI units** is the **Celsius scale**. On the Celsius scale, ice point and steam point are assigned the numerical values of 0 and 100 °C respectively.

The **English system** uses the **Fahrenheit scale**, which assigns 32 and 212 °F as the ice point and steam point respectively.

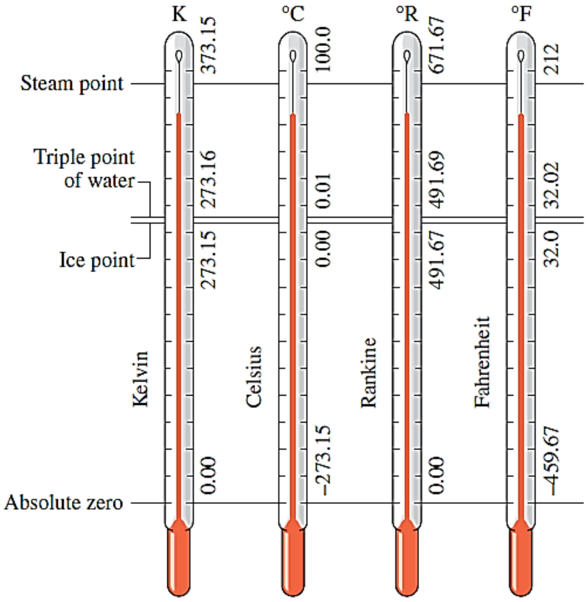


Fig.1.15 – Temperature Scales

A more useful temperature scale in thermodynamics is the absolute temperature scale and is called the **Kelvin scale**. The temperature unit on this scale is Kelvin designated as K, without the degree symbol.

The Kelvin scale is related to the Celsius scale by,

$$T(K) = T(°C) + 273.15$$

In the **English system**, the absolute temperature scale is the **Rankine scale** and it is related to Farhenheit scale by,

$$T(R) = T(°\mathrm{F}) + 459.67$$

The two temperature scales and corresponding absolute temperature scales are shown in *Fig.1.15*. The values 273.15 and 459.67 are often replaced by approximate values of 273 and 460, respectively.

1.10 Important Terminologies

1.10.1 Density

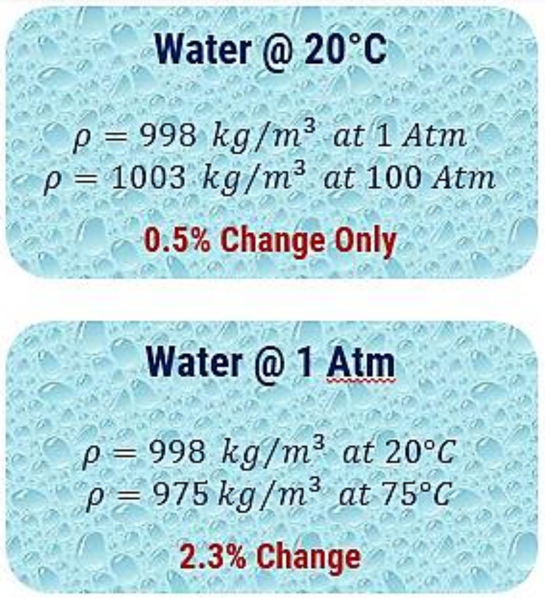
Density is defined as mass per unit volume.

$$\rho = \frac{m}{V}\ (kg/m^3)$$

The density of a substance, in general, depends on **temperature** and **pressure**. The density of most ***gases*** is **proportional to pressure** and **inversely proportional to temperature.**

Liquids and solids, on the other hand, are essentially **incompressible** substances, and the variation of their density with pressure is usually negligible.

The density of liquids and solids depends more strongly on temperature than it does on the pressure as shown in *Fig.1.16*. but still, it can be neglected in many engineering analysis.



Water @ 20°C

$\rho = 998\ kg/m^3\ at\ 1\ Atm$

$\rho = 1003\ kg/m^3\ at\ 100\ Atm$

0.5% Change Only

Water @ 1 Atm

$\rho = 998\ kg/m^3\ at\ 20°C$

$\rho = 975\ kg/m^3\ at\ 75°C$

2.3% Change

Fig.1.16 – Change in Density

1.10.2 Specific Heat

"The specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree". *Its unit is J/kg-K and denoted by C.*

This energy depends on how the process is executed.

Gases have two specific heats, C_p and C_v but for liquids and solids, the specific volume is very small and its change with pressure and temperature is negligible, thus they have only one specific heat.

The specific heat at constant pressure C_p is always greater than the specific heat at constant volume C_v because at constant pressure the system is allowed to expand, and the energy for this expansion work must also be supplied to the system.

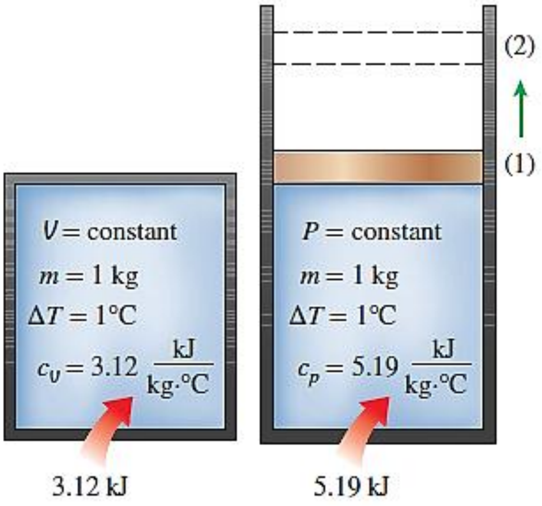


Fig.1.17 – Specific heat at constant volume and constant pressure

1.10.3 Heat & Work

Energy can cross the boundary of a closed system in two distinct forms: heat and work. It is important to distinguish between these two forms of energy.

Heat:

"Heat is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference". The ***temperature difference*** is the ***driving potential*** for heat transfer.

All heat interaction need not result in temperature changes e.g. Evaporation and Condensation.

Work:

"An energy interaction between a system and its surroundings during a process can be considered as work transfer if its sole effect on everything external to the system could have been to raise a weight."

Sign Convention for Heat & Work:

Heat and Work are directional quantity, and its specification requires magnitude and direction both. Universally accepted sign convections for heat and work energy are shown in *Fig.1.18*.

- Heat transferred to a system (heat supply) and Work done by a system is considered ***positive.***
- Heat transferred from a system (heat rejection) and Work done on a system is considered ***negative.***

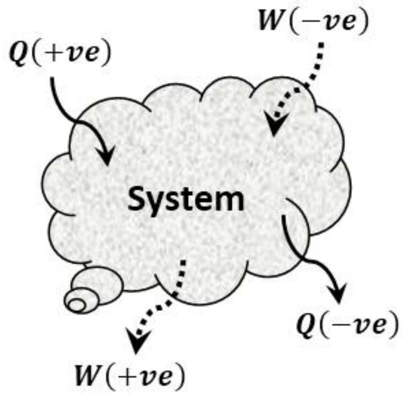


Fig.1.18 – Sign convention for heat and work

Different forms of Work Transfer:

1. Electrical work
2. **Mechanical work**
3. **Moving boundary work**
4. **Flow work**
5. Gravitational work
6. Acceleration work
7. Shaft work
8. Spring work

Some of the important forms of work transfer are discussed below:

Mechanical Work:

In mechanics work done by a system is expressed as a product of force (F) and displacement (s)

$$W = F \times s$$

If the force is not constant, the work done is obtained by adding the differential amounts of work,

$$W = \int_1^2 F\, ds$$

The ***pressure difference*** is the ***driving force*** for mechanical work.

Moving Boundary Work / Displacement Work / pdV Work:

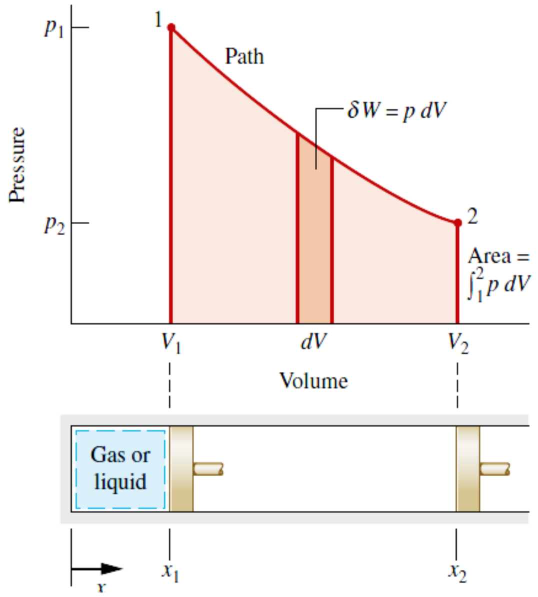


Fig.1.19 – Moving boundary work

In many thermodynamic problems, mechanical work is the form of moving boundary work. The moving boundary work is associated with real engines and compressors.

Consider the gas enclosed in a frictionless piston-cylinder arrangement as shown in *Fig.1.19*.

Let the initial gas pressure p_1 and volume V_1. The piston is the only boundary which moves due to gas pressure. Let the piston moves out to a new final position 2, specified by pressure p_2 and volume V_2.

At any intermediate point in the travel of the piston, let the pressure be p, volume V and piston cross-sectional area is A. When the piston moves through an infinitesimal distance ds in a quasi-equilibrium manner, the force applied on the piston is given by,

$$F = p \times A$$

Then differential work transfer through a displacement of ds during this process,

$$\delta W = F \times ds = p \times A \times ds = p \times dV$$

When the piston moves out from initial state 1 to final state 2 with volume changing from V_1 to V_2, The total boundary work done by the system will be,

$$W_{1-2} = \int_{V_1}^{V_2} pdV \;\; (kJ)$$

This work transfer during a process is equal to the area under the curve on a $p - V$ diagram as shown in *Fig.1.19*.

Flow Work:

"Flow energy or flow work refers to work required to push a certain mass of fluid into and out of the control volume". It is necessary for maintaining continuous flow through a control volume.

Consider a fluid element of volume V, entering the control volume through a cross-sectional area A as shown in *Fig.1.20*.

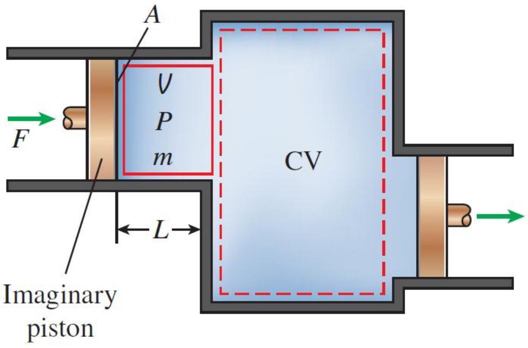


Fig.1.20 – Flow work

If P is the fluid pressure acting uniformly at the imaginary piston at the entrance of the control volume, the force applied on the fluid element by the imaginary piston is,

$$F = P \times A$$

If the fluid is pushed by a distance L, then the flow work will be,

$$W_f = P \times A \times L = P \times V$$

Flow work at the entrance, $W_{f1} = P_1 V_1$

Flow work at the exit, $W_{f2} = P_2 V_2$

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6) National Programme on Technology Enhanced Learning (NPTEL), A Joint Initiate by IIT's and IISc. (Web: http://nptel.ac.in/)