

POWER PLANTS (ME-403)

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Contents

- 1. Introduction to Power Plant Technology**
- 2. Review of Basic Thermodynamics**
- 3. Steam Power Plants: Cycles and Materials**
- 4. Gas Turbine Power Plants: Cycles and Materials**
- 5. Fossil Fuels and Combustion Calculations**
- 6. Combustion Systems and Steam Generators**
- 7. Overview of Non-Conventional Power Plants**

References:

- 1. Lecture Slides**
- 2. Black & Veatch, 2005. Power Plant Engineering, CBS New Delhi**
- 3. Spliethoff, H., 2010. Power Generation from Solid Fuels, Springer, Heidelberg.**
- 4. Regnauld, Alfred: Modern power engineering, Caxton, London**
- 5. Books on Engineering Thermodynamics**

1. Introduction to Power Plants

The aim of the lecture is to convey a general overview of power plant technology

1. Introduction to Power Plant Technology

1.1. Energy Resources

The primary energy resources are:

- Fossil fuels
 - Nuclear fuels (uranium and thorium)
 - Nuclear fusion (hydrogen, lithium)
- } Non-renewable energy resources
- Geothermal energy,
 - Solar thermal energy
 - Photovoltaic
 - Hydro power energy
 - Biomass energy
 - wind energy
 - Tidal and wave energy
 - Fuel cells
- } Renewable energy resources

1. Introduction to Power Plant Technology

Forms of energy

Energy can exist in numerous forms

- Thermal
- Mechanical
- Kinetic
- Potential
- Electric
- Magnetic
- Chemical
- Nuclear

Useful forms of energy

- Electrical
- Heat or Thermal
- Mechanical

1. Introduction to Power Plant Technology

Different factors are affecting the conversion and utilization of the primary energies in the form of useful energy

- Productivity and availability
- Potential environmental damages
(Land use, anthropogenic greenhouse gas emissions, etc.)
- Utilization risk to humans
- Effectiveness of use (efficiency factor, capacity factor or yield factor)
- State of the technology of the conversion process
- Economic value
- etc.

1. Introduction to Power Plant Technology

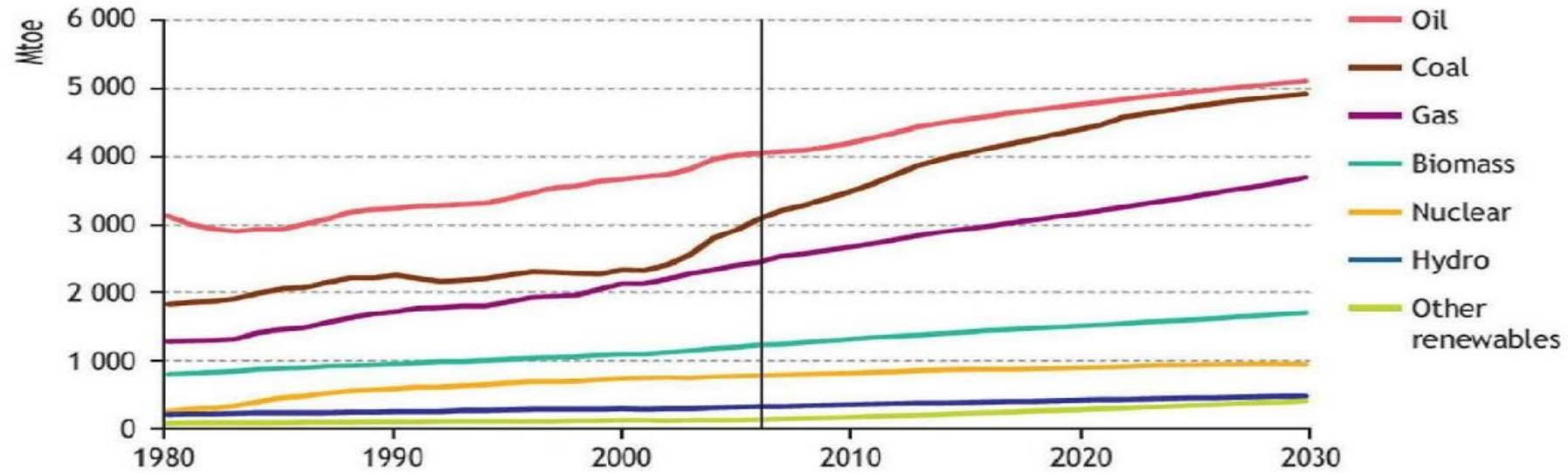
Energy Units

1 kJ = 10^3 J
1 MJ = 10^6 J
1 GJ = 10^9 J
1 TJ = 10^{12} J
1 PJ = 10^{15} J

1 Btu (British Thermal Unit)	1.05506 kJ
1 Therm	0.105506 GJ
1 calorie	4.1868 J
1 kcal (or Kal)	4.1868 kJ
1 tonne coal equivalent (UK)	24 GJ
1 tonne coal equivalent (EC)	29.4 GJ
1 tonne oil equivalent	46 GJ
1 barrel of oil	6.7 GJ
1 gallon (UK) oil	192 MJ
1 litre oil	42 MJ
1 tonne peat	14 GJ
1 tonne wood	15-20 GJ
1 cu m gas	38 MJ
1 kWh	3.6 MJ
1 MWh	3.6 GJ
1 GWh	3.6 TJ
1 TWh	3.6 PJ

1. Introduction to Power Plant Technology

1.2. World Energy Statistics: An Overview

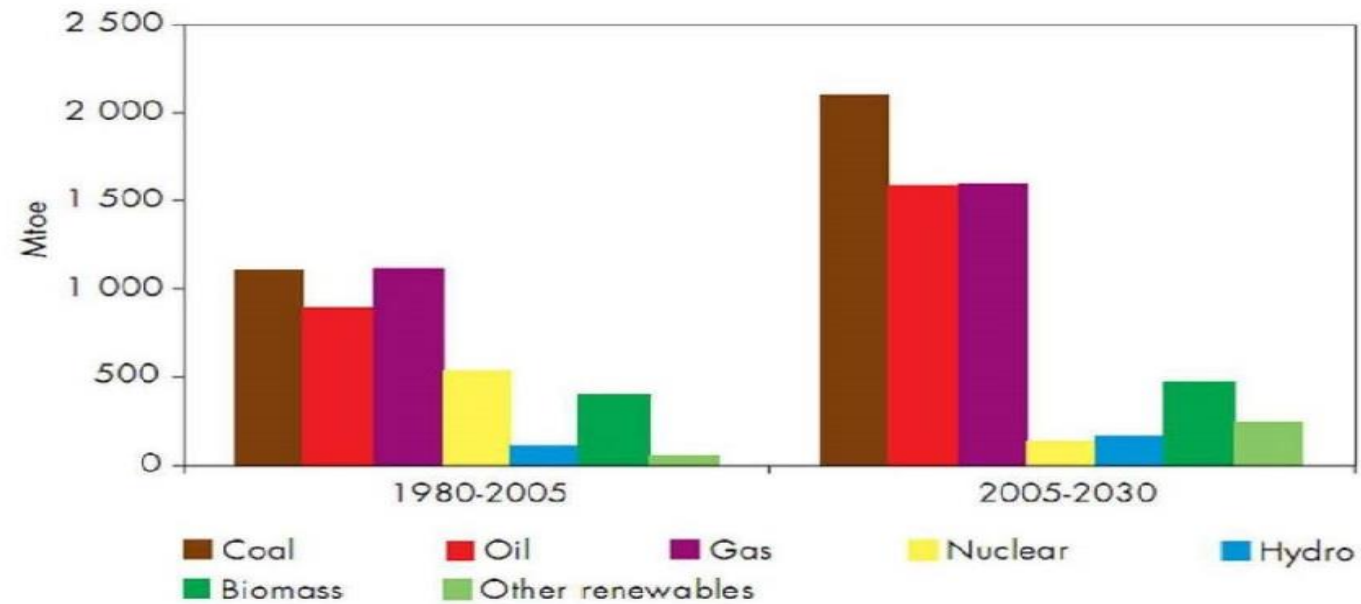


World Primary Energy Demand in the Reference Scenario

Source: IEA, WEO 2008

1. Introduction to Power Plant Technology

Increase in World Primary Energy Demand by Fuel in the Reference Scenario

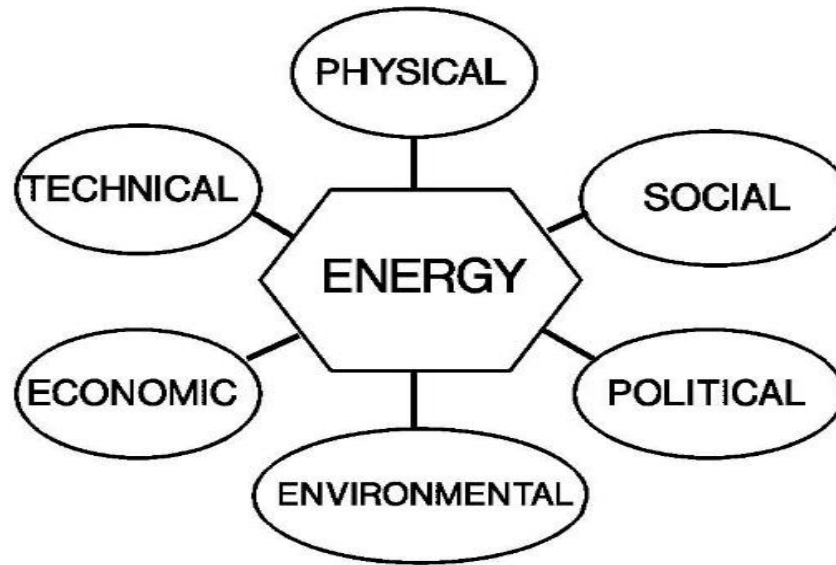


Source: IEA, WEO 2007

1. Introduction to Power Plant Technology

1.5. Requirements for Power Plants

Energy issues are complex and involve an understanding of the following topics



1. Introduction to Power Plant Technology

1.6. Classification of Power Plants

Power plant types are classified according to the following criteria:

Classification based on conversion processes (hot, cold)

- Hot power plants (conventional, nuclear)
- Cold power plants (water, wind)

Classification based on energy input (primary energy)

- Hard coal power plants
- Brown coal power plants
- Natural gas power plants
- Oil power plants
- Nuclear power plants
- Running water and pumped storage power plants
- Power plants for renewable energy (except hydro power plants)

1. Introduction to Power Plant Technology

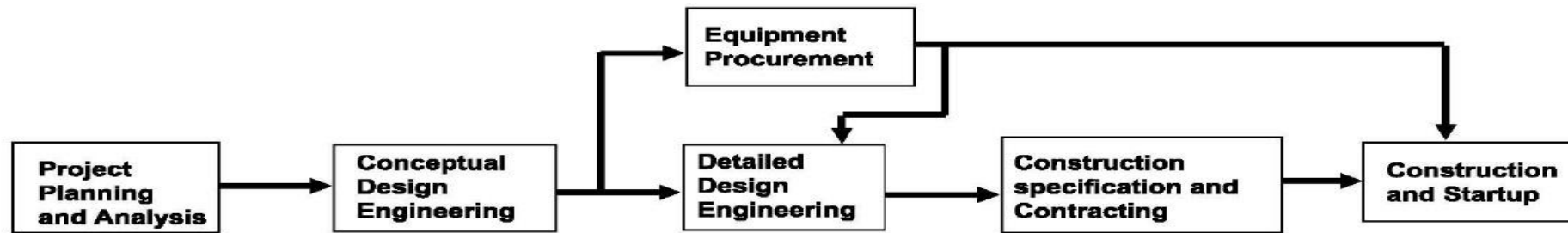
Classification based on power generating unit (machine)

Example fossil fuel power plants

- Gas turbine power plants
- Steam turbine power plants
- Gas and steam turbine power plants
- Combined cycle power plants
- Motorized (block heated) power plants

1. Introduction to Power Plant Technology

1.7. Planning, Construction and Operation of Power Plants



Planning of a new power plant should consist of:

- fuel supply studies
- system planning studies
- siting evaluation
- transmission planning analysis
- environmental feasibility analysis
- economic and financial feasibility analyses

Conceptual design consists of systematically defining and evaluating the basic conditions and constraints applicable to a specific electric generating plant

Detailed design includes determining the technical requirements for all plant components. It includes:

- equipment sizing
- reliability constraints
- performance requirements, and
- codes and standards

Location of Power Plants (P.K Nag)

- For Conventional Thermal Power Plants, following factors are to be considered,
 1. **Availability of cooling water (if cooling towers are used the possibility of adequate make-up water).**
 2. **Availability of fuel (water, rail or pipe connection to the fuel source, and the cost of fuel transport).**
 3. **Distance from the centre of gravity of load demand.**
 4. **Cost of land (including space for extension, maintenance workshop and storage yard).**
 5. **Character of soil.**
 6. **Main wind direction and water currents in cooling water source (sea, lake or river) in order to minimize air and water pollution, and other ecological considerations.**
 7. **With coal-fired stations, disposal of ash.**
 8. **If the plant is erected far from a town, accommodation for staff.**
 9. **Rail and road connections.**
 10. **Security considerations.**

Location of Power Plants (P.K Nag)

For nuclear power plants two additional factors are to be considered.

11. Density of population in the vicinity.
12. Danger of earthquakes.

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2. A Review to Thermodynamics

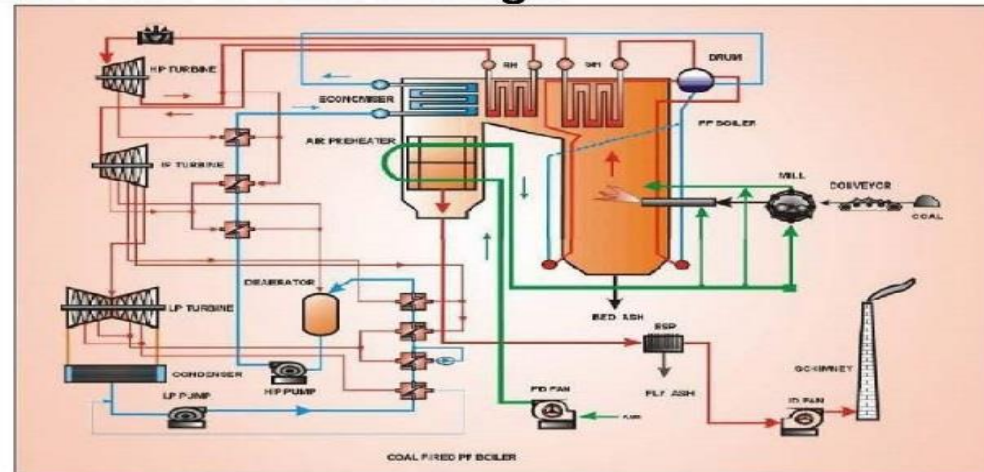
Chapter Two: Review of Basic Thermodynamics: Basic Concepts and Definitions

2. A Review to Thermodynamics

2.1. Basic Definitions

- Thermodynamics can be defined as the science of **energy**.
- **Thermodynamics deals with:**
 - the relationship between work, heat, and energy.
 - the conversion of energy from one form to another.
 - the interaction of a system and its surroundings.

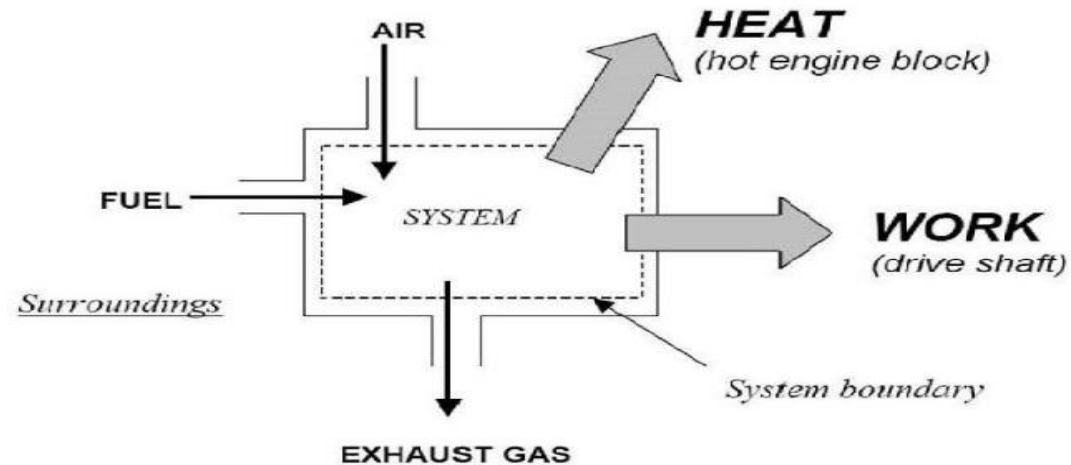
Application of thermodynamics
in power plants



Typical components of coal fired power plants

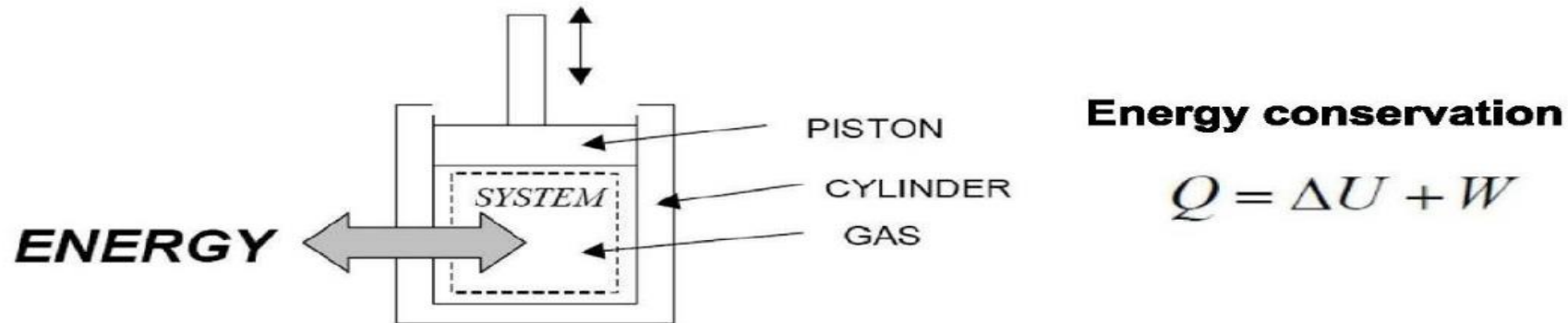
2. A Review to Thermodynamics

- **System** - contains a fixed quantity of matter under study in a given boundary
- **Surroundings** - everything outside the system boundary.
- The **boundary** of a system can be *fixed* or *movable*.
 - The boundary is the contact surface shared by both the system and the surroundings.
 - Mathematically, the boundary has zero thickness, and thus it can neither contain any mass nor occupy any volume in space.



2. A Review to Thermodynamics

- **Closed System** – (also known as a **control mass**) consists of a fixed amount of mass, and no mass can cross its boundary.
 - That is, no mass can enter or leave a closed system, but energy in the form of heat or work can cross the boundary.
 - Example: piston-cylinder assembly

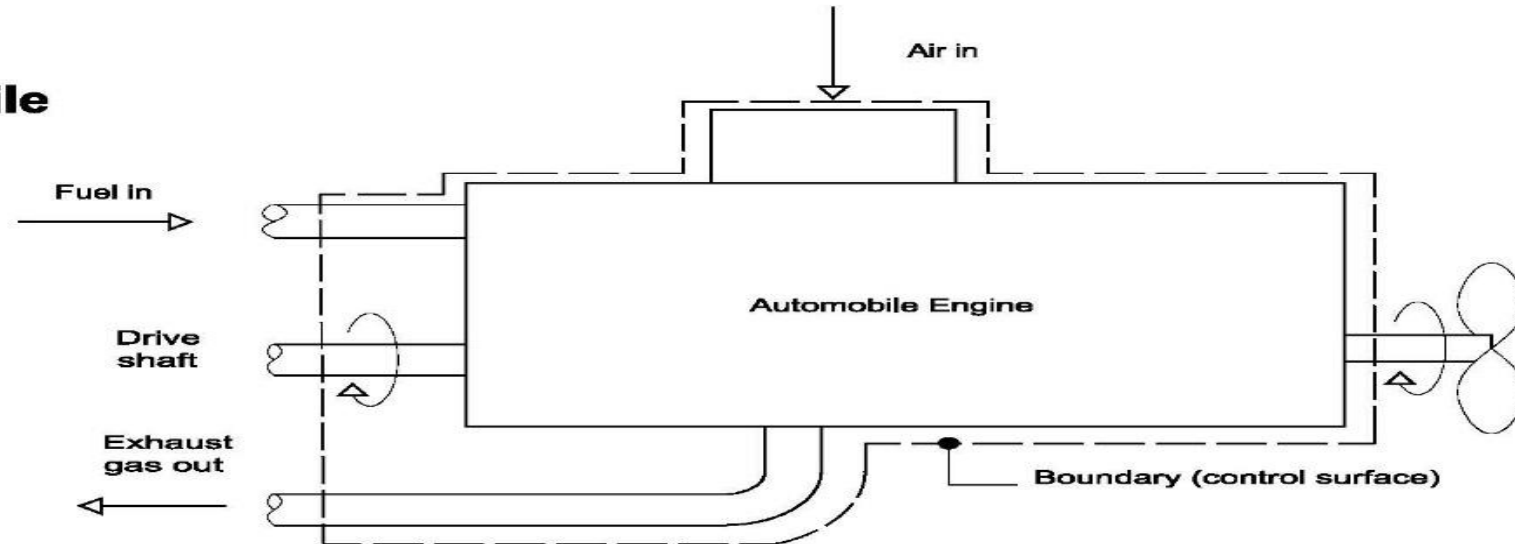


- **Isolated System** - does not interact with its surroundings- no mass, heat or work will cross its boundaries

2. A Review to Thermodynamics

- **Open System (Control Volume)** - is a properly selected region in space. In this system energy as well as mass can cross the system boundary (control surface).
- It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.

eg.
an automobile
engine



2. A Review to Thermodynamics

An open system allows both mass and energy flow through it. As a result, the mass and energy may vary with time

Mass conservation $\frac{dm}{dt} = \sum \dot{m}_i - \sum \dot{m}_e$

Energy conservation $\dot{Q} + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) = \frac{dE}{dt} + \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) + \dot{W}$

For steady state steady flow system

$$\frac{dm}{dt} = 0$$

$$\dot{m}_i = \dot{m}_e = \dot{m}$$

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

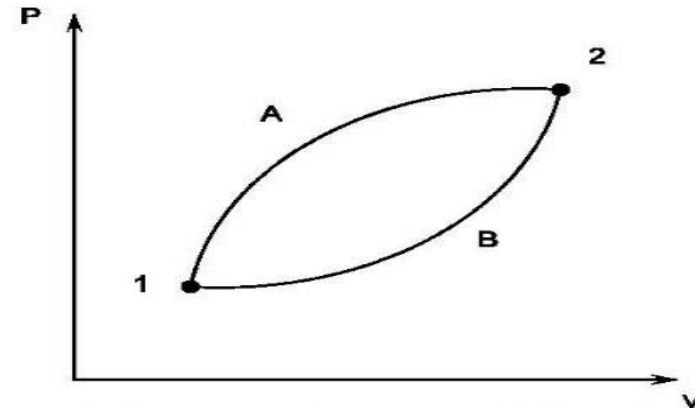
$$q + h_i + \frac{V_i^2}{2} + gz_i = h_e + \frac{V_e^2}{2} + gz_e + w$$

$$q + h_i = h_e + w$$

2. A Review to Thermodynamics

Property –any observable macroscopic characteristics of a system which can be described numerically such as pressure, temperature, mass etc.

- Mathematically it is defined as any quantity that is independent of the path by which the system arrived to the final condition
- Two types:
- **Extensive property** – depends on the size or mass of the system, e.g., mass, volume, energy, enthalpy, entropy
- **Intensive property**– is independent of the size or mass of system e.g., pressure, temperature, density, specific enthalpy, specific entropy
- **Specific properties**- are obtained by dividing extensive properties with mass. E.g.



•Different paths are used to arrive at 2 for the same $P_2 - P_1$

$$v = \frac{V}{m}, \quad h = \frac{H}{m}, \quad u = \frac{U}{m}, \quad s = \frac{S}{m}$$

2. A Review to Thermodynamics

- The **state** of a system is made up of several independent properties which can fully define the status of the system. In a simple system, a thermodynamic state can be determined explicitly by two independent
- When any of the properties of a system changes as a result of interaction with other system or the environment, then the state will change. At this time the system is said to have undergone a **process**.
- When a system, after having undergone a series of processes, returns to its initial state the system is said to have undergone a **thermodynamic cycle**.
- **In many processes one property may remain constant**
 - **Isothermal process** - **Constant temperature process**
 - **Isobaric process** - **Constant pressure process**
 - **Isochoric process** - **Constant volume process**
 - **Isenthalpic process** - **Constant enthalpy process**
 - **Isentropic process** - **Constant entropy process**

2. A Review to Thermodynamics

- **Pure substance** systems are formed by a single chemical composition. Examples are vapor, oxygen, nitrogen, etc.
- **Mixture systems** involve two or more chemical compositions. Some examples are air, air fuel mixture, etc.
- **Single phase** systems are formed by a single physical structure (solid, liquid or gas) and a single chemical composition. Examples are ice, liquid water or vapor, a water/alcohol mixture, etc.
- **Multiphase systems** involve two or more phases either in physical structure or chemical composition. Some examples are water/vapor and water/oil mixtures.
- The term ***steady*** implies *no change with time*. The opposite of steady is ***unsteady***, or ***transient***.
- The term ***uniform***, however, implies *no change with location* over a specified region.

2. A Review to Thermodynamics

2.2. Properties of Pure Substances

- A substance that has a fixed chemical composition throughout is called a **pure substance**.
 - E.g. Water, nitrogen, helium, and carbon dioxide.
- A pure substance does not have to be of a single chemical element or compound. A mixture of various elements or compounds also can be a pure substance as long as the mixture is homogeneous. For example;
 - Air, is a mixture of several gases, but it is often considered to be a **pure substance** because it has a uniform chemical composition
 - A mixture of oil and water is **not a pure substance**. Since oil is not soluble in water, it floats and forming two chemically dissimilar regions.
- Mixture of two or more phases of a pure substance is a pure substance as long as the chemical composition of all phases is the same
 - A mixture of ice and liquid water, for example, is a pure substance

2. A Review to Thermodynamics

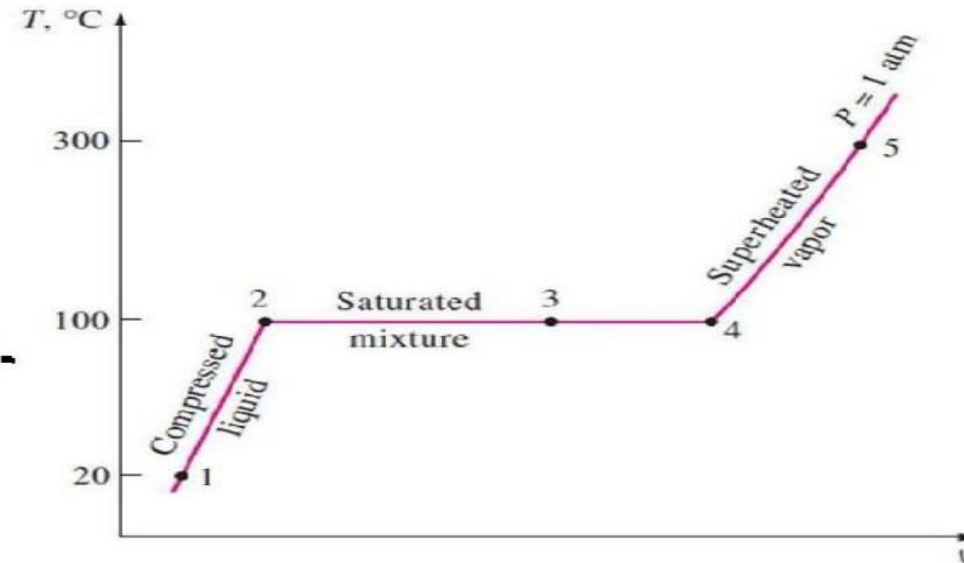
2.2.1. Phases of a Pure Substance

- Substances exist in different phases, i.e.
 - Solid,
 - Liquid, or
 - Gas
- A **phase** is identified as having a distinct molecular arrangement that is homogeneous throughout and separated from the others by easily identifiable boundary surfaces.
- There are many practical situations where two phases of a pure substance coexist in equilibrium.
 - Water exists as a mixture of liquid and vapor in the boiler and the condenser of a steam power plant.

2. A Review to Thermodynamics

2.2.2. Phase change of pure substance, e.g. water

- 1-2: **compressed liquid**, or a **subcooled liquid**, meaning that it is *not about to vaporize*.
- **Point 2: Saturated liquid** meaning a liquid that is *about to vaporize*
- **Between 2 and 4: saturated liquid-vapor mixture**; *liquid and vapor phases coexist in equilibrium*
- **Point 4: Saturated vapor** meaning a vapor that is *about to condense*
- **Beyond point 4: superheated vapor**

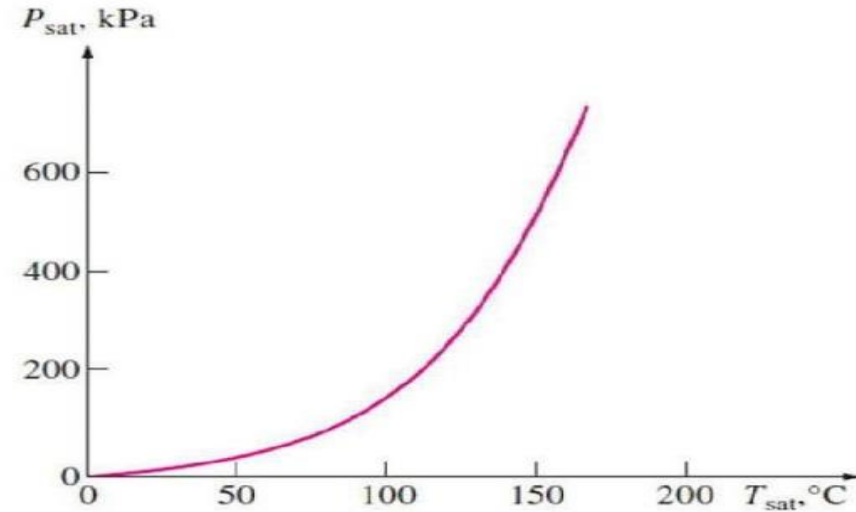


T-v diagram for the heating process of water at constant pressure.

2. A Review to Thermodynamics

2.2.3. Saturation Temperature and Saturation Pressure

- The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.
- At a **given pressure**, the temperature at which a pure substance changes phase is called the **saturation temperature** T_{sat} .
- Likewise, at a **given temperature**, the pressure at which a pure substance changes phase is called the **saturation pressure** P_{sat} .

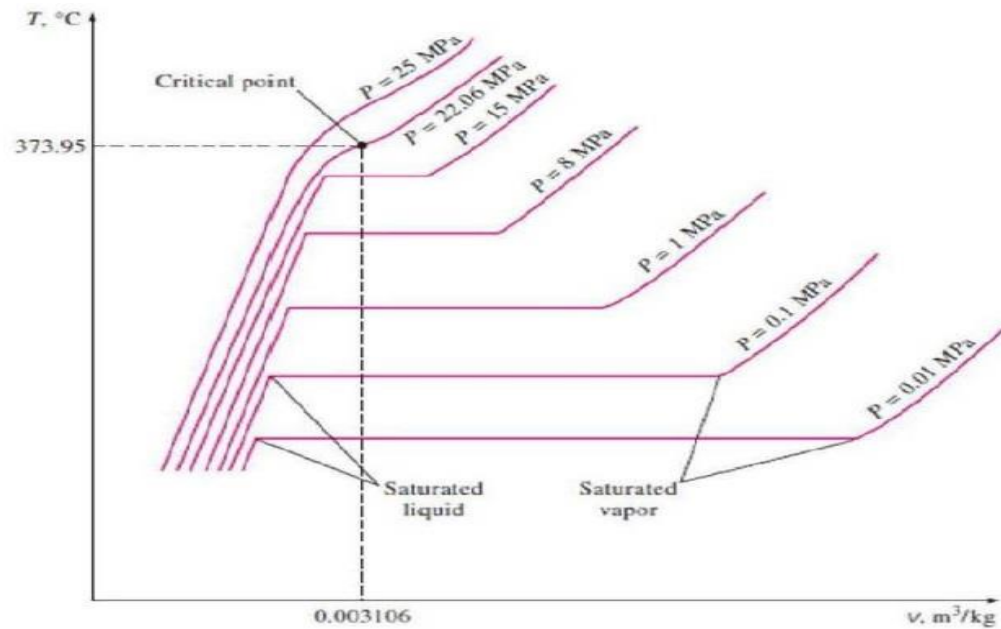


The liquid–vapor saturation curve of water

2. A Review to Thermodynamics

2.2.4. Property Diagrams for Phase-Change Processes of Water

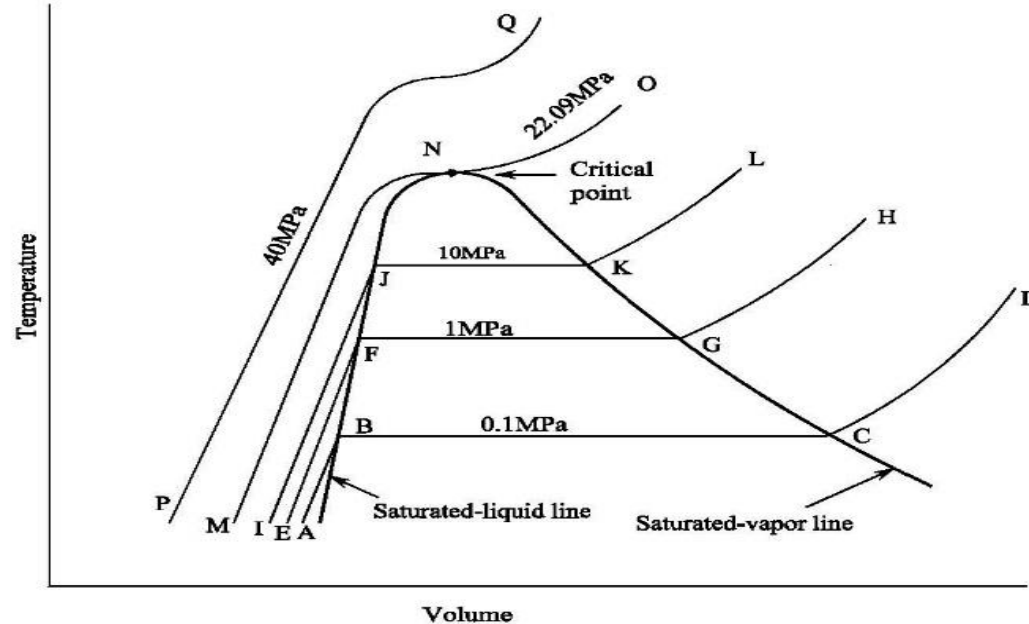
- T - v diagram of constant-pressure phase-change processes



2. A Review to Thermodynamics

States and change of phases of a pure substance (eg. water)

- Saturation temperature
- Saturation pressure
- Compressed liquid
- Saturated liquid
- Saturation region (mixture of vapor and liquid in equilibrium)
- Saturated vapor
- Superheated vapor

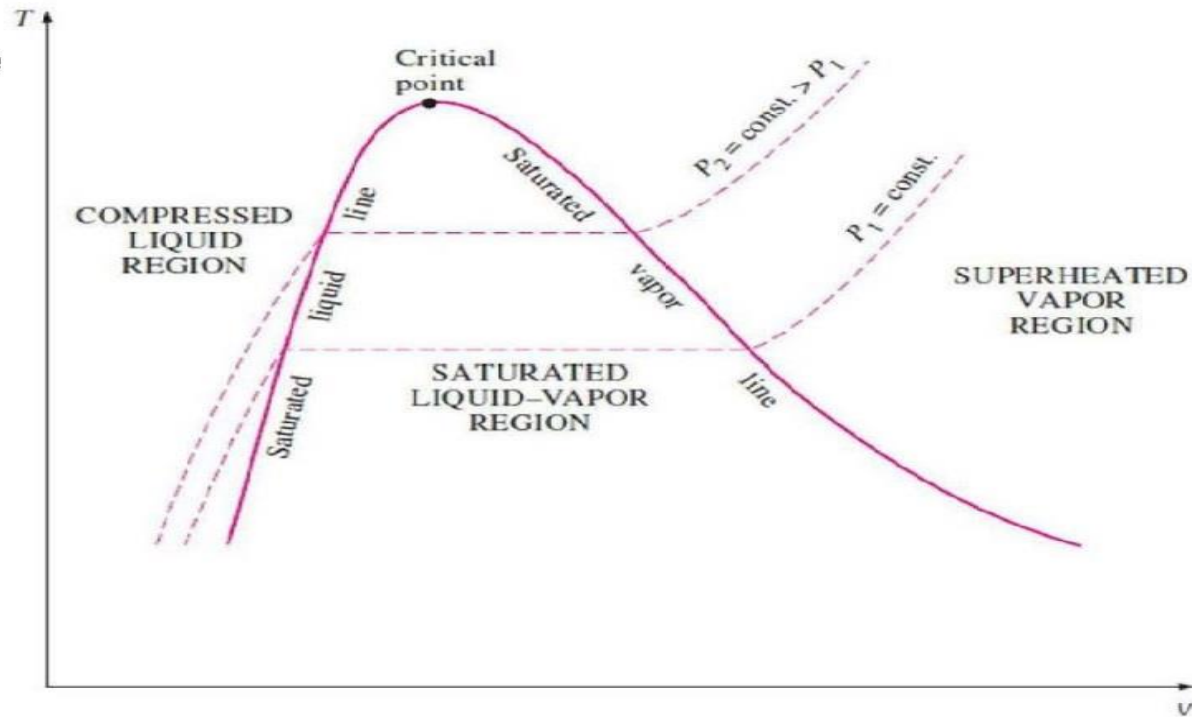


Temperature-volume diagram for water

2. A Review to Thermodynamics

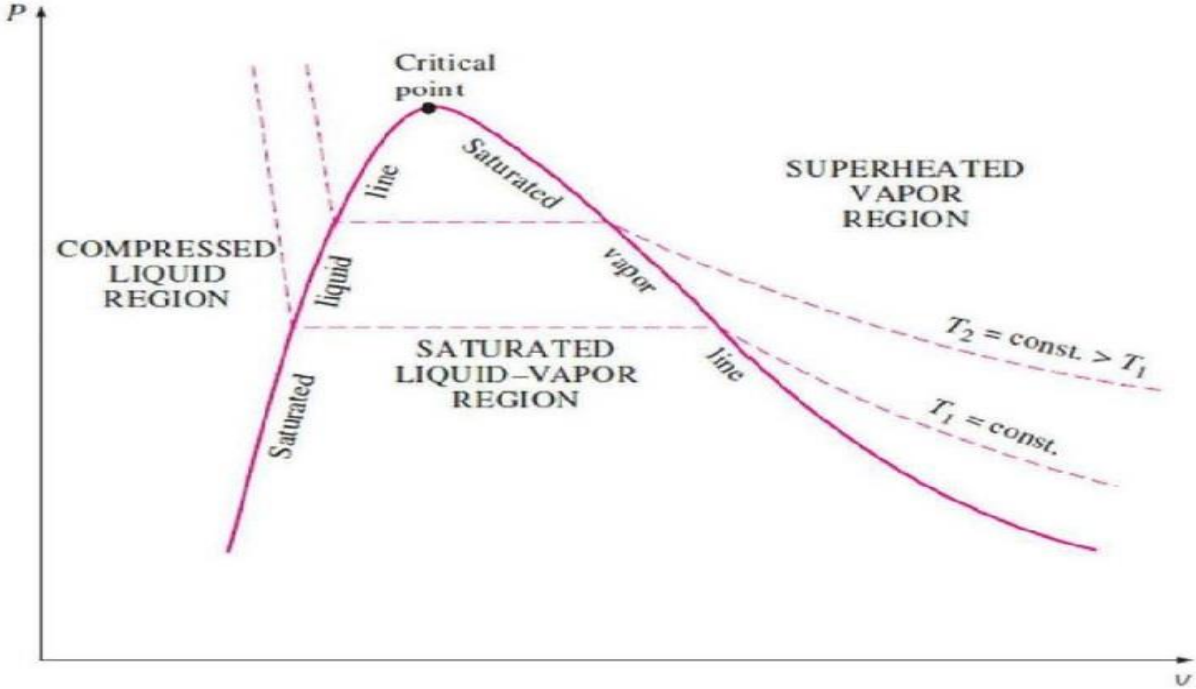
- **The T-v Diagram**

- Saturation temperature
- Saturation pressure
- Compressed liquid
- Saturated liquid
- Saturation region (mixture of vapor and liquid in equilibrium)
- Saturated vapor
- Superheated vapor



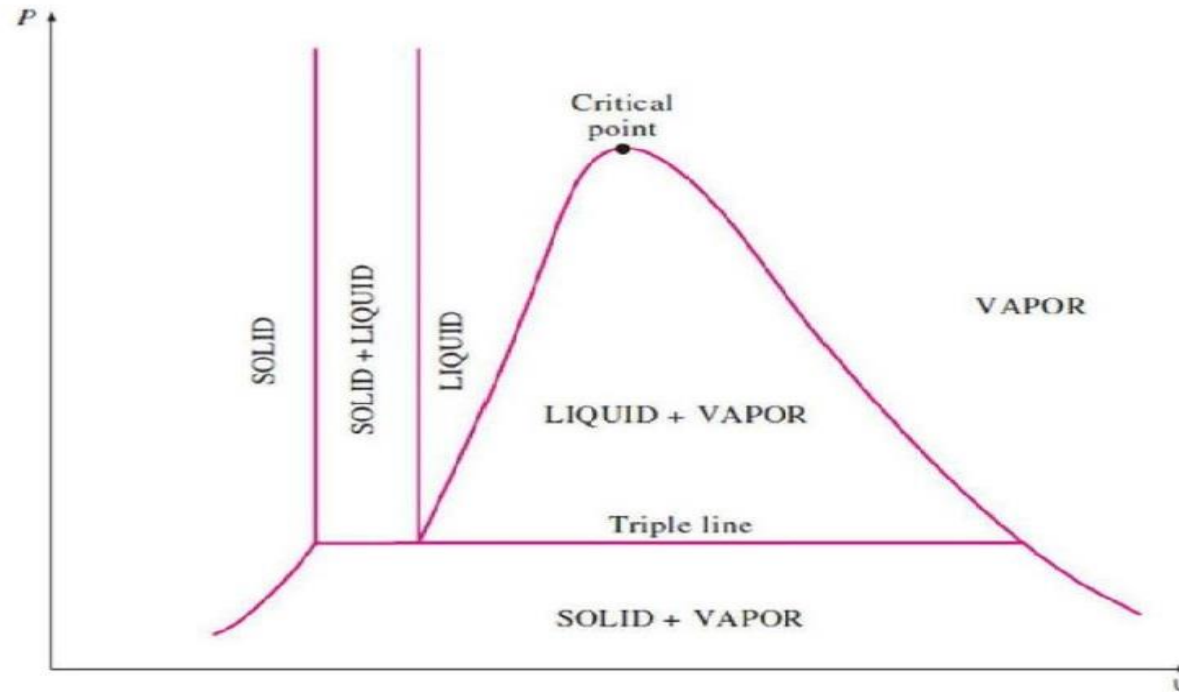
2. A Review to Thermodynamics

- The P-v Diagram



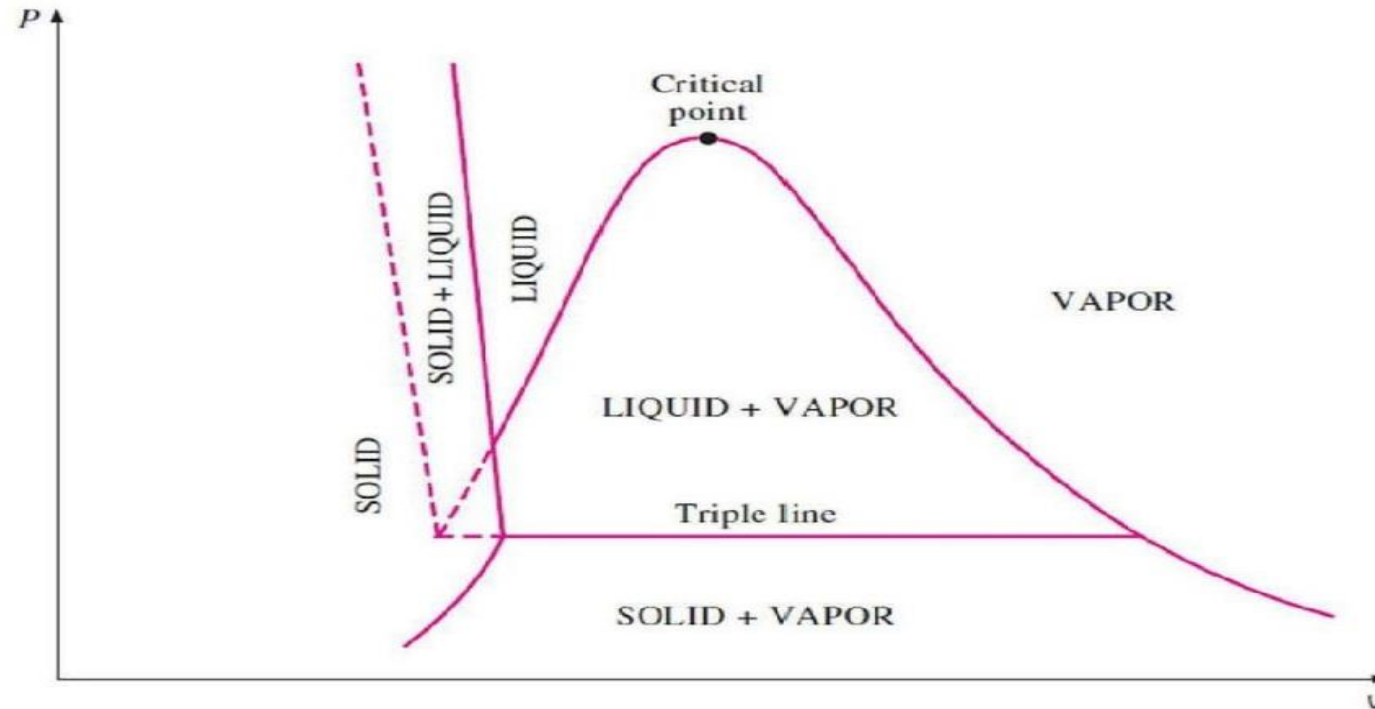
2. A Review to Thermodynamics

- P - v diagram of a substance that contracts on freezing



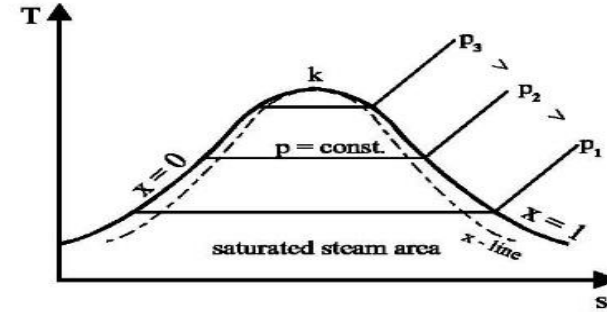
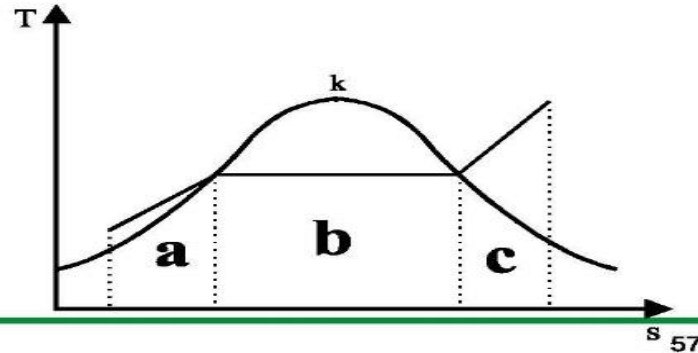
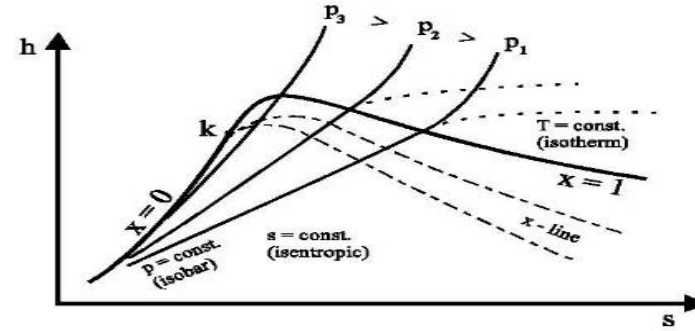
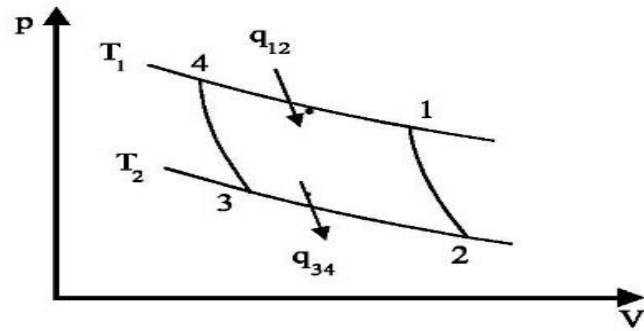
2. A Review to Thermodynamics

- P - v diagram of a substance that expands on freezing (such as water).



2. A Review to Thermodynamics

These two dimensional phase diagrams are usually used in thermodynamics. In power plant the T-s and h-s diagrams are frequently used



2. A Review to Thermodynamics

2.3. Energy

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy** E of a system.
- Thermodynamics provides no information about the absolute value of the total energy.
 - It deals only with the *change* of the total energy, which is what matters in engineering problems.
 - Thus the total energy of a system can be assigned a value of zero ($E = 0$) at some convenient reference point.
 - The change in total energy of a system is independent of the reference point selected.

2. A Review to Thermodynamics

- In thermodynamic analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups: *macroscopic* and *microscopic*.
- The **macroscopic** forms of energy are those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.
 - It is related to motion and the influence of some external effects such as gravity, magnetism, electricity, and surface tension.
- The **microscopic** forms of energy are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames.
 - The sum of all the microscopic forms of energy is called the internal energy of a system and is denoted by U .

2. A Review to Thermodynamics

- The magnetic, electric, and surface tension effects are significant in some specialized cases only and are usually ignored.
- In the absence of such effects, the total energy of a system consists of the kinetic, potential, and internal energies and is expressed as

$$E = U + \text{KE} + \text{PE} = U + m \frac{V^2}{2} + mgz \quad (\text{kJ})$$

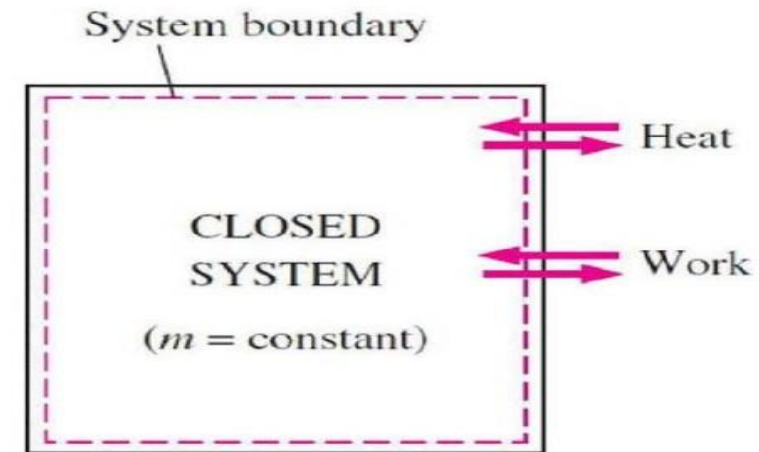
- or, on a unit mass basis,

$$e = u + \text{ke} + \text{pe} = u + \frac{V^2}{2} + gz \quad (\text{kJ/kg})$$

2. A Review to Thermodynamics

Heat and Work

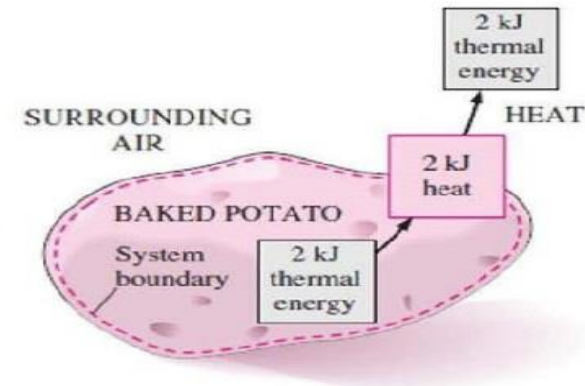
- Energy can cross the boundary of a closed system in two distinct forms: **heat and work**
- Work output/input and heat transfer are the two principal ways of energy exchange between a thermodynamic system and its environment.
- The energy contained in ordered motion (**Work**) can be totally converted to random motion (**Heat**). However, the energy contained in **random motion** can not be totally converted to **ordered motion**.
- The inequality of the conversion between heat and work is the basis of the second law of thermodynamics



2. A Review to Thermodynamics

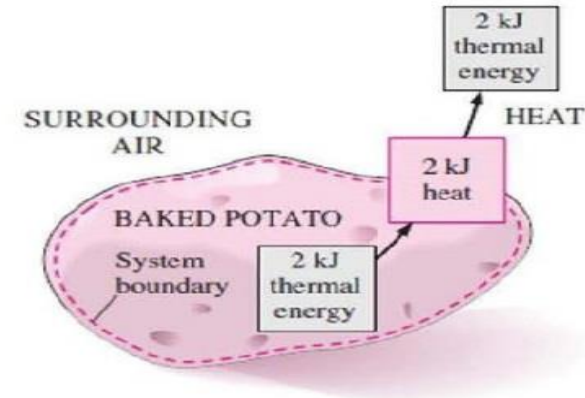
Heat

- ***Heat is a form of energy that is transferred across the boundary of a system to another system or surroundings due to a temperature difference existing between them***
- Heat transfer is carried out by means of random motion of atoms and molecules.
- Heat is energy in transition. It is recognized only as it crosses the boundary of a system.
- Consider the hot baked potato:
- The potato contains energy, but this energy is heat transfer only as it passes through the skin of the potato (the system boundary) to reach the air



2. A Review to Thermodynamics

- Once in the surroundings, the transferred heat becomes part of the internal energy of the surroundings.
- Thus, in thermodynamics, the term *heat* simply means *heat transfer*.
- The sign convention for heat uses a positive value if heat is transferred to the system from the surroundings and negative when heat is transferred from the system to the surroundings.
- A process during which there is no heat transfer is called an **adiabatic process**
- Heat is transferred by three mechanisms:
 - conduction,
 - convection, and
 - radiation.



2. A Review to Thermodynamics

Work

- Work, like heat, is an energy interaction between a system and its surroundings.
- Since energy can cross the boundary of a closed system in the form of heat or work, then ***if the energy crossing the boundary of a closed system is not heat, it must be work.***
- Heat is easy to recognize: Its driving force is a temperature difference between the system and its surroundings.
- Then we can simply say that an energy interaction that is not caused by a temperature difference between a system and its surroundings is work.
- More specifically, ***work is the energy transfer associated with a force acting through a distance.***
- A rising piston, a rotating shaft, and an electric wire crossing the system boundaries are all associated with work interactions.

2. A Review to Thermodynamics

- Work transfer is conducted through ordered motion of atoms or molecules.

$$W = \int_1^2 \mathbf{F} \cdot d\mathbf{s}$$

- ***Work is done by a system if the sole effect on the surroundings could be the raising of a weight***
- It is positive when work is done by a system or control volume on the surroundings and negative sign when work is done on the system or control volume by the surroundings.
- e.g. of work
 - changes in volume which is a result of boundary movement due to non equilibrium situations (expansion and compression),
 - A rising piston
 - shaft rotation in turbines, pumps, fans etc
 - an electric wire crossing the system boundaries

2. A Review to Thermodynamics

2.4. The First law of thermodynamics

- *Is the conservation of energy principle and states that energy can be neither created nor destroyed during a process; it can only change forms.*
 - In any process, the total energy of the universe remains constant; it can neither be produced nor destroyed.
 - For a system undergoes a cyclic process it states that the cyclic integral of the heat equals the cyclic integral of the work.

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

i.e.

- **During a cycle only work and heat cross the boundary of the system;**
- **as there will be no change in the properties of the system at the end of the cycle**

2. A Review to Thermodynamics

The First law for a system undergoing a process

“The increase in the internal energy of a thermodynamic system is equal to the amount of heat energy added to the system minus the work done by the system on the surroundings.”

- **Generally the first law of thermodynamics can be simplified as:**

$$Q_{1,2} - W_{1,2} = U_2 - U_1 \text{ (close process)}$$

$$Q_{1,2} - W_{1,2} = H_2 - H_1 \text{ (open process)}$$

- Where
 - Q = heat supplied to the system
 - W = work done by system
 - U = internal energy
 - H = enthalpy

2. A Review to Thermodynamics

2.5. The second law of thermodynamics

- There is no process known to have taken place in violation of the first law of thermodynamics.
 - Therefore, it is reasonable to conclude that a process must satisfy the first law to occur.
- However satisfying the first law alone does not ensure that the process will actually take place.

E.g. Consider a cup of hot coffee left in a cooler room;

- The coffee eventually cools off and satisfies the 1st law since the amount of energy lost by the coffee is equal to the amount gained by the surrounding air
- Now consider the reverse process- heating of the coffee by absorbing heat from the surrounding air. this process never takes place, yet satisfies the 1st law



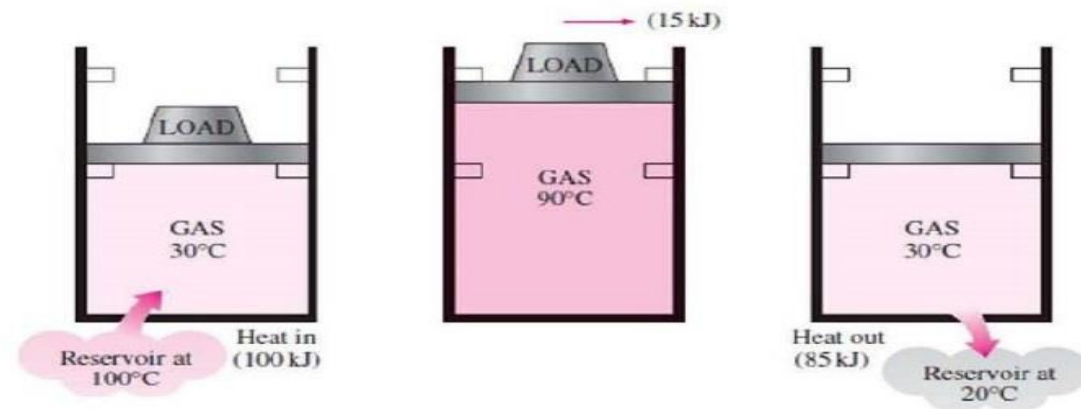
2. A Review to Thermodynamics

- The first law places no restriction on the direction of a process
- This inadequacy of the first law is remedied by introducing another general principle, the **second law of thermodynamics**.
- The second law also asserts that energy has quality as well as quantity.
 - The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality.
 - the second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process.
- The second law of thermodynamics is also used in determining the theoretical limits for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting the degree of completion of chemical reactions.

2. A Review to Thermodynamics

Can We Save Q_{out} ?

- In a steam power plant, the condenser is the device where large quantities of waste heat is rejected to rivers, lakes, or the atmosphere.
- **Question:** Can we not just take the condenser out of the plant and save all that waste energy?
- **Answer: NO!** Because without a heat rejection process in a condenser, the cycle cannot be completed.
- This is demonstrated next with the help of a simple heat engine.



2. A Review to Thermodynamics

- **Kelvin–Planck Statement**
 - *“It is impossible to construct a device that will operate in a cycle and produce no effect other than the production of net work output and exchange of heat with a single heat source.”*
 - i.e. no heat engine can attain a cycle thermal efficiency of 100%
- **The Clausius Statement:**
 - *“It is impossible to construct a device that operates in a cycle where the sole effect is only the transfer of heat from a cooler body to a hotter body.”*
 - OR**
 - Heat cannot be transferred from a low temperature body to a high temperature body on its own accord or spontaneously

2. A Review to Thermodynamics

Reversible and Irreversible Processes

- If a system undergoes a process from the initial state to the final state, and then the system moves back to the initial state in a reversed direction along the same path without causing any net effect on either the system or its environment, then this process is said to be a **reversible process**.
- Reversible processes actually do not occur in nature. They are merely *idealizations* of actual processes and all actual processes are, **irreversible**
- Reversible processes can be viewed as *theoretical limits* for the corresponding irreversible ones.
- Sources of Irreversibility:
 - Presence of inherent dissipative effects such as friction
 - Presence of a non quasi equilibrium process, occurring due to finite temperature difference

2. A Review to Thermodynamics

Entropy

- The second law of thermodynamics often leads to expressions that involve inequalities.
- For example, an irreversible (i.e., actual) heat engine is less efficient than a reversible one operating between the same two thermal energy reservoirs.
- Another important inequality that has major consequences in thermodynamics is the **Clausius inequality**.

$$\oint \frac{\delta Q}{T} \leq 0$$

- This inequality is valid for all cycles, reversible or irreversible.
- The equality in the Clausius inequality holds for reversible cycles and the inequality for the irreversible ones.

2. A Review to Thermodynamics

Entropy: is a property which can be defined as:

$$dS \geq \left(\frac{dQ}{T} \right) \quad \text{where the equality is for reversible process and the inequality is for irreversible processes}$$

Removing the inequality sign we can rewrite as:

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$

Entropy change of the system
Entropy transfer to the system
Entropy generated in the system due to irreversibilities

$S_{gen} \begin{cases} > 0 \text{ irreversible process} \\ = 0 \text{ reversible process} \\ < 0 \text{ impossible process} \end{cases}$

For isolated system

$$\Delta S_{isol} = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$

$$\Rightarrow S_{gen} \geq 0$$

Thus, for an isolated system containing a system and its surrounding we have: $\Delta S_{isol} = S_{gen} = \Delta S_{system} + \Delta S_{surr} \geq 0$

Increase in Entropy Principle

From the above and the 1st law we can deduce the following:

$$TdS = dU + pdV \quad \text{where } S = \text{entropy} \quad U = \text{internal energy}$$

$$= dH - Vdp \quad \quad \quad p = \text{pressure} \quad V = \text{volume}$$

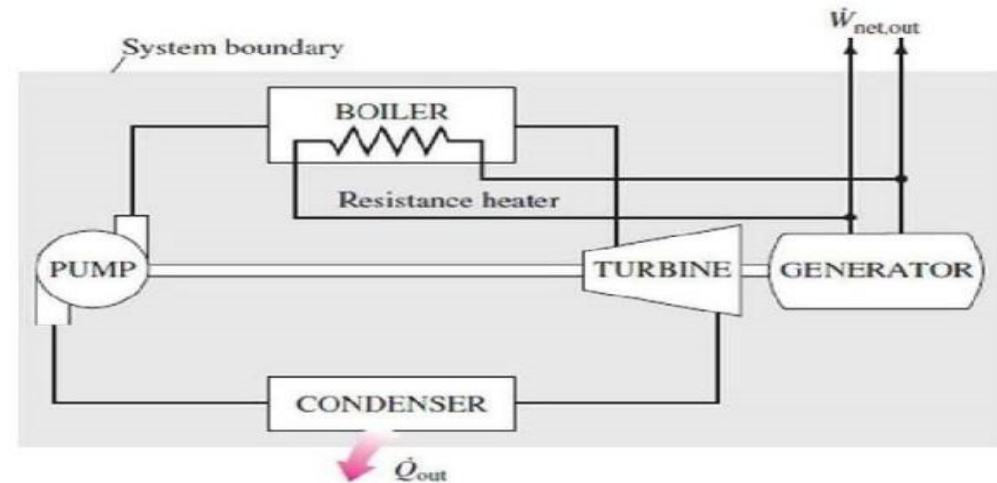
$$\quad \quad \quad \quad \quad \quad \quad T = \text{temperature} \quad H = \text{enthalpy}$$

PERPETUAL-MOTION MACHINES

- A process cannot take place unless it satisfies both the first and second laws of thermodynamics
- Any device that violates either law is called a **perpetual-motion machine**,
 - and despite numerous attempts, no perpetual-motion machine is known to have worked.
 - But this has not stopped inventors from trying to create new ones.
- A device that violates the first law of thermodynamics (by *creating* energy) is called a **perpetual-motion machine of the first kind** (PMM1), and
- a device that violates the second law of thermodynamics is called a **perpetual-motion machine of the second kind** (PMM2).

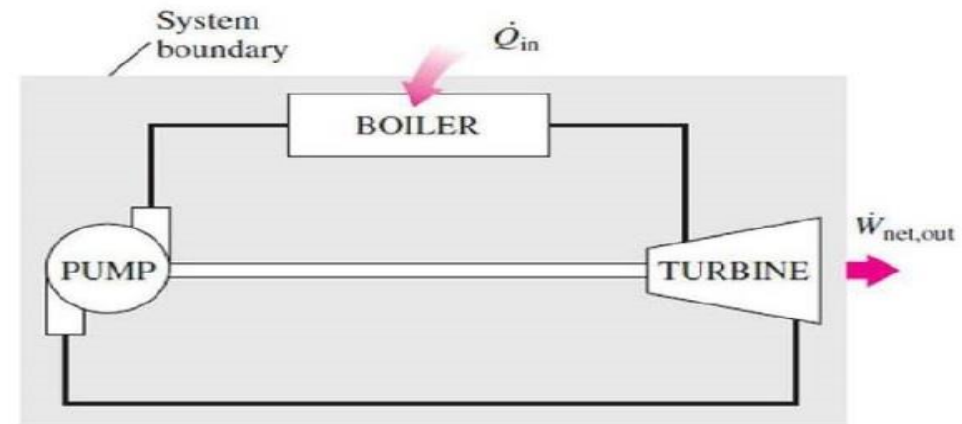
- **Examples of Perpetual-motion Machines**

- It is proposed to heat the steam by resistance heaters placed inside the boiler, instead of by the energy supplied from fossil or nuclear fuels.
- Part of the electricity generated by the plant is to be used to power the resistors as well as the pump.
- The rest of the electric energy is to be supplied to the electric network as the net work output.
- The inventor claims that once the system is started, this power plant will produce electricity indefinitely without requiring any energy input from the outside.



A perpetual-motion machine that violates the first law of thermodynamics (PMM1).

- The same inventor suggests getting rid of this wasteful component and sending the steam to the pump as soon as it leaves the turbine
- This way, all the heat transferred to the steam in the boiler will be converted to work, and thus the power plant will have a theoretical efficiency of 100 %.
- The inventor realizes that some heat losses and friction between the moving components are unavoidable and that reduce the efficiency somewhat, but still expects the efficiency to be no less than 80 percent (as opposed to 40 % in most actual power plants).
- It satisfies the first law but violates the second law, and therefore it will not work hence is PMM2.



A perpetual-motion machine that violates the second law of thermodynamics (PMM2).

2. A Review to Thermodynamics

2.7. Property Tables

- There are three ways to calculate the properties of a pure substance at a given state
 - Manual calculations using equations of state (form **IAPWS-IF97**)
 - Special software (e.g. FluidExcel)
 - Property tables
- For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations.
 - Therefore, properties are frequently presented in the form of tables
- For water, the properties can be read directly from the tables provided that there are at least two known independent variable.

2. A Review to Thermodynamics

Water-Steam tables

- **For water-steam there are three different tables:**
 - the compressed liquid water,
 - the saturated and
 - the superheated tables
- The compressed liquid and superheated tables are conveniently used when pressure and temperature are given. The properties u , u , h and s , given without any subscripts, and can be directly read from the tables
- **NOTE:** In the absence of compressed liquid data, a general approximation is to treat compressed liquid as saturated liquid at the given temperature. Thus, values of saturated liquid properties from saturation tables at the given temperature can be used instead of compressed liquid tables. This is because the compressed liquid properties depend on temperature much more strongly than they do on pressure.

2. A Review to Thermodynamics

Saturated Liquid and Saturated Vapor States

- The properties of saturated liquid and saturated vapor for water are given in two ways:
 - Temperature table: tabulated as a function of temperature
 - Pressure table: tabulated as a function of pressure
- The subscript f is used to denote properties of a saturated liquid, and the subscript g to denote the properties of saturated vapor
- Another subscript commonly used is fg , which denotes the difference between the saturated vapor and saturated liquid values of the same property.
 - v_f specific volume of saturated liquid
 - v_g specific volume of saturated vapor
 - v_{fg} difference between v_g and v_f ; that is, $v_{fg} = v_g - v_f$

2. A Review to Thermodynamics

- For saturated liquid or saturated vapour direct reading at the give temperature or pressure
- For mixture of saturated liquid and saturated vapour

$$\begin{aligned}V &= V_f + V_g \\m\nu &= m_f\nu_f + m_g\nu_g \\ \Rightarrow \nu &= \frac{m_f\nu_f}{m} + \frac{m_g\nu_g}{m} \\ &= \frac{(m - m_g)}{m}\nu_f + x\nu_g \\ &= (1 - x)\nu_f + x\nu_g = \nu_f + x\nu_{fg}\end{aligned}$$

Where x is the quality of steam given by:

$$x = \frac{m_g}{m_{total}} = \frac{m_g}{m_g + m_f}$$

2. A Review to Thermodynamics

Similarly we can write:

$$v = (1-x)v_f + xv_g = v_f + x(v_g - v_f) = v_f + xv_{fg}$$

$$h = (1-x)h_f + xh_g = h_f + x(h_g - h_f) = h_f + xh_{fg}$$

$$u = (1-x)u_f + xu_g = u_f + x(u_g - u_f) = u_f + xu_{fg}$$

$$s = (1-x)s_f + xs_g = s_f + x(s_g - s_f) = s_f + xs_{fg}$$

- The quantity h_{fg} is called the **enthalpy of vaporization** (or latent heat of vaporization). It represents the amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.

Steady State Steady Flow (SSSF) Open System

We will now discuss the *steady-state open system*, also called the *steady-state steady-flow (SSSF) system*. This is one in which mass and energy flows across the boundaries do *not* vary with time and in which the mass within the system remains constant. The SSSF system, applicable to mechanical energy (i.e., ignoring electrical, magnetic, chemical, and other effects) is shown schematically in Fig. 1-1. The first-law equation for that system is...

$$PE_1 + KE_1 + IE_1 + FE_1 + \Delta Q = PE_2 + KE_2 + IE_2 + FE_2 + \Delta W_{sf} \quad (1-1a)$$

where the subscripts 1 and 2 indicate the inlet and exit stations of the open system. Equation (1-1a) assumes for simplicity that only one inlet and one exit exist, although the SSSF equation can be written easily enough for multiple inlets, exits, or both. In Eq. (1-1a)

$$PE = \text{potential energy} = mz \frac{g}{g_c} \quad (1-2)$$

where m is the mass of a quantity of matter or fluid entering and leaving the system (both equal in SSSF), z is the elevation of stations 1 or 2 above a common datum, g is the gravitational acceleration, and g_c is a conversion factor numerically equal to $32.2 \text{ lb}_m \cdot \text{ft}/(\text{lb}_f \cdot \text{s}^2)$ or $1.0 \text{ kg} \cdot \text{m}/(\text{N} \cdot \text{s}^2)$

$$KE = \text{kinetic energy} = m \frac{V_z^2}{2g_c} \quad (1-3)$$

where V_z is the velocity of the mass at 1 or 2.

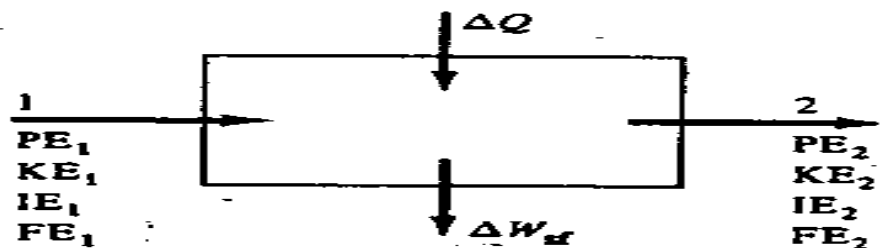


Figure 1-1 Schematic of a steady-state steady-flow (SSSF) system with one inlet and one outlet.

$$\text{IE} = \text{internal energy} = U \quad (1-4)$$

Internal energy is a sole function of temperature for perfect gases and a strong function of temperature and weak function of pressure for nonperfect gases, vapors, and liquids. It is a measure of the internal (molecular) activity and interaction of the fluid.

$$\text{FE} = \text{flow energy} = PV = Pmv \quad (1-5)$$

Flow energy, or flow work, is the work done by the flowing fluid to push the quantity represented by mass m into, and out of, the system. Mathematically it is equal to the product of pressure P and volume V .

$$\Delta Q = \text{net heat added} = Q_A - |Q_R| \quad (1-6)$$

where Q_A is heat *added* to (entering) and Q_R is the heat *rejected* by (leaving) the system across its boundaries. It is convenient to consider that heat added is positive and heat rejected is negative. Mathematically

$$\Delta Q = mc_n(T_2 - T_1) \quad (1-7)$$

where c_n is a specific heat that depends upon the process taking place between 1 and 2. Values for c_n for various processes are given in Table 1-1.

$$\begin{aligned} \Delta W_{sf} &= \text{net steady-flow mechanical work done by the system} \\ &= W_{by} - |W_{on}| \end{aligned} \quad (1-8)$$

where W_{by} is the work done by the system and W_{on} is the work done on the system. The convention is that the work done by the system is positive and the work done on the system is negative. Mathematically the steady-flow work is given by

$$\Delta W_{sf} = - \int_1^2 V dP \quad (1-9)$$

Equation (1-9) requires a relationship between pressure P and volume V for evaluation. The most general relationship is given by

$$PV^n = \text{constant} \quad (1-10)$$

where n is called the *polytropic exponent* and varies from zero to infinity. Its value for certain processes is given in Table 1-1.

Table 1-1 Values of c_n and n for various processes

Process	c_n	n
Constant pressure	c_p	0
Constant temperatures	∞	1
Adiabatic reversible	0	$k = \frac{c_p}{c_v}$
Constant volume	c_v	∞
Polytropic	$c_v \frac{k - n}{1 - n}$	0 - ∞

Equation (1-1a) may now be written for mass m entering and leaving the system as

$$\begin{aligned}
 mz_1 \frac{g}{g_c} + m \frac{V_{s1}^2}{2g_c} + U_1 + P_1 V_1 + \Delta Q \\
 = mz_2 \frac{g}{g_c} + m \frac{V_{s2}^2}{2g_c} + U_2 + P_2 V_2 + \Delta W_{st}
 \end{aligned} \quad (1-1b)$$

and for a unit mass

$$\begin{aligned}
 z_1 \frac{g}{g_c} + \frac{V_{s1}^2}{2g_c} + u_1 + P_1 v_1 + \Delta q \\
 = z_2 \frac{g}{g_c} + \frac{V_{s2}^2}{2g_c} + u_2 + P_2 v_2 + \Delta w_{st}
 \end{aligned} \quad (1-1c)$$

where the lowercase symbols represent specific values of the uppercase ones, i.e., per unit mass. Thus u = specific internal energy = U/m , v = specific volume = V/m , etc.

Equations of some open (SSSF) systems

1. A steam generator

$$\Delta W_{sf} = 0$$

$$PE_2 - PE_1 = \text{negligible}$$

$$KE_2 - KE_1 = \text{negligible}$$

Thus

$$\Delta Q = H_2 - H_1 \quad (1-20a)$$

and

$$\Delta q = h_2 - h_1 \quad (1-20b)$$

2. A gas or steam turbine

$$\Delta Q = \text{negligible}$$

$$PE_2 - PE_1 = \text{negligible}$$

$$KE_2 - KE_1 = \text{negligible}$$

thus

$$\Delta W_{sf} = H_1 - H_2 \quad (1-21a)$$

and

$$\Delta w_{sf} = h_1 - h_2 \quad (1-21b)$$

3. A water (or incompressible fluid) pump

$$\Delta Q = \text{negligible}$$

$$PE_2 - PE_1 = 0 \quad (\text{considering immediate inlet and exit})$$

$$KE_2 - KE_1 = \text{negligible}$$

$$U_2 = U_1$$

And, because water is essentially incompressible and little or no change in temperature or volume takes place,

$$V_2 = V_1 = V$$

Thus $\Delta W_{sf} = FE_1 - FE_2 = V(P_1 - P_2)$ (1-22a)

and $\Delta w_{sf} = v(P_1 - P_2)$ (1-22b)

Both should be negative.

4. A nozzle

$$\Delta Q = 0$$

$$\Delta W_{sf} = 0$$

$$PE_2 - PE_1 = 0 \quad (\text{considering immediate inlet and exit})$$

$$KE_1 = \text{usually negligible compared with } KE_2$$

Thus $V_{s2} = \sqrt{2g_c J(h_1 - h_2)}$ (1-23a)

$$= \sqrt{2g_c J c_p (T_1 - T_2)} \quad \text{ideal gas} \quad (1-23b)$$

$$= \sqrt{2g_c v (P_1 - P_2)} \quad \text{incompressible fluid} \quad (1-23c)$$

5. Throttling

$$\Delta Q = 0$$

$$\Delta W_{sf} = 0$$

$$PE_2 - PE_1 = 0 \quad \text{or negligible}$$

$$KE_2 - KE_1 = \text{negligible}$$

Thus $H_1 = H_2$ (1-24a)

and $h_1 = h_2$ (1-24b)