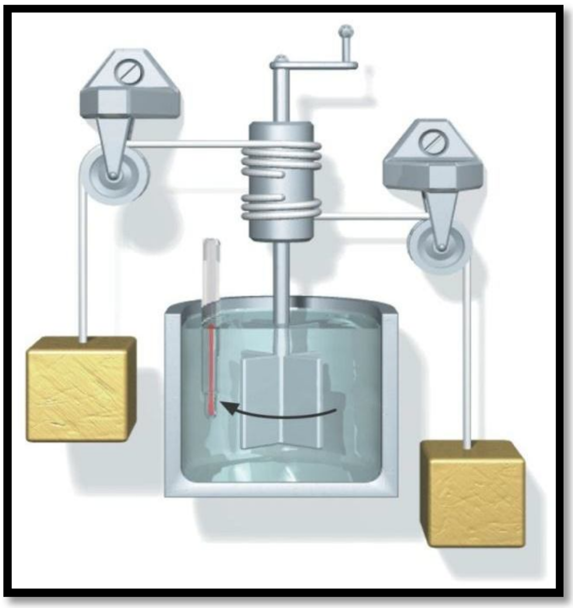
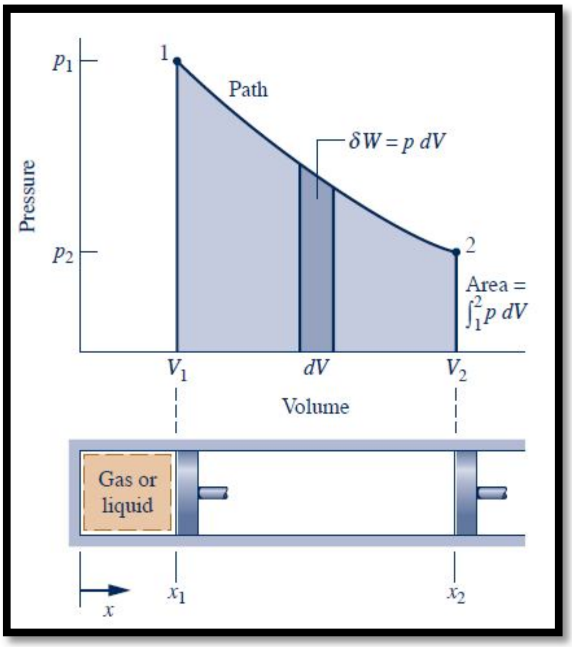
2

FIRST LAW OF THERMODYNAMICS





Course Contents

2.1 Introduction to 1st Law of Thermodynamics

- The first law of thermodynamics, also known as the conservation of energy principle. It states that *"Energy can neither be created nor destroyed; it can only change its form."*
- Total energy of an isolated system in all its form remains constant.
- The first law of thermodynamics cannot be proved mathematically but no process in nature is known to have violated the first law of thermodynamics.
- It is the relation of energy balance and is applicable to any kind of system (open or closed) undergoing any kind of process.

2.2 First Law Applied to a Cyclic Process – Joule's Experiment

- **Cyclic Process:** *"A process is cyclic if the initial and final states of the system executing the process are identical."*
- A system represented by a state point 1 undergoes a process 1-a-2, and comes back to initial state following the path 2-b-1.
- All properties of the system are restored, when the initial state is reached.
- During the execution of these processes:

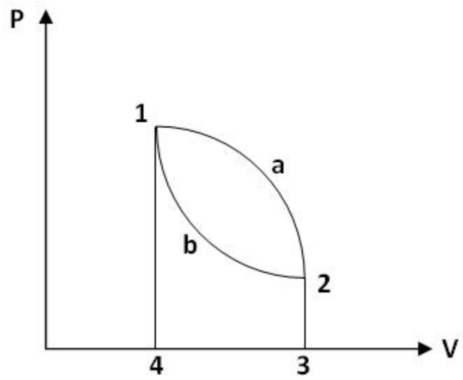


Fig. 2.1 Cyclic process

  i. Area 1-a-2-3-4-1 represents the work done by the system (W_1) during expansion process 1-a-2.
  ii. Similarly area 2-3-4-1-b-2 gives work supplied to the system (W_2) during compression process 2-b-1.
  iii. Area 1-a-2-b-1 represents the net work $(W_1 - W_2)$ delivered by the system.
- Since the system regains its initial state, there is no change in the energy stored by the system.
- For a cyclic process, the First Law of Thermodynamics can be stated as follows :

  "When a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to net work done by the system on its surroundings."

  Mathematically,

$$\oint \delta Q = \oint \delta W - - - - - - - - -(2.1)$$

Joule's Experiment

- The first law can be illustrated by considering the following experiment (Fig. 2.2).

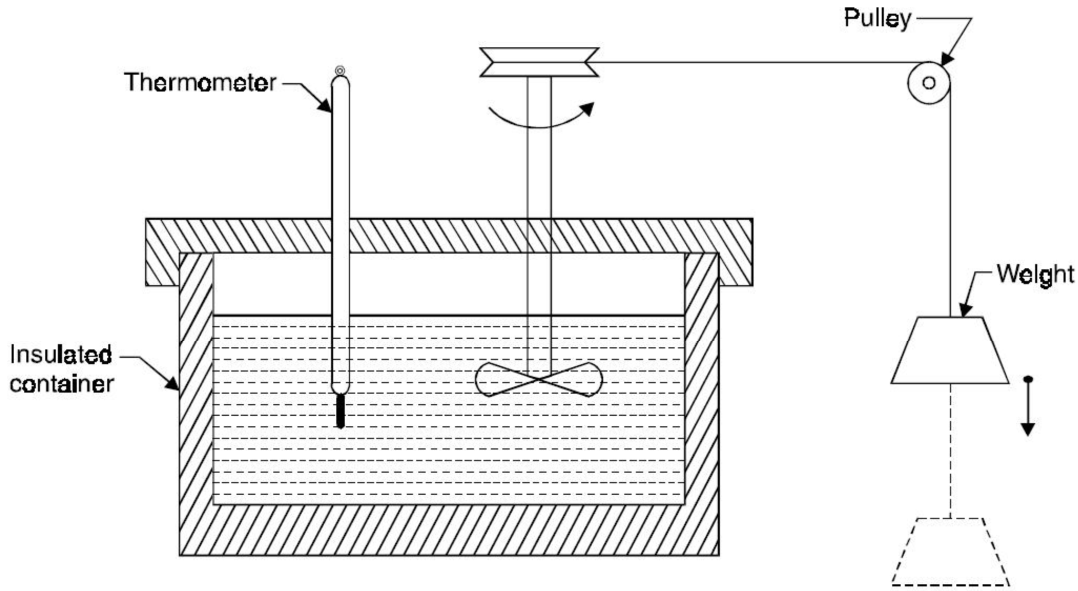


Fig. 2.2 Joule's paddle-wheel experiment

- A known mass of water is taken into a rigid and well insulated container provided with a paddle wheel.
- The insulation is provided to prevent any heat interaction with surroundings.
- The work input to the paddle wheel is measured by the fall of weight while the corresponding temperature rise of the liquid in the insulated container is measured by the thermometer.
- Joule conducted a number of experiments involving different types of work interactions and found that the work expended was proportional to increase in thermal energy, i.e.

$$Q \propto W$$
$$\therefore Q = \frac{W}{J}$$
$$\therefore W = JQ$$

Where,

$J =$ Joule's equivalent or mechanical equivalent of heat

- In SI system of units, both heat and work are measured in Joules.

2.3 First Law Applied to a Process

- The first law of thermodynamics is often applied to a process as the system changes from one state to another.
- According to first law of thermodynamics,

$$\Delta E = Q - W - - - - - - - - -(2.2)$$

Where,

$\Delta E = \Delta U + \Delta KE + \Delta PE + other\ forms\ of\ energy =$ Net change in total energy of the system

- If a ***closed system*** undergoes a change of state during which both heat and work transfer are involved, the net energy transfer will be stored or accumulated within the system. If Q is the heat transfer to the system and W is the work transferred from the system during process, the net energy transfer $(Q - W)$ will be stored in the system. Energy in storage is neither heat nor work and is given the name "***Internal Energy***" or "***Stored Energy***" of the system.

$$\therefore Q - W = \Delta U - - - - - - - - -(2.3)$$

- Most closed systems in practice are stationary, i.e. they do not involve kinetic energy and potential energy during the process. Thus the stationary systems are called non-flow systems and the first law of thermodynamics is reduced to equation 2.3.
- In differential form first law of thermodynamics for a process can be written as,

$$\delta Q - \delta W = dE - - - - - - - - -(2.4)$$

- Also for a ***cyclic process*** $\Delta U = 0$, as the system regains its original state hence,

$$Q - W = 0$$

$$\therefore Q = W - - - - - - - - -(2.5)$$

2.4 Internal Energy: A Property of the System

- Consider a closed system which changes from state 1 to state 2 by path A and returns back to original state 1 by one of the following path as shown in Fig.2.3:
  (i) 2-B-1 (ii) 2-C-1 (iii) 2-D-1

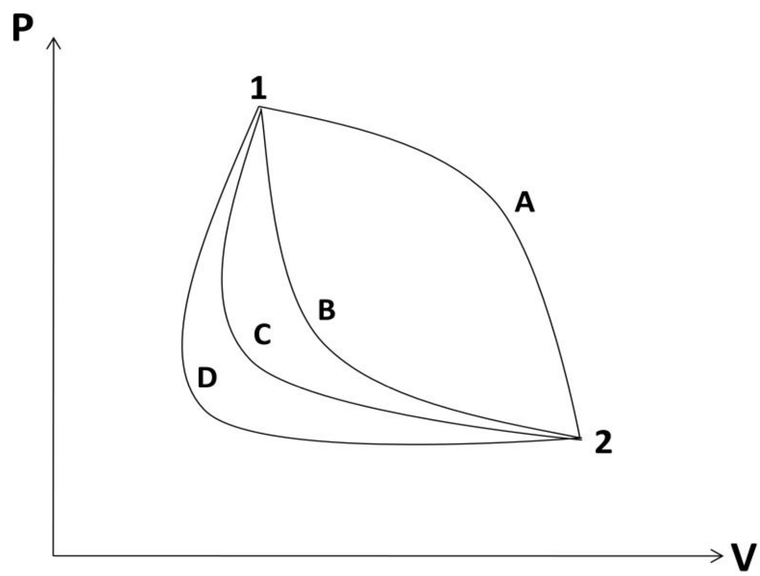


Fig. 2.3 Cyclic process with different paths

- Applying the 1st law for the cyclic process 1-A-2-**B**-1,

$$\oint (\delta Q - \delta W) = 0$$

$$\therefore \int_{1, via\ A}^{2} (\delta Q - \delta W) + \int_{2, via\ B}^{1} (\delta Q - \delta W) = 0 - - - - - - - - -(2.6)$$

Similarly,

- Applying the 1st law for the cyclic process 1-A-2-**C**-1,

$$\therefore \int_{1, via\ A}^{2} (\delta Q - \delta W) + \int_{2, via\ C}^{1} (\delta Q - \delta W) = 0 - - - - - - - - -(2.7)$$

And,

- Applying the 1st law for the cyclic process 1-A-2-**D**-1,

$$\therefore \int_{1, via\ A}^{2} (\delta Q - \delta W) + \int_{2, via\ D}^{1} (\delta Q - \delta W) = 0 - - - - - - - - -(2.8)$$

- Comparing equations 2.6, 2.7 and 2.8, we get,

$$\int_{2, via\ B}^{1} (\delta Q - \delta W) = \int_{2, via\ C}^{1} (\delta Q - \delta W) = \int_{2, via\ D}^{1} (\delta Q - \delta W)$$

- Since B, C and D represents arbitrary paths between the state point 2 and state point 1, it can be concluded that the integral $\int_2^1 (\delta Q - \delta W)$
  - (i) Remains the same irrespective of the path along which the system proceeds,
  - (ii) Is solely dependent on the initial and final states of the system; ***is a point function and hence property***.
- The integral $\int_2^1 (\delta Q - \delta w)$ is called energy of the system and is given by a symbol *E*.
- Further the energy is a property of the system; its differential is exact and is denoted by *dE*.
- Thus for a process,

$$\delta Q - \delta W = dE$$

- The energy, E is an extensive property.
- The specific energy $\left(e = \frac{E}{m}\right)$ is an intensive property.

2.5 First Law Applied to Steady Flow Processes

Conservation of Mass Principle – Continuity Equation

- Conservation of mass is one of the most fundamental principles for flow systems. ***"It states that the mass of a system can neither be created nor destroyed but its amount remains constant during any process. It only changes its form (phase)."***
- The conservation of mass principle for a control volume (CV) can be expressed as,

  Total mass entering CV – Total mass leaving CV = Net change in mass within CV

- The amount of mass flowing through a cross-section per unit time is called the ***mass flow rate*** and it is calculated as,

$$\dot{m} = \frac{AC}{v} ---------(2.9)$$

Where,
$\dot{m} =$ Mass flow rate in kg/sec,
$A =$ Cross-sectional area of flow in m^2,
$v =$ Specific volume of fluid in m^3/kg,
$C =$ Fluid velocity in m/sec.
Further,

$$Specific\ volume = \frac{1}{Density}$$

$$\therefore v = \frac{1}{\rho}$$

Equation (2.9) can be expressed as,

$$\dot{m} = \rho AC ---------(2.10)$$

- The volume flow rate through a cross-sectional area per unit time is called fluid ***discharge*** rate (Q),

$$Q = AC$$

- For a ***steady flow***,

$$\dot{m} = Constant = \rho_1 A_1 C_1 = \rho_2 A_2 C_2 ---------(2.11)$$

Steady and Un-steady Flow Process

- A flow process is said to be steady when the fluid parameters (P) at any point of the control volume remains constant with respect to time; the parameters may, however, be different at different cross-section of the flow passage.

$$\therefore \frac{\partial P}{\partial t} = 0$$

- A flow process is un-steady when the conditions vary with respect to time.

$$\therefore \frac{\partial P}{\partial t} \neq 0$$

Steady Flow Energy Equation (SFEE)

- ***Assumptions***

  The following assumptions are made in the steady flow system analysis:

  a) The mass flow through the system remains constant.

  b) Fluid is uniform in composition.

  c) The only interaction between the system and surroundings are work and heat.

  d) The state of fluid at any point remains constant with time.

  e) In the analysis only potential, kinetic and flow energies are considered.

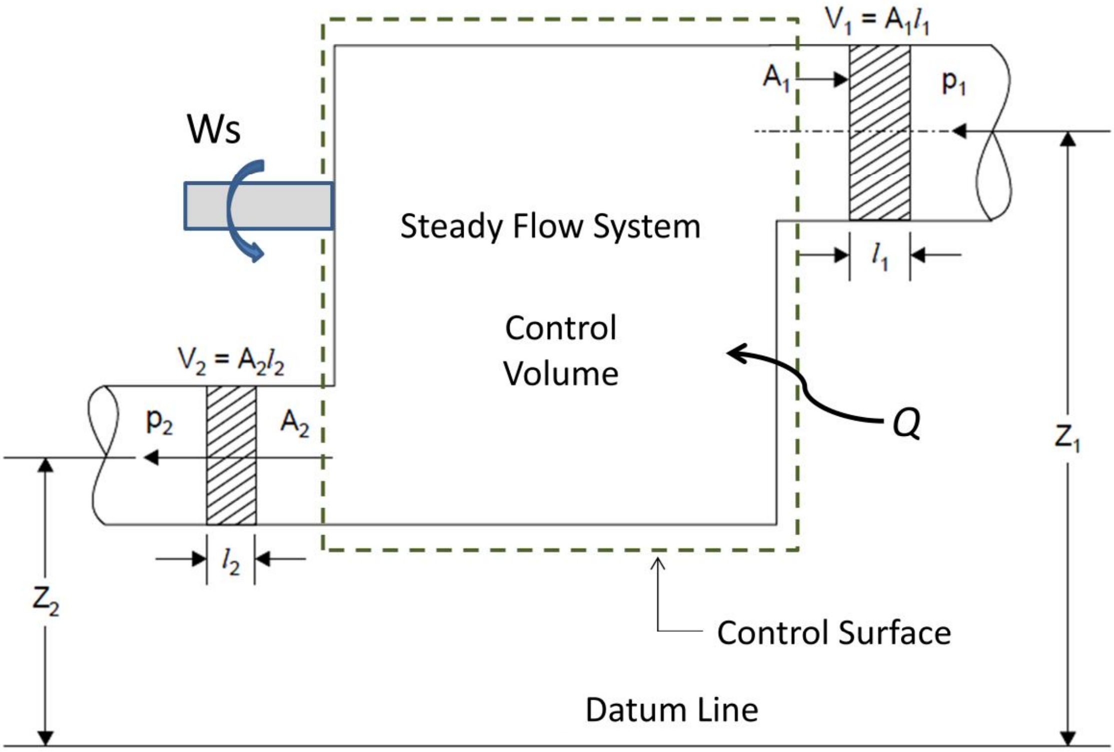


Fig. 2.4 Schematic flow process for an open system

- Consider a flow of fluid through an open system as shown in Fig. 2.4.
- During a small time interval dt there occurs a flow of mass and energy into the fixed control volume; entry is at section 1 and exit occurs at section 2.
- The fluid enters the control volume at section 1 with average velocity C_1, Pressure P_1, Specific volume v_1, and Specific internal energy u_1.
- The corresponding values at the exit section 2 are C_2, P_2, v_2 *and* u_2.
- Further during, the fluid flow between the two selected sections, heat (Q) and mechanical or shaft work (W_s) may also cross the control surface.
- The following species of energy are taken into account while drawing up the energy balance:

A. Internal energy stored by the fluid $= U$

B. Kinetic energy $= \frac{1}{2} mC^2$

C. Potential energy $= mgZ$

D. Flow work $= P_1 V_1$

E. Heat interaction $= Q$

F. Work interaction i.e. shaft work $= W_s$

- According to 1st law of thermodynamics, energy balance in the symbolic form may be written as,

$$m_1 \left(u_1 + P_1 v_1 + \frac{C_1^2}{2} + gZ_1 \right) + Q = m_2 \left(u_2 + P_2 v_2 + \frac{C_2^2}{2} + gZ_2 \right) + W_s \quad ---------(2.12)$$

- Equation (2.12) is the general steady flow energy equation (SFEE) and is equally applicable to compressible and incompressible; ideal and real fluids, liquids and gases.
- But according to assumption (1),

$$m = m_1 = m_2$$

Also enthalpy,

$$h = u + Pv$$

$$\therefore m \left(h_1 + \frac{C_1^2}{2} + gZ_1 \right) + Q = m \left(h_2 + \frac{C_2^2}{2} + gZ_2 \right) + W_s$$

- SFEE can be written on the basis of unit mass or on the basis of unit time.
- **SFEE on unit mass basis:**

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q = h_2 + \frac{C_2^2}{2} + gZ_2 + w_s \quad --------(2.13)$$

Here, all the terms represents energy flow per unit mass of the fluid (J/kg)

2.6 SFEE Applied to Engineering Applications

- The SFEE applies to flow processes in many of the engineering applications, such as Turbines, Compressors, Pumps, Heat exchangers and flows through nozzles and diffusers.
- In certain flow processes, some of the energy terms in SFEE are negligibly small and can be omitted without much error.

1. Nozzles and Diffusers

– A nozzle is a device for increasing the velocity of a steadily flowing steam at the expense of its pressure and hence enthalpy.
– A diffuser is a device that increases the pressure of a fluid by slowing it down. That is nozzles and diffusers perform opposite task.
– Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses. Fig. 2.5 shows a commonly used convergent-divergent nozzle.

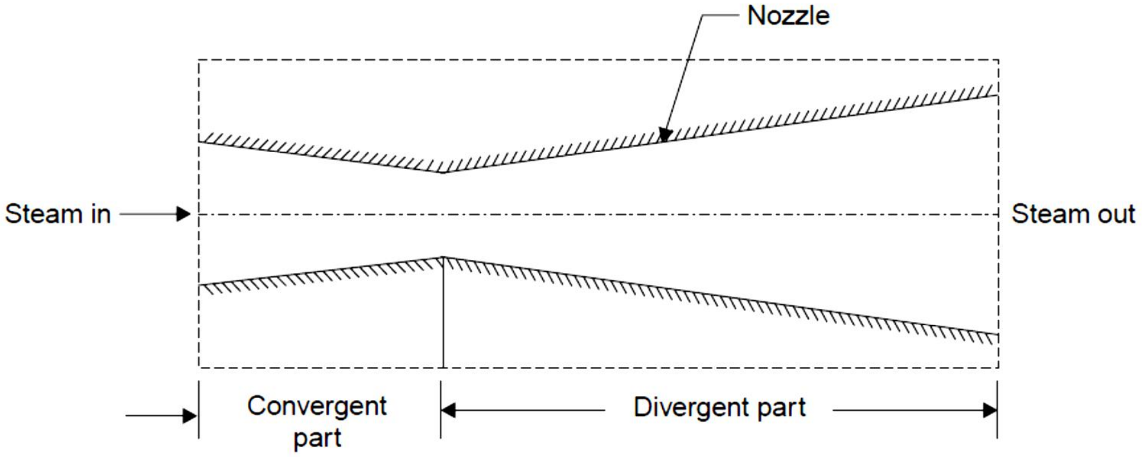


Fig. 2.5 A convergent-divergent nozzle

– Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

– The characteristic features of the flow through a ***nozzle*** are:
  - No shaft work; $W_s = 0$
  - If walls are thermally insulated; $Q = 0$
  - Nozzle is horizontal i.e No elevation difference between inlet and exit; $Z_1 = Z_2$

– Hence, the SFEE is reduced to

$$\therefore m\left(h_1 + \frac{C_1^2}{2}\right) = m\left(h_2 + \frac{C_2^2}{2}\right)$$

$$\therefore \frac{C_2^2}{2} - \frac{C_1^2}{2} = h_1 - h_2$$

$$\therefore C_2^2 - C_1^2 = 2(h_1 - h_2)$$

$$\therefore C_2 = \sqrt{C_1^2 + 2(h_1 - h_2)}$$

If, $C_1 <<<< C_2$, then,

$$C_2 = \sqrt{2(h_1 - h_2)}$$

– Similar way SFEE can be reduced for diffusers also.

2. Heat Exchangers

- Condensers and Evaporators are the main types of heat exchangers.
- These are the devices where the objective is to transfer heat energy between hot and cold fluids. Therefore the heat transfer rate cannot be taken as zero.
- These devices are widely used in refrigeration system, air conditioning system, thermal power plant and various industries.
- A ***steam condenser*** is also a heat exchanger in which steam losses heat as it passes over the tubes through which cold fluid is flowing.
- An ***evaporator*** is also a heat exchanger and is used to extract heat from the cold places or fluids.
- **Boiler** is a type of evaporator and hence heat exchanger; used for the generation of steam. Thermal energy released by combustion of fuel is transferred to water which vaporizes and gets converted into steam at the desired pressure and temperature.

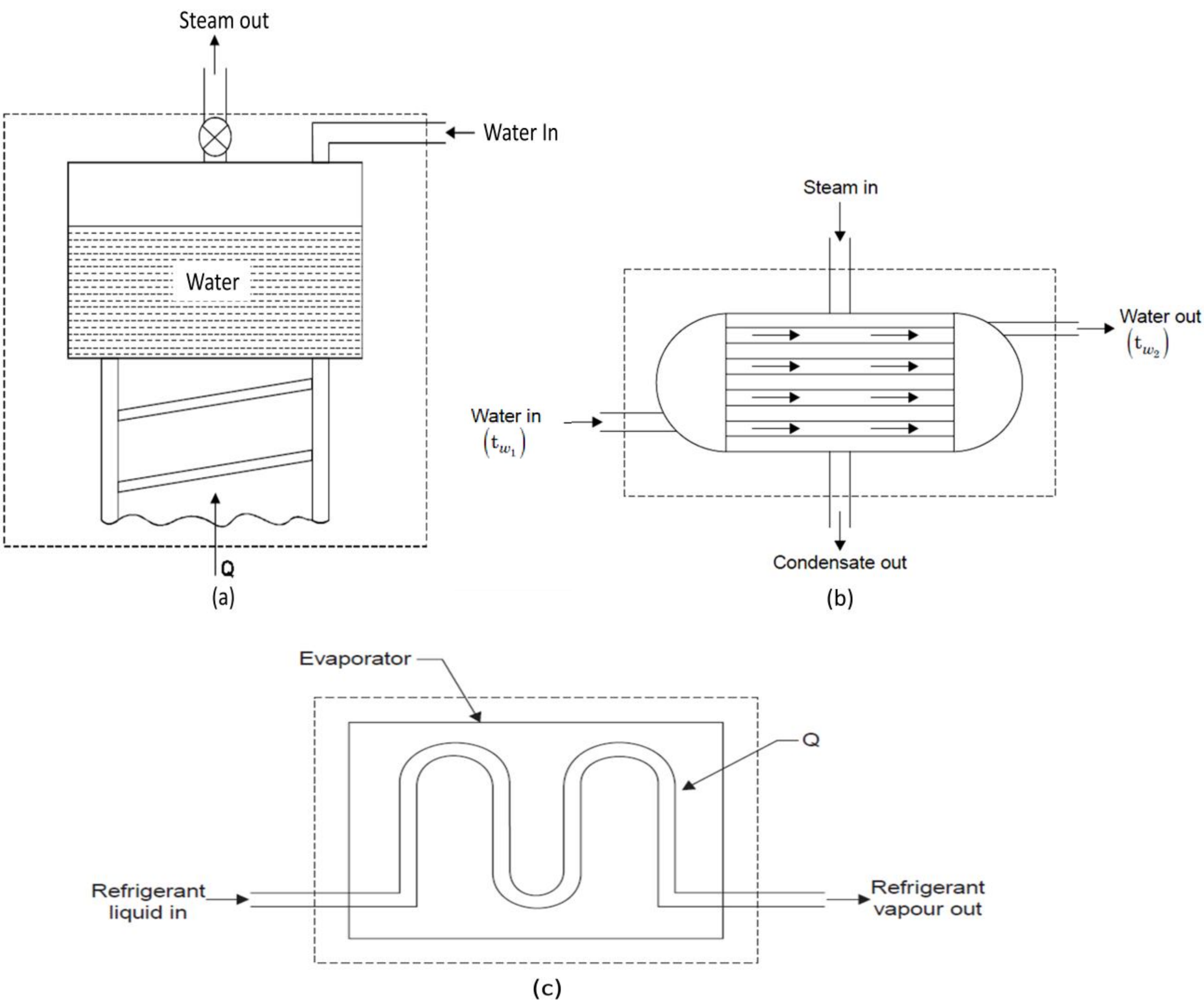


Fig. 2.6 Schematic diagram of (a) Boiler (b) Condenser (c) Evaporator

- Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

- The characteristic features of the flow through a ***heat exchangers*** are:
  - No shaft work; $W_s = 0$
  - Heat transfer, $Q \neq 0$ (Compulsory)
  - Change in kinetic energy is negligible (compare to change in enthalpy);

$$\frac{C_2^2}{2} - \frac{C_1^2}{2} = 0$$

  - Change in potential energy is negligible (i.e. No elevation difference between inlet and exit); $Z_1 = Z_2$
- Hence, SFEE is reduced to,

$$mh_1 + Q = mh_2$$
$$\therefore Q = m(h_2 - h_1)$$

- For condenser and evaporator, from energy balance equation,

$$Heat\ lost\ by\ the\ steam = Heat\ gained\ by\ the\ cooling\ water$$
$$m_s(h_{si} - h_{so}) = m_w(h_{wo} - h_{wi})$$

Where,

m_s = Mass flow of steam

m_w = Mass flow of cooling water

3. Steam or Gas Turbine

- A turbine is a device for obtaining work from a flow of fluid expanding from high pressure to low pressure.

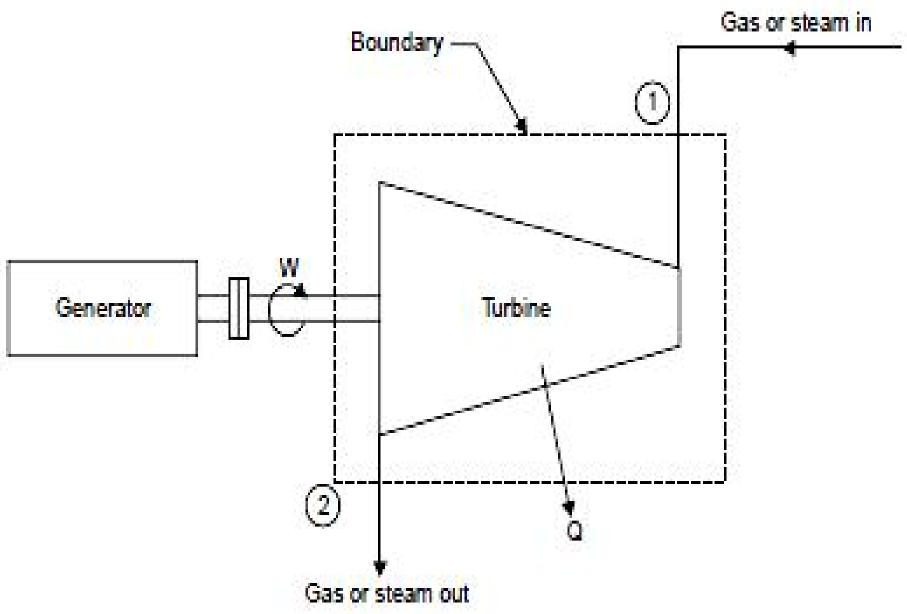


Fig. 2.7 Schematic of steam or gas turbine

- Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

- The characteristic features of flow through a ***steam or gas turbine*** are:
  - Shaft work produced; $W_s = +ve$
  - Negligible velocity change in the flow of fluid; $C_1 = C_2$
  - Negligible potential energy change; $Z_1 = Z_2$
  - No transfer of heat as its walls are thermally insulated; $Q = 0$
- Hence, SFEE is reduced to,

$$m(h_1) + 0 = m(h_1) + W_s$$
$$W_s = m(h_1 - h_2)$$

- Apparently work is done at the expense of enthalpy.

4. Hydraulic Turbine

- A hydraulic turbine or water turbine is a device which takes in water from a height. The water enters into the turbine, a part of its potential energy is converted into useful work (shaft work), which is used to generate electric power in a generator.

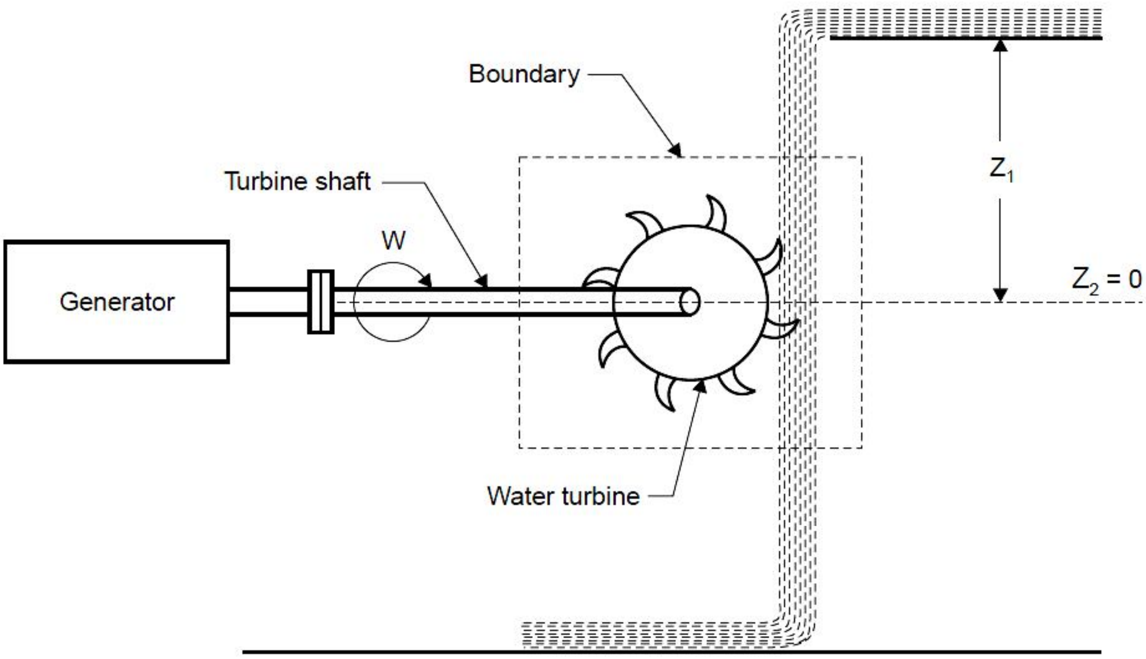


Fig. 2.8 Schematic of hydraulic turbine

- Applying Steady Flow Energy Equation (SFEE),

$$m\left(u_1 + P_1v_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(u_2 + P_2v_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

- The characteristic features of flow through a ***hydraulic turbine*** are:
  - Shaft work produced; $W_s = +ve$

- Negligible change in temperature of water so,
  - Heat transfer rate from turbine; $Q = 0$
  - Change in specific internal energy; $\Delta u = u_2 - u_1 = 0$
- As water is an incompressible fluid, its specific volume and hence density will remain constant; $v_1 = v_2 = v$

– Hence, SFEE is reduced to,

$$W_s = m\left[(P_1 v_1 - P_2 v_2) + \left(\frac{C_1^2}{2} - \frac{C_2^2}{2}\right) + g(Z_1 - Z_2)\right]$$

5. Centrifugal Water Pump

– A centrifugal water pump is a device that transfers the mechanical energy of a motor or an engine into the pressure energy of incompressible fluid like water.

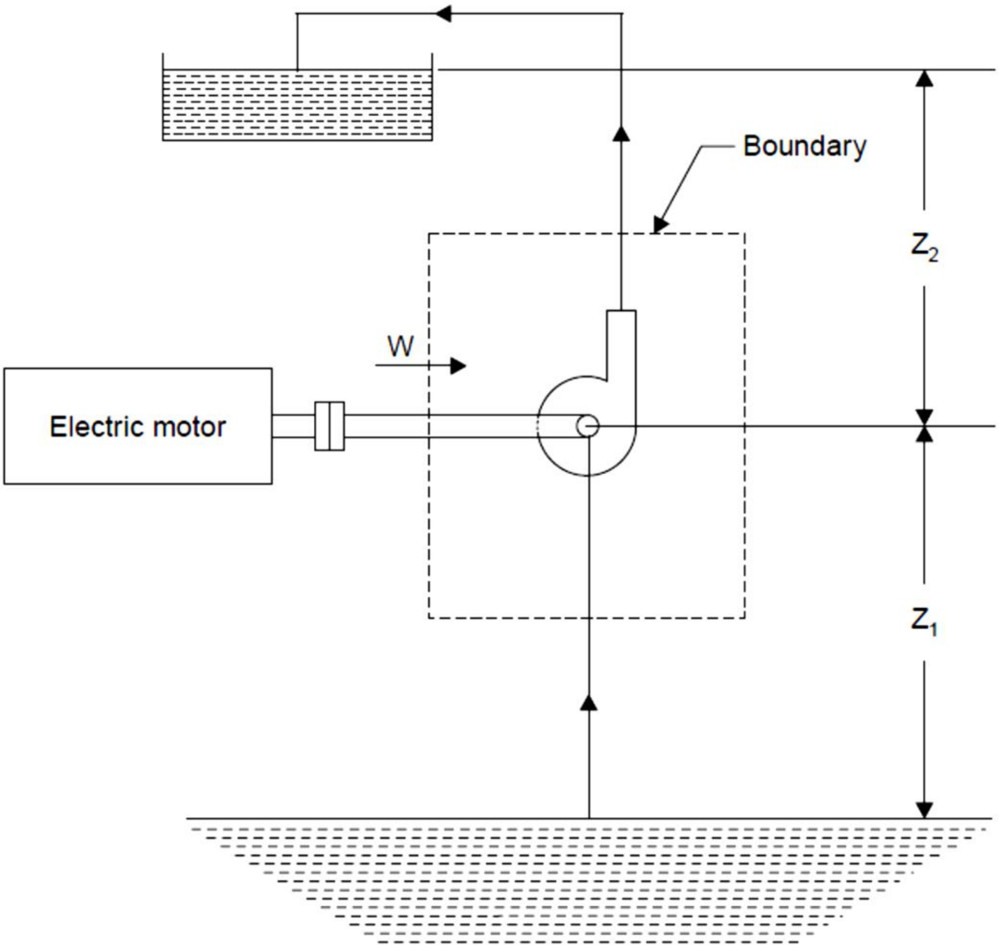


Fig. 2.9 Schematic of centrifugal water pump

– Applying Steady Flow Energy Equation (SFEE),

$$m\left(u_1 + P_1 v_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(u_2 + P_2 v_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

– The characteristic features of flow through a ***centrifugal water pump*** are:

- Shaft work required; $W_s = -ve$
- Negligible change in temperature of water so,
  - Heat transfer rate from turbine; $Q = 0$
  - Change in specific internal energy; $\Delta u = u_2 - u_1 = 0$
- As water is incompressible fluid, its specific volume and hence density will remain constant; $v_1 = v_2 = v$

– Hence, SFEE is reduced to,

$$m\left(P_1v_1 + \frac{C_1^2}{2} + gZ_1\right) = m\left(P_2v_2 + \frac{C_2^2}{2} + gZ_2\right) - W_s$$

$$W_s = m\left[(P_2v_2 - P_1v_1) + \left(\frac{C_2^2}{2} - \frac{C_1^2}{2}\right) + g(Z_2 - Z_1)\right]$$

6. Reciprocating Compressor

– A reciprocating compressor is used for increasing the pressure of a fluid and has a piston cylinder mechanism as the primary element.

– The unit sucks in definite quantity of fluid, compresses through a required pressure ratio and then delivers the compressed air/gas to a receiver.

– Reciprocating compressors are used when small quantity of fluid with high pressure is required.

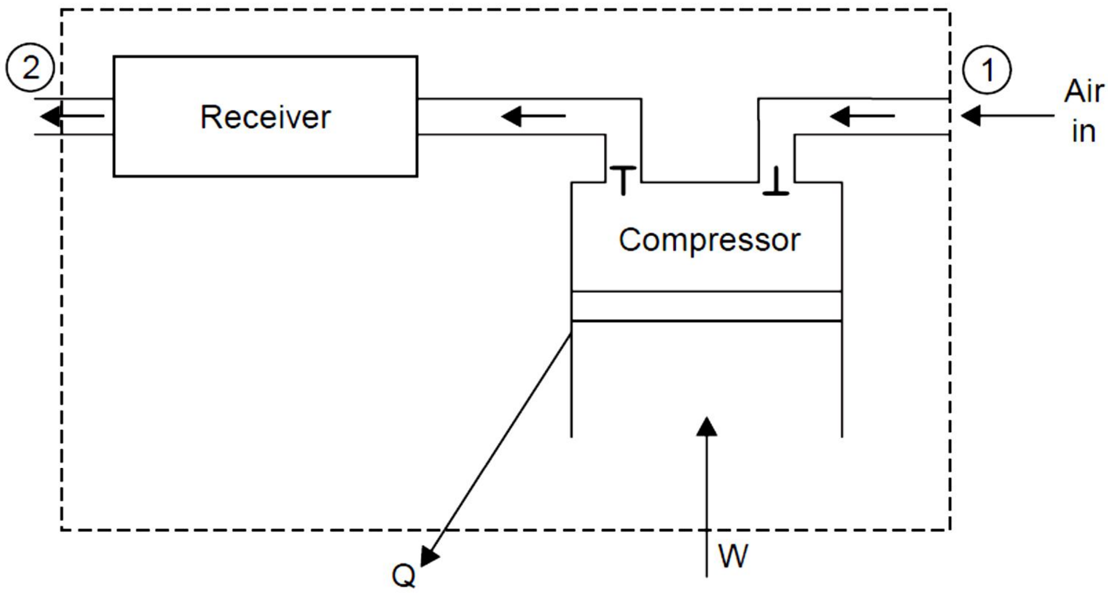


Fig. 2.10 Schematic of reciprocating compressor

– Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

– The characteristic features of flow through a ***reciprocating compressor*** are:

- Shaft work required; $W_s = -ve$
- Negligible velocity change in the flow of fluid; $C_1 = C_2$
- Negligible potential energy change; $Z_1 = Z_2$
- Appreciable amount of heat transfer is involved; heat is lost from the system as it gets sufficient time to interact with surrounding because of low speed; $Q \neq 0$ and $Q = -ve$

– Hence, SFEE is reduced to,

$$mh_1 - Q = mh_2 - W_s$$
$$\therefore W_s = Q + m(h_2 - h_1)$$

7. Rotary Compressor

– Rotary compressors are used for increasing the pressure of a fluid and have a rotor as the primary element.

– Rotary compressors are employed where high efficiency, medium pressure rise and large flow rate are the primary considerations.

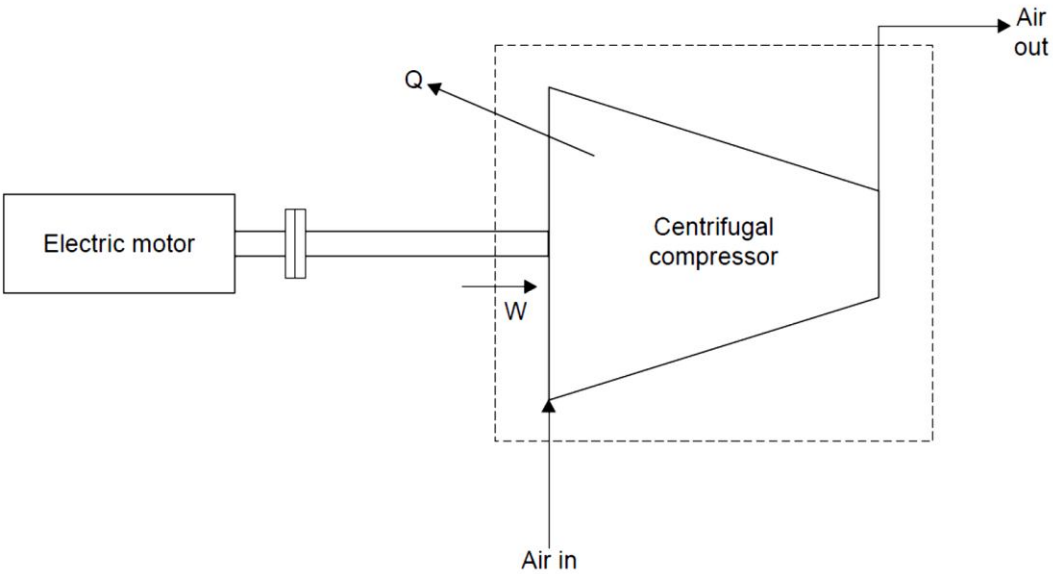


Fig. 2.11 Schematic of rotary compressor

– Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

– The characteristic features of flow through a ***rotary compressor*** are:

- Shaft work required; $W_s = -ve$
- Negligible velocity change in the flow of fluid; $C_1 = C_2$
- Negligible potential energy changes; $Z_1 = Z_2$
- Flow process is treated as adiabatic due to vary high flow rates; $Q = 0$

– Hence, SFEE is reduced to,

$$mh_1 = mh_2 - W_s$$
$$\therefore W_s = m(h_2 - h_1)$$

8. Throttling Process

- Throttling is the expansion of fluid from high pressure to low pressure. This process occurs when fluid passes through an obstruction (partially opened valve, porous plug or a small orifice) placed in the fluid flow passage.
- The throttling process is commonly used for the following purposes :
  I. For determining the condition of steam (dryness fraction).
  II. For controlling the speed of the turbine.
  III. Used in refrigeration plant for reducing the pressure of the refrigerant before entry into the evaporator.
- Fig. 2.12 shows the schematic of porous plug experiment performed by Joule and Thomson in 1852. A stream of incompressible fluid is made to pass steadily through a porous plug placed in an insulated and horizontal pipe.

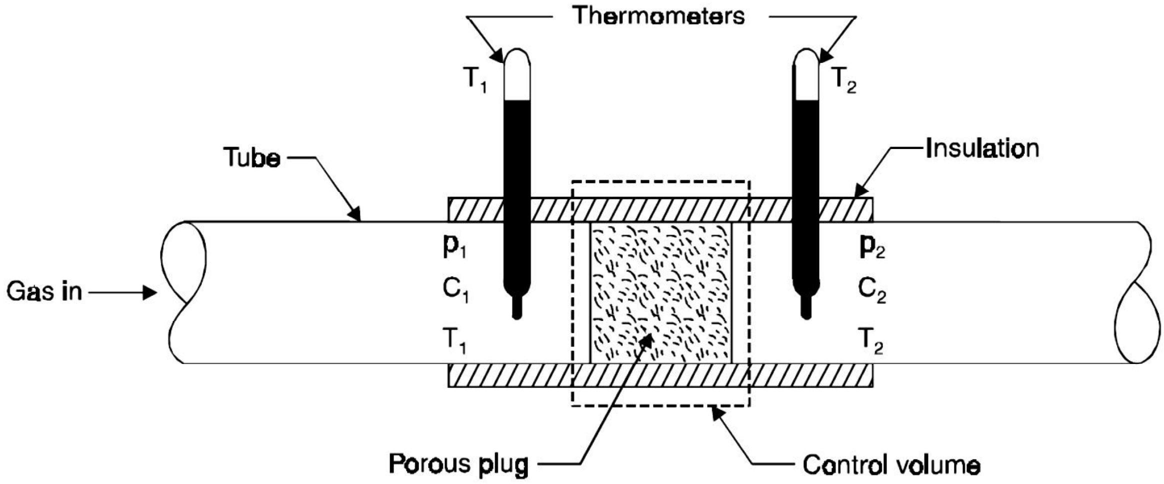


Fig. 2.12 The Joule – Thomson porous plug experiment

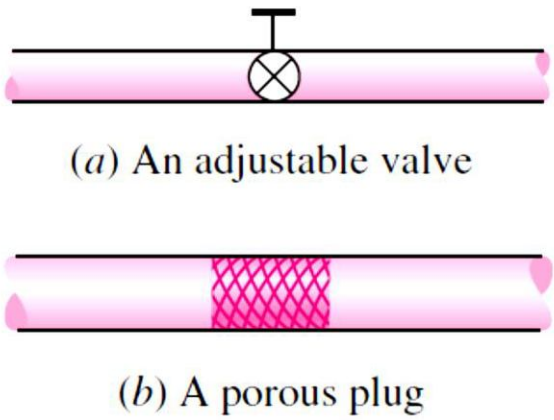


Fig. 2.13 Throttling devices (a) An adjustable valve (b) A porous plug

- Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1+\frac{C_1^2}{2}+gZ_1\right)+Q$$
$$=m\left(h_2+\frac{C_2^2}{2}+gZ_2\right)+W_s$$

- The characteristic features of a ***throttling process*** are:
  - No shaft work required; $W_s=0$
  - No heat interaction as pipe is thermally insulated; $Q=0$
  - Negligible velocity change in the flow of fluid; $C_1=C_2$
  - Negligible potential energy changes as the pipe is placed horizontally; $Z_1=Z_2$
- Hence steady flow energy equation reduced to,

$$h_1=h_2$$

- Enthalpy of fluid remains constant during throttling process. Thus the throttling expansion process is an ***isenthalpic process***.
- For a perfect gas,

$$C_pT_1=C_pT_2$$
$$\therefore T_1=T_2$$

- Thus for a perfect gas, the temperature before and after throttling is always same.

2.7 Unsteady Flow Processes: Filling and Emptying Process

- In engineering practice, the variable flow process applications are as common as the steady flow process. The rate of energy and mass transfer into and out of the control volume are not same in the case of unstable (or variable or transient or unsteady) flow process.
- Following two cases only will be discussed :
  1. Tank Filling Process.
  2. Tank Emptying Process ***or*** Tank Discharge Process

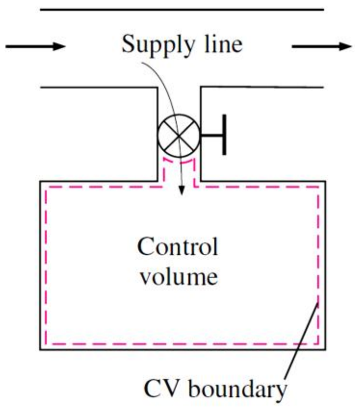


Fig. 2.14 Tank/ CV filling process

1. Tank Filling Process

- The tank/bottle initially contains fluid having mass m_i, at the state $P_i, v_i\ and\ T_i$. The corresponding values after the filling operation are $m_f, P_f, v_f\ and\ T_f$.
- In addition there may be heat and work interactions with the surroundings.
- The work interaction is possible by change in volume of the bottle or by internal electrical or mechanical devices.

- Mass of fluid entering $= m_f - m_i$
- Energy of entering fluid $= (m_f - m_i)e$
- Energy balance gives,

$$(m_f - m_i)e + Q = (m_f u_f - m_i u_i) + W$$

Where,

u_f & u_i = Final & Initial sp. Internal energy of fluid mass

- In a filling process of a tank from a large reservoir (pipeline), the properties of the entering fluid stream are essentially constant and so will be the energy e_p accompanying unit mass of fluid at entrance to control volume.

$$e_p = u_p + P_p v_p + \frac{C_p^2}{2} = h_p + \frac{C_p^2}{2}$$

$$\therefore (m_f - m_i)\left(h_p + \frac{C_p^2}{2}\right) + Q = (m_f u_f - m_i u_i) + W$$

The suffix 'p' refers to state of fluid in the pipe line.

- In the absence of any work interaction $(W = 0)$ and when the tank is thermally insulated $(Q = 0)$.

$$\therefore (m_f - m_i)\left(h_p + \frac{C_p^2}{2}\right) = (m_f u_f - m_i u_i)$$

- Neglecting kinetic energy of the incoming fluid,

$$(m_f - m_i)(h_p) = (m_f u_f - m_i u_i)$$

- If the tank is initially empty,

$$m_f h_p = m_f u_f$$

$$\therefore h_p = u_f$$

- Thus the specific internal energy of fluid charged into empty insulated tank is equal to the specific enthalpy of the filling fluid in the charging pipe line.
- If the fluid is an ideal gas, then temperature of gas in the tank after it is charged is given by,

$$C_p T_p = C_v T_2$$

$$\therefore T_2 = \gamma T_p$$

2. Tank Emptying Process

- The tank emptying process is the reverse of filling process, i.e. there is flow of fluid from the tank to the surrounding.
- The surroundings are much larger than the tank being emptied and so the energy $e_p = h_p + \frac{C_p^2}{2}$ accompanying unit mass of fluid at exit from the control volume will be constant.

– Energy balance gives,

$$(m_i - m_f)\left(h_p + \frac{C_p^2}{2}\right) + Q = (m_i u_i - m_f u_f)$$

– For no heat transfer and negligible exit velocity,

$$(m_i - m_f)(h_p) = (m_i u_i - m_f u_f)$$

– Further if the tank is to be fully emptied $(m_f = 0)$

$$\therefore m_i h_p = m_i u_i$$

$$\therefore h_p = u_i$$

2.8 First Law Applied to Non Flow Processes

– Following are the important non-flow processes, which are commonly used in engineering applications:

A. Constant Volume Process (Isochoric)

B. Constant Pressure Process (Isobaric)

C. Constant Temperature Process (Isothermal)

D. Adiabatic Process $(Q = 0)$ ***or*** Isentropic Process (Reversible Adiabatic; $S = C$)

E. Polytropic Process

– Fig. 2.15 to 2.19 shows schematic and P-v diagram for all the processes listed above.

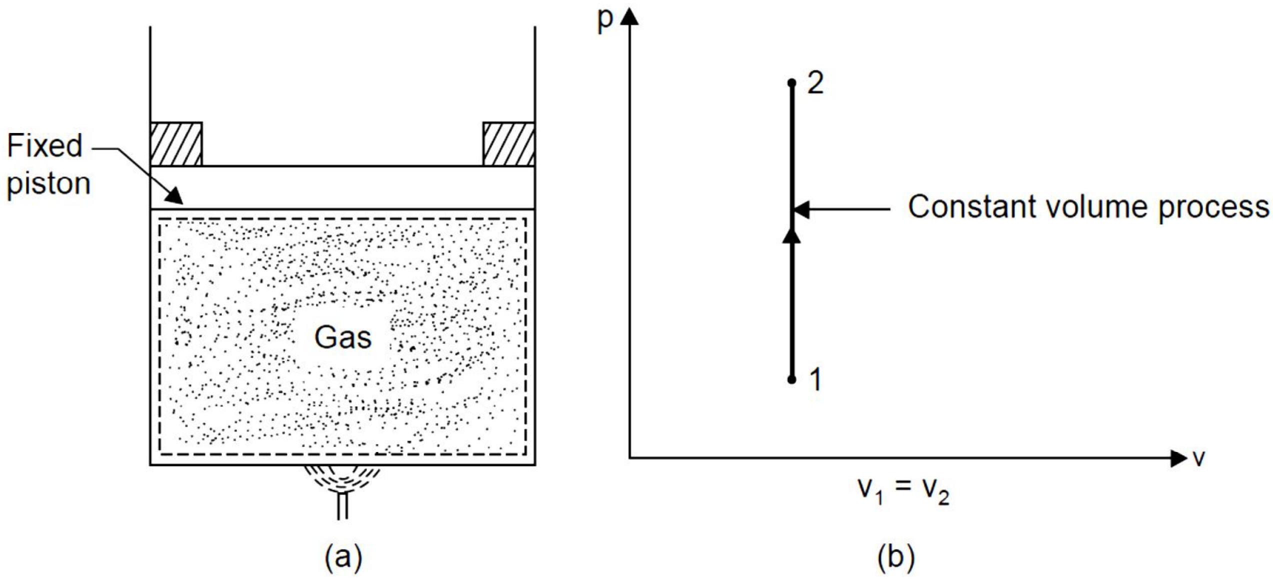


Fig. 2.15 Constant volume process (Isochoric)

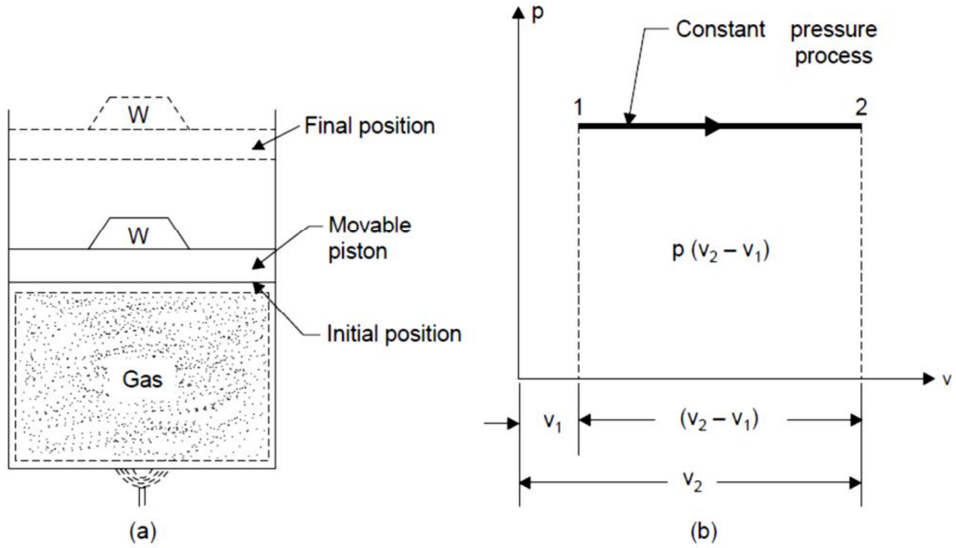


Fig. 2.16 Constant pressure process (Isobaric)

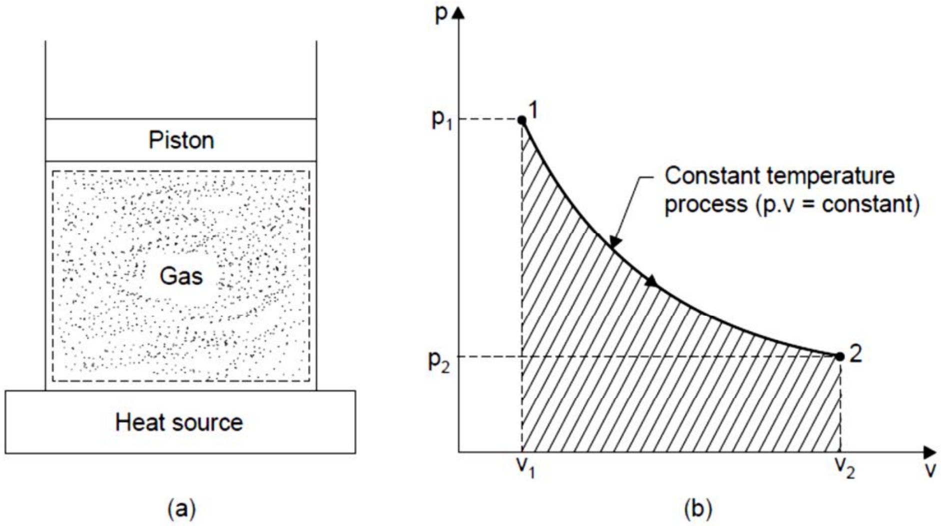


Fig. 2.17 Constant temperature process (Isothermal)

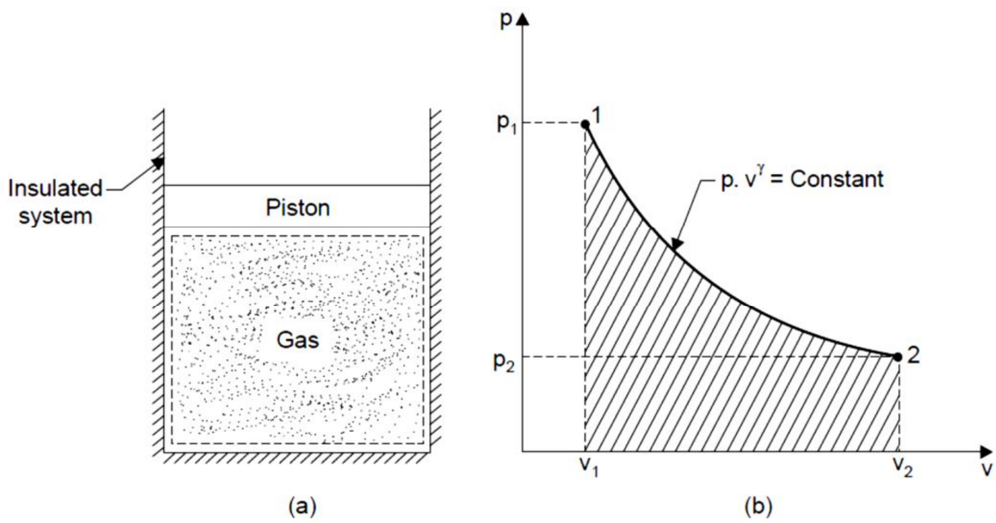


Fig. 2.18 Reversible Adiabatic Process (Isentropic process)

- In a Polytropic process, the index n depends only on the heat and work quantities during the process. The various processes considered earlier are special cases of Polytropic process for a perfect gas. This is illustrated on P-v diagram in Fig. 2.19.

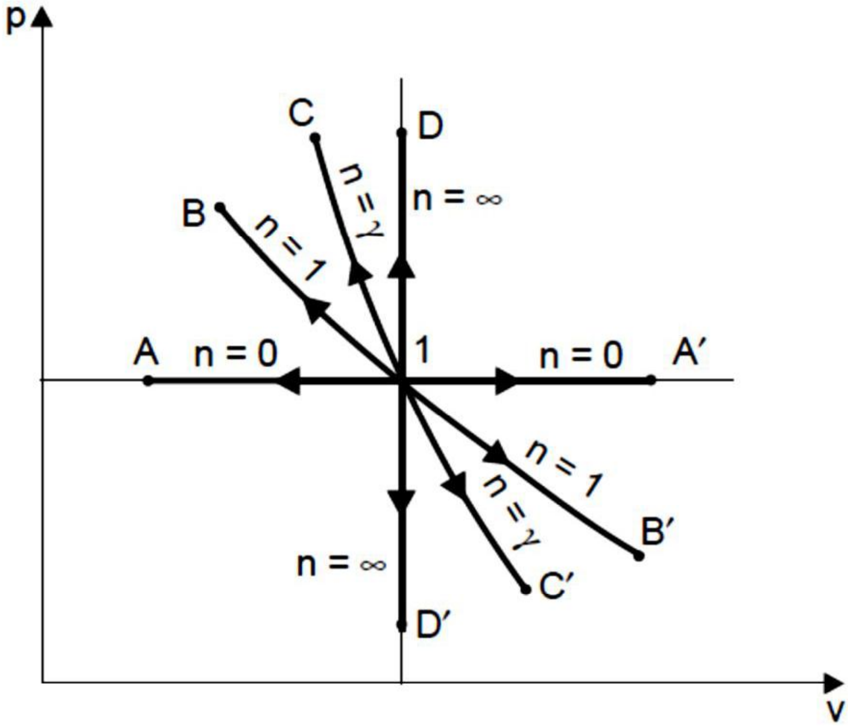


Fig. 2.19 Polytropic process for different values on index 'n'

For Air (Perfect Gas)

$R = 0.287\ KJ/kg - k$

$C_p = 1.005\ KJ/kg - k$

$C_v = 0.718\ KJ/kg - k$

$\gamma = 1.4$

Relationship between R, C_p, C_v and γ

$R = C_p - C_v$

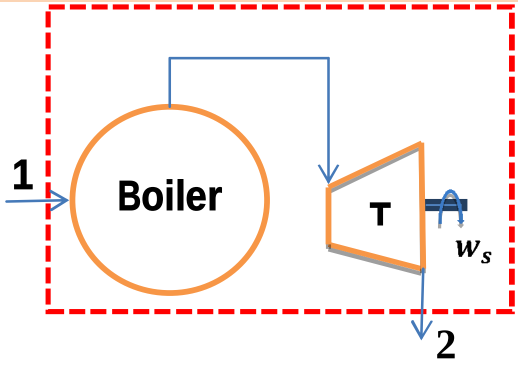
$$\gamma = \frac{C_p}{C_v}$$

2.9 Solved Numerical

Ex 2.1. ***[GTU; Jun-2014; 7 Marks]***

In steam power plant 1 kg of water per second is supplied to the boiler. The enthalpy and velocity of water entering the boiler are 800 kJ/kg and 5 m/s. the water receives 2200 kJ/kg of heat in the boiler at constant pressure. The steam after passing through the turbine comes out with a velocity of 50 m/s, and its enthalpy is 2520 kJ/kg. The inlet is 4 m above the turbine exit. Assuming the heat losses from the boiler and the turbine to the surroundings are 20 kJ/sec. Calculate the power developed by the turbine. Consider the boiler and turbine as single system.

Solution:



Given Data:

$\dot{m}_w = 1\ kg/sec$

$h_1 = 800\ kJ/kg$

$C_1 = 5\ m/s$

$q_s = 2200\ kJ/kg$

$C_2 = 50\ m/s$

$h_2 = 2520\ kJ/kg$

$Z_1 - Z_2 = 4\ m$

$\dot{q}_r = -20\ kJ/sec$

$\therefore q_r = \frac{\dot{q}_r}{\dot{m}_w} = \frac{-20}{1}$

$\therefore q_r = -20\ kJ/kg$

To be Calculated:

$P = ?$

⇨ Net Heat Transfer to the System,

$$q_{net} = q_s - q_r$$
$$\therefore q_{net} = 2200 - 20$$
$$\therefore q_{net} = 2180\ kJ/kg$$

⇨ Apply Steady Flow Energy Equation,

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q_{net} = h_2 + \frac{C_2^2}{2} + gZ_2 + w_{net}$$
$$\therefore w_{net} = (h_1 - h_2) + \left(\frac{C_1^2}{2} - \frac{C_2^2}{2}\right) + g(Z_1 - Z_2) + q_{net}$$
$$\therefore w_{net} = (800 - 2520) \times 10^3 + \left(\frac{5^2}{2} - \frac{50^2}{2}\right) + 9.81(4) + (2180 \times 10^3)$$
$$\therefore w_{net} = 458801.74\ J/kg$$
$$\therefore w_{net} = 458.801\ kJ/kg$$

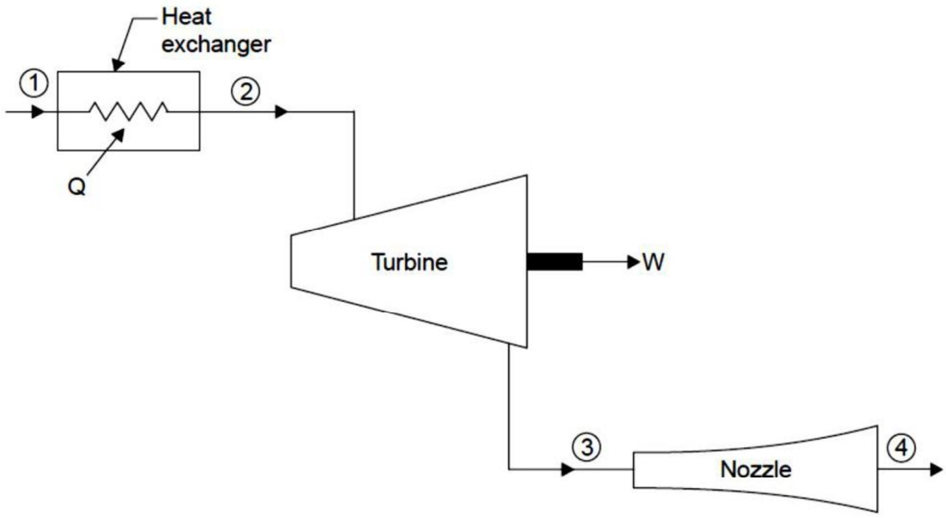
⇨ **Power Developed by the Turbine:**

$$P = \dot{m}_w \times w_{net}$$
$$\therefore P = 1 \times 458.801$$
$$\therefore \boldsymbol{P = 458.801\ kW}$$

Ex 2.2. ***[GTU; Jun-2010; 7 Marks]***

Air at a temperature of 15°C passes through a heat exchanger at velocity of 30 m/s, where temperature is raised to 800°C. It then enters a turbine with same velocity of 30m/s and expands until temperature falls to 650°C. On leaving the turbine the air is taken at velocity of 60m/s to a nozzle where it expands until the temperature has fallen to 500°C, If the air flow rate is 2kg/s, calculate (a) rate of heat transfer to air in the heat exchanger, (b) power output from turbine assuming no heat loss and (c) velocity at exit from the nozzle. Assuming no heat loss.

Solution:



Given Data:

$\dot{m}_a = 2\ kg/sec$

$C_1 = C_2 = 30\ m/s$

$T_1 = 15\ °C$

$T_2 = 800\ °C$

$T_3 = 650\ °C$

$C_3 = 60\ m/s$

$T_4 = 500\ °C$

To be Calculated:

a) $\dot{q}_s = ?$

b) $P = ?$

c) $C_4 = ?$

[1] Heat Exchanger

⇨ For H.E.

$$w_{net} = 0$$
$$Z_1 = Z_2\ (Assume)$$

Also,

$$C_1 = C_2\ (Given)$$

⇨ Apply Steady Flow Energy Equation to Heat Exchanger (1 – 2),

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q_{net} = h_2 + \frac{C_2^2}{2} + gZ_2 + w_{net}$$
$$\therefore q_{net} = (h_2 - h_1)$$
$$\therefore q_{net} = C_p(T_2 - T_1)$$
$$\therefore q_{net} = 1.005(800 - 15)$$
$$\therefore q_{net} = 788.925\ kJ/kg$$

⇨ **Rate of Heat transfer:**

$$\dot{q}_{net} = \dot{m}_a \times q_{net}$$
$$\dot{q}_{net} = 2 \times 788.925$$
$$\boldsymbol{\dot{q}_{net} = 1577.85\ kW}$$

[2] Turbine

⇨ For Turbine,

$$q_{net} = 0 \ (No\ heat\ loss)$$

$$Z_2 = Z_3 \ (Assume)$$

⇨ Apply Steady Flow Energy Equation to Turbine (2 – 3),

$$h_2 + \frac{C_2^2}{2} + gZ_2 + q_{net} = h_3 + \frac{C_3^2}{2} + gZ_3 + w_{net}$$

$$\therefore w_{net} = (h_2 - h_3) + \left(\frac{C_2^2}{2} - \frac{C_3^2}{2}\right)$$

$$\therefore w_{net} = C_p(T_2 - T_3) + \left(\frac{C_2^2}{2} - \frac{C_3^2}{2}\right)$$

$$\therefore w_{net} = 1.005 \times 10^3 \times (800 - 650) + \left(\frac{30^2}{2} - \frac{60^2}{2}\right)$$

$$\therefore w_{net} = 149400\, J/kg$$

⇨ **Power Output from Turbine:**

$$P = \dot{m}_a \times w_{net}$$

$$P = 2 \times 149400$$

$$\boldsymbol{P = 298800\, W}$$

[3] Nozzle

⇨ For Nozzle.

$$w_{net} = 0$$

$$Z_1 = Z_2 \ (Assume\ that\ nozzle\ is\ horizontal)$$

$$q_{net} = 0 \ (No\ heat\ loss)$$

⇨ Apply Steady Flow Energy Equation to Nozzle (3 – 4),

$$h_3 + \frac{C_3^2}{2} + gZ_3 + q_{net} = h_4 + \frac{C_4^2}{2} + gZ_4 + w_{net}$$

$$\therefore \frac{C_4^2}{2} = (h_3 - h_4) + \frac{C_3^2}{2}$$

$$\therefore \frac{C_4^2}{2} = C_p(T_3 - T_4) + \frac{C_3^2}{2}$$

$$\therefore \frac{C_4^2}{2} = 1.005 \times 10^3 \times (650 - 500) + \frac{60^2}{2}$$

$$\therefore \frac{C_4^2}{2} = 152550$$

$$\therefore \boldsymbol{C_4 = 552.358\, m/sec}$$

2.10 References

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4. Thermal Science and Engineering by D. S. Kumar, S K Kataria and Sons Publications.
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