$$Q = 0$$

$\therefore$ $0 = \Delta u + W$

$\therefore$ $W = -\Delta u = -(u_2 - u_1) = (u_1 - u_2)$

i.e., $$W = (u_1 - u_2) \quad \text{...(4.80)}$$

Adiabatic process (not reversible) is also a polytropic process with an index n. The appropriate value of n for adiabatic compression of steam are

$$n = 1.13 \text{ for wet steam}$$

$$n = 1.3 \text{ for superheated steam}$$

When the initial condition and end condition are *both in wet region* then $p_1 v_1^n = p_2 v_2^n$ reduces to :

$$p_1(x_1 v_{g_1})^n = p_2(x_2 v_{g_2})^n.$$

As p_1, x_1, n and p_2 are specified the value of x_2 can be calculated.

When the end condition is *superheated*, then

$$p_1(x_1 v_{g_1})^n = p_2(v_{sup_2})^n.$$

Solving for v_2, then using

$$\frac{v_2}{v_{g_2}} = \frac{T_{sup_2}}{T_{s_2}}$$

T_{sup_2} can be calculated. Knowing T_{s_2} and T_{sup} all properties at the end condition can be calculated.

☞**Example 4.58.** *In a steam engine the steam at the beginning of the expansion process is at 7 bar, dryness fraction 0.98 and expansion follows the law $pv^{1.1}$ = constant, down to a pressure of 0.34 bar. Calculate per kg of steam :*

(*i*) *The work done during expansion ;*

(*ii*) *The heat flow to or from the cylinder walls during the expansion.*

Solution. Initial pressure of steam, $p_1 = 7 \text{ bar} = 7 \times 10^5 \text{ N/m}^2$

Dryness fraction, $x_1 = 0.98$

Law of expansion, $pv^{1.1} = \text{constant}$

Final pressure of steam, $p_2 = 0.34 \text{ bar} = 0.34 \times 10^5 \text{ N/m}^2$.

At 7 bar : $v_g = 0.273 \text{ m}^3/\text{kg}$

$\therefore$ $v_1 = x_1 v_g = 0.98 \times 0.273 = 0.267 \text{ m}^3/\text{kg}$

Also, $p_1 v_1^n = p_2 v_2^n$

i.e., $$\frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{1/n}$$

$\therefore$ $$\frac{v_2}{0.267} = \left(\frac{7}{0.34}\right)^{\frac{1}{1.1}} \quad \text{or} \quad v_2 = 0.267 \left(\frac{7}{0.34}\right)^{\frac{1}{1.1}} = 4.174 \text{ m}^3/\text{kg}.$$

(*i*) **Work done by the steam during the process :**

$$W = \frac{p_1 v_1 - p_2 v_2}{n - 1} = \frac{7 \times 10^5 \times 0.267 - 0.34 \times 10^5 \times 4.174}{(1.1 - 1)}$$

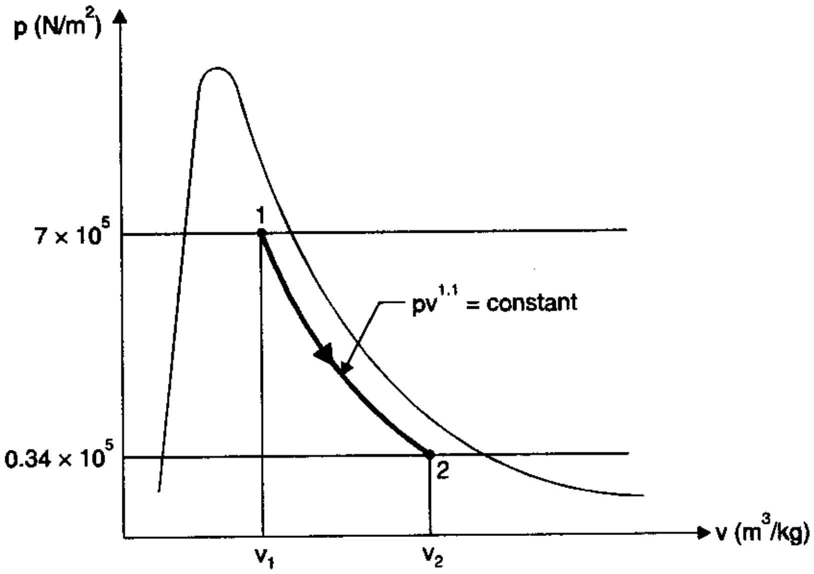


Fig. 4.69

$$= \frac{10^5}{0.1}(1.869 - 1.419) = 10^5 \times 4.5 \text{ N-m/kg}$$

i.e., **Work done** $= \dfrac{10^5 \times 4.5}{10^3}$ = **450 kJ/kg. (Ans.)**

At 0.34 bar : v_{g2} = 4.65 m³/kg, therefore, steam is *wet* at state 2 (since $v_2 < v_{g2}$).

Now, $v_2 = x_2 v_{g2}$, where x_2 = dryness fraction at pressure p_2 (0.34 bar)

$$4.174 = x_2 \times 4.65 \quad \text{or} \quad x_2 = \frac{4.174}{4.65} = 0.897$$

The expansion is shown on a *p-v* diagram in Fig. 4.69, the area under 1-2 represents the work done per kg of steam.

(*ii*) **Heat transferred :**

Internal energy of steam at initial state 1 per kg,

$$u_1 = (1 - x_1)u_{f1} + x_1 u_{g_1} = (1 - 0.98)\, 696 + 0.98 \times 2573 = 2535.46 \text{ kJ/kg}$$

Internal energy of steam at final state 2 per kg,

$$u_2 = (1 - x_2)\, u_{f2} + x_2 u_{g2}$$

$$= (1 - 0.897)\, 302 + 0.897 \times 2472 = 2248.49 \text{ kJ/kg}$$

Using the non-flow energy equation,

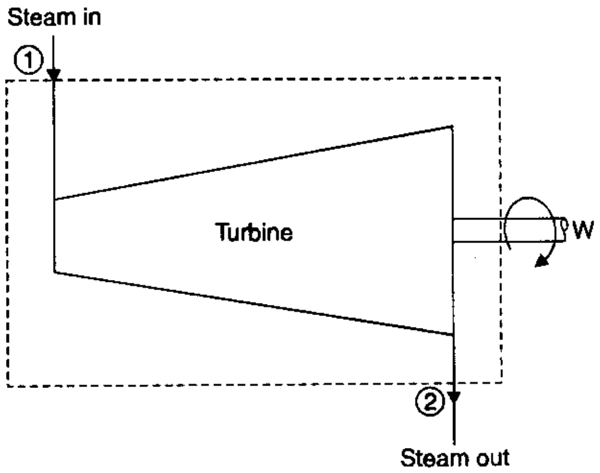
$$Q = (u_2 - u_1) + W$$

$$= (2248.49 - 2535.46) + 450 = 163.03 \text{ kJ/kg}$$

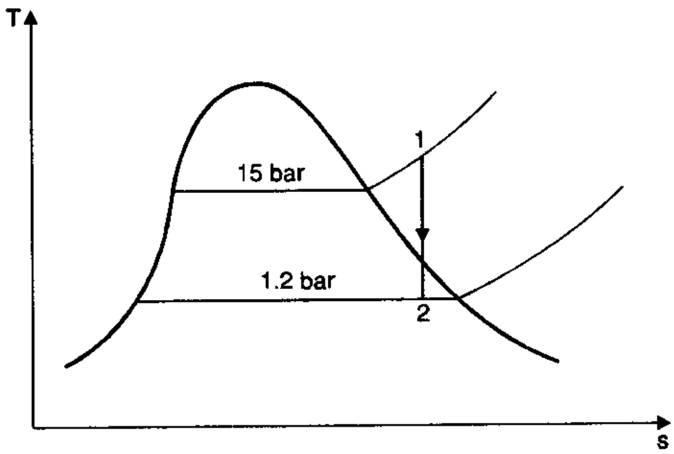
i.e., **Heat supplied** **= 163.03 kJ/kg. (Ans.)**

Example 4.59. *Steam enters a steam turbine at a pressure of 15 bar and 350°C with a velocity of 60 m/s. The steam leaves the turbine at 1.2 bar and with a velocity of 180 m/s. Assuming the process to be reversible adiabatic, determine the work done per kg of steam flow through the turbine.*

Neglect the change in potential energy.



(*a*)



(*b*)

Fig. 4.70

Solution. Initial pressure of steam, p_1 = 15 bar

Initial temperature of steam, $t_1 = t_{sup}$ = 350°C

Initial velocity of steam, C_1 = 60 m/s

Final pressure, p_2 = 1.2 bar

Final velocity, C_2 = 180 m/s

Process of expansion : *Reversible adiabatic*

As the process is reversible adiabatic, it will be represented by a vertical line on T-s diagram by 1-2 as it is also constant entropy process.

The condition at point '2' can be calculated by equating the entropy at point '1' and point '2', *i.e.*,

$$s_1 = s_2 \text{ .....per kg of steam}$$

$$7.102 = s_{f_2} + x_2(s_{g_2} - s_{f_2})$$

$$= 1.3609 + x_2(7.2984 - 1.3609)$$

$$\therefore \quad x_2 = \frac{7.102 - 1.3609}{7.2984 - 1.3609} = 0.967$$

$$h_2 = h_{f_2} + x_2 h_{fg_2} = 439.4 + 0.967 \times 2244.1 = 2609.44 \text{ kJ/kg}$$

$$h_1 \text{ (at 15 bar and 350°C)} = 3147.5 \text{ kJ/kg}$$

Applying the first law energy equation for steady flow process,

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2} + W$$

i.e.,

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

$$= 3147.5 - 2609.44 + \left(\frac{60^2 - 180^2}{2 \times 10^3}\right)$$

$$= 3147.5 - 2609.44 - 14.4 = 523.66 \text{ kJ/kg.}$$

Hence **work done per kg of steam = 523.66 kJ/kg. (Ans.)**

Example 4.60. *Steam at 10 bar and 200°C enters a convergent divergent nozzle with a velocity of 60 m/s and leaves at 1.5 bar and with a velocity of 650 m/s. Assuming that there is no heat loss, determine the quality of the steam leaving the nozzle.*

Solution. Initial pressure of steam, $p_1 = 10$ bar

Initial temperature of steam, $t_1 = t_{sup} = 200°C$

Initial velocity, $C_1 = 60$ m/s

Final velocity, $C_2 = 650$ m/s

Final pressure, $p_2 = 1.5$ bar

Heat loss = nil

Quality of steam at the outlet :

It is a steady-state non-work developing system. Applying the steady flow energy equation to the process, we get

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2} \qquad (\because \quad Q = 0,\ W = 0)$$

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

At 10 bar, 250°C : $h_1 = 2827.9$ kJ/kg (from steam tables)

$$\therefore \quad h_2 = 2827.9 + \left[\frac{60^2 - 650^2}{2 \times 10^3}\right] = 2618.45 \text{ kJ/kg}$$

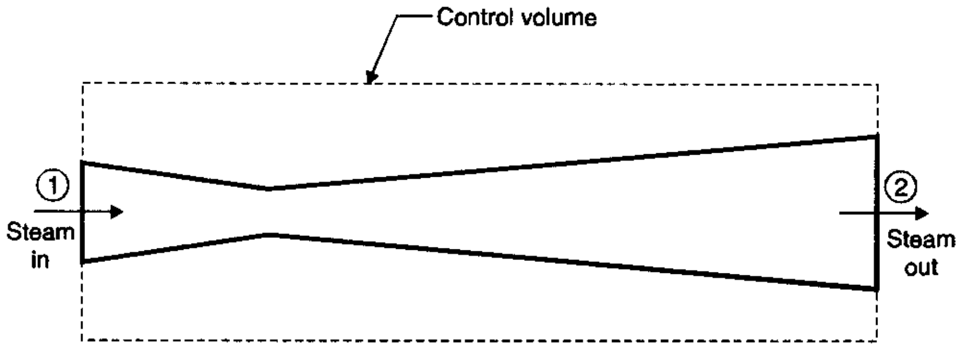


Fig. 4.71

As the enthalpy and pressure of steam at the exit of the nozzle are known, we can find out quality of steam,

$$h_{g_2} \text{ (at 1.5 bar)} = 2693.4 \text{ kJ/kg}$$

As $h_2 < h_{g_2}$, the steam is *wet*.

The enthalpy of wet steam is given by

$$h_2 = h_{f_2} + x_2 h_{fg_2}$$

$$2618.45 = 467.1 + x_2 \times 2226.2$$

$$\therefore \quad x_2 = \frac{2618.45 - 467.1}{2226.2} = 0.966.$$

Hence **the condition of steam leaving the nozzle is 96.6% dry. (Ans.)**

6. Throttling. A flow of fluid is said to be throttled when there is some *restriction to the flow*, when the velocities before and after the restriction are either equal or negligibly small, and when there is a *negligible heat loss to the surroundings.*

The restriction to the flow can be :

(*i*) partly open valve

(*ii*) an orifice or

(*iii*) any other sudden reduction in the cross-section of the flow.

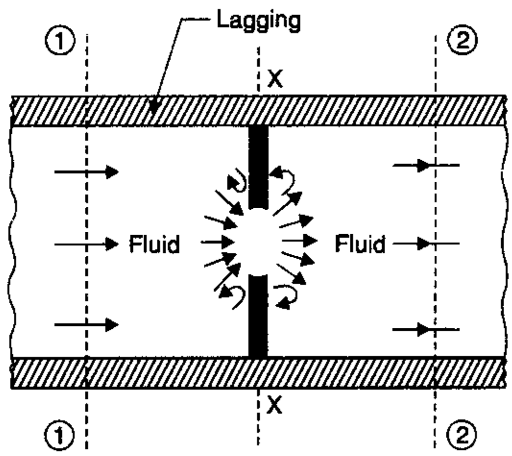


Fig. 4.72. Throttling.

An example of throttling is shown in Fig. 4.72. It is represented on *T-s* and *h-s* diagrams as shown in Figs. 4.73 and 4.74 respectively. The fluid (say steam) flowing steadily along a well-lagged pipe, passes through an orifice at section *X*. Since the pipe is well-lagged it can be assumed that no heat flows to or from the fluid.

Applying flow equation between any two sections of the flow, we have

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W$$

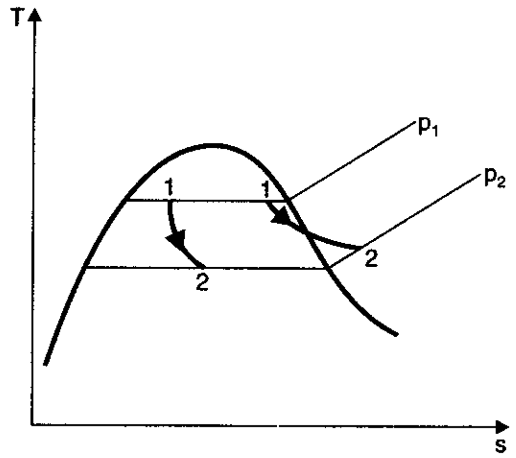


Fig. 4.73. *T-s* diagram.

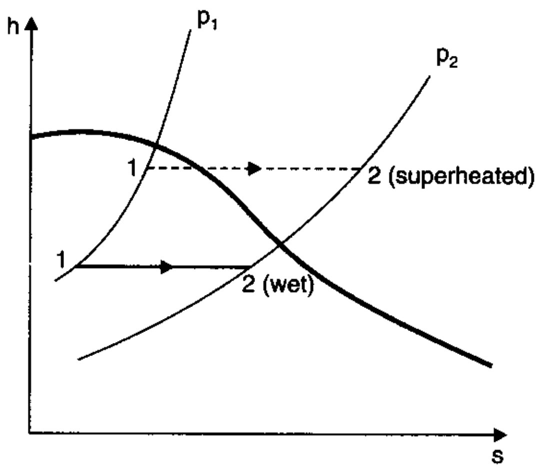


Fig. 4.74. *h-s* diagram.

Now since $Q = 0$, and $W = 0$, then

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

When the velocities C_1 and C_2 are small, or when C_1 is very nearly equal to C_2, then the K.E. terms may be neglected.

Then $$h_1 = h_2 \quad \text{...(4.81)}$$

i.e., For a throttling process :

Initial enthalpy = Final enthalpy.

The process is adiabatic but highly irreversible because of the eddying of the fluid around the orifice at X. Between sections 1 and *X* the enthalpy drops and K.E. increases as the fluid accelerates through the orifice. Between sections *X* and 2 the *enthalpy increases as K.E. is destroyed by fluid eddies.*

During throttling *pressure always falls.*

The throttling process is *used* for the following *purposes* :

1. To *determine the dryness fraction of steam.*
2. To *control the speed of the engine and turbine.*
3. To *reduce* the pressure and temperature of the liquid refrigerant from the condenser condition to evaporator condition in a *refrigeration system.*

☞**Example 4.61.** *Steam at 18 bar is throttled to 1 bar and the temperature after throttling is found to be 150°C. Calculate the initial dryness fraction of the steam.*

Solution. Pressure of steam before throttling, $p_1 = 18$ bar

Pressure of steam after throttling = 1 bar

Temperature after throttling = 150°C

Initial dryness fraction, x_1 :

From superheat tables at **1 bar and 150°C,** we have

$$h_2 = 2776.4 \text{ kJ/kg}$$

Then for throttling, $h_1 = h_2 = 2776.4$

But $$h_1 = h_{f_1} + x_1 h_{fg_1}$$

At 18 bar : $h_f = 884.6$ kJ/kg, $h_{fg} = 1910.3$ kJ/kg

$\therefore \quad 2776.4 = 884.6 + x_1 \times 1910.3$

or $\quad x_1 = \dfrac{2776.4 - 884.6}{1910.3} = 0.99$

i.e., **Initial, dryness fraction = 0.99. (Ans.)**

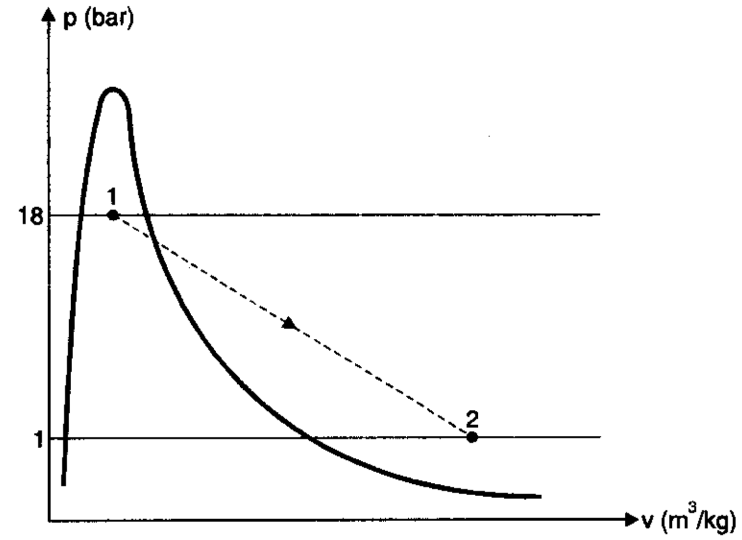


Fig. 4.75

The process is shown on a *p-v* diagram in Fig. 4.75. States 1 and 2 are fixed, but the intermediate states are indeterminate ; the process must be drawn dotted, as shown. No work is done during the process, and the area under the line 1-2 is **not equal to work done.**

Example 4.62. *Steam at 10 bar and 0.9 dryness fraction is throttled to a pressure of 2 bar. Determine the exit condition of steam using* **Mollier chart.**

Solution. Refer to Fig. 4.76.

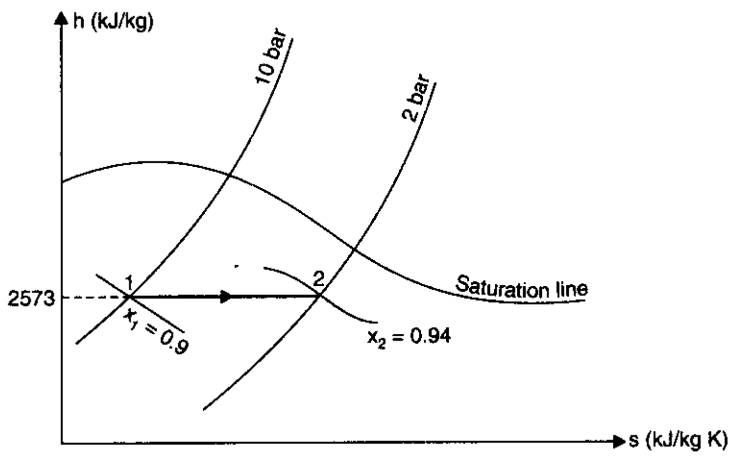


Fig. 4.76

Locate the point '1' at an intersection of the 10 bar pressure line and 0.9 dryness fraction line.

Throttling is a constant enthalpy line so draw a line parallel to X-axis till it cuts the 2 bar line and locate the point 2. The dryness fraction of steam at point 2 is 0.94.

(The total enthalpy before and after throttling = 2573 kJ/kg)

Hence **exit condition of steam = 0.94. (Ans.)**

Note. This process occurs during the control of flow of steam supplied to a turbine to take care of the varying load.

☞**Example 4.63.** *Steam initially at a pressure of 15 bar and 0.95 dryness expands isentropically to 7.5 bar and is then throttled until it is just dry. Determine per kg of steam :*

(i) Change in entropy ;

(ii) Change in enthalpy ;

(iii) Change in internal energy.

Using : (a) Steam tables

(b) Mollier chart.

Is the entire process reversible ? Justify your statement.

Solution. (*a*) **Using steam tables**

Condition 1 : 15 bar, 0.95 dryness

h_{f_1} = 844.7 kJ/kg ; t_{s_1} = 198.3°C, s_{f_1} = 2.3145 kJ/kg K,

s_{g_1} = 6.4406 kJ/kg K, v_{g_1} = 0.132 m³/kg

$$h_1 = h_{f_1} + x_1 h_{fg_1} = 844.7 + 0.95 \times 1945.2 = 2692.64 \text{ kJ/kg}$$

$$s_1 = s_{f_1} + x_1 (s_{g_1} - s_{f_1}) = 2.3145 + 0.95(6.4406 - 2.3145) = 6.2343 \text{ kJ/kg K.}$$

Condition 2 : 7.5 bar

h_{f_2} = 709.3 kJ/kg, t_{s_2} = 167.7°C, h_{fg_2} = 2055.55 kJ/kg, s_{f_2} = 2.0195 kJ/kg K

s_{g_2} = 6.6816 kJ/kg K, v_{g_2} = 0.255 m³/kg.

Consider **isentropic expansion 1-2 :**

(*i*) **Change in entropy** = 0

i.e., Entropy at 1 = entropy at 2

$$\therefore \quad s_1 = s_2$$

$$6.2343 = s_{f_2} + x_2 (s_{g_2} - s_{f_2})$$

$$= 2.0195 + x_2(6.6816 - 2.0195)$$

$$\therefore \quad x_2 = \frac{6.2343 - 2.0195}{6.6816 - 2.0195} = 0.9$$

Now, enthalpy at point 2,

$$h_2 = h_{f_2} + x_2 h_{fg_2} = 709.3 + 0.9 \times 2055.55 = 2559.29 \text{ kJ/kg.}$$

(*ii*) **Change in enthalpy** $= h_2 - h_1$

$= 2559.29 - 2692.64 = -$ **133.35 kJ/kg. (Ans.)**

(–ve sign indicates *decrease*).

(*iii*) **Change in internal energy :**

Internal energy at point 1,

$$u_1 = h_1 - p_1x_1v_{g_1}$$

$$= 2692.64 - 15 \times 10^5 \times 0.95 \times 0.132 \times 10^{-3} = 2504.54 \text{ kJ/kg}$$

Internal energy at point 2,

$$u_2 = h_2 - p_2x_2v_{g_2}$$

$$= 2559.29 - 7.5 \times 10^5 \times 0.9 \times 0.255 \times 10^{-3} = 2387.16 \text{ kJ/kg}$$

∴ Change in internal energy

$$= u_2 - u_1 = 2387.16 - 2504.54 = - 117.38 \text{ kJ/kg}$$

(–ve sign indicates *decrease*)

Consider the **throttling expansion 2-3 :**

Entropy at point 2,

$$s_2 = (s_1) = 6.2343 \text{ kJ/kg K}$$

Entropy at point 3,

$$s_3 = s_{f_3} + x_3(s_{g_3} - s_{f_3})$$

The pressure at point 3 can be read from *h-s* chart ($p_3 = 0.06$ bar) and the corresponding values of sf_3 and h_{fg_3} from steam tables.

Condition 3. At 0.06 bar, $x_3 = 1$. From steam tables,

$$s_{f_3} = 0.521 \text{ kJ/kg K}, \; s_{g_3} = 8.330 \text{ kJ/kg K}$$

∴ $s_3 = 0.521 + 1 \times (8.330 - 0.521) = 8.330$ kJ/kg K

Change in entropy $= s_3 - s_2$

$= 8.330 - 6.2343 = 2.0957$ kJ/kg K

Change in enthalpy $= 0$

i.e., $h_2 = h_3$

Change in internal energy = 0

i.e., $u_3 = u_2$

Combining the results obtained from isentropic and throttling expansion, we get during the entire process :

(*i*) **Change in entropy = 2.0957 kJ/kg K (increase). (Ans.)**

(*ii*) **Change in enthalpy = 133.35 kJ/kg K (decrease). (Ans.)**

(*iii*) **Change in internal energy = 117.38 kJ/kg (decrease). (Ans.)**

Only the expansion of steam from point 1 to 2 (*i.e., isentropic expansion*) is *reversible* because of unresisted flow whereas the expansion from point 2 to point 3 (*i.e., throttling expansion*) is *irreversible* because of frictional resistance to flow. *Increase of entropy also shows that expansion from point 2 to point 3 is irreversible.*

(*b*) **Using Mollier chart.**

Refer to Fig. 4.77.

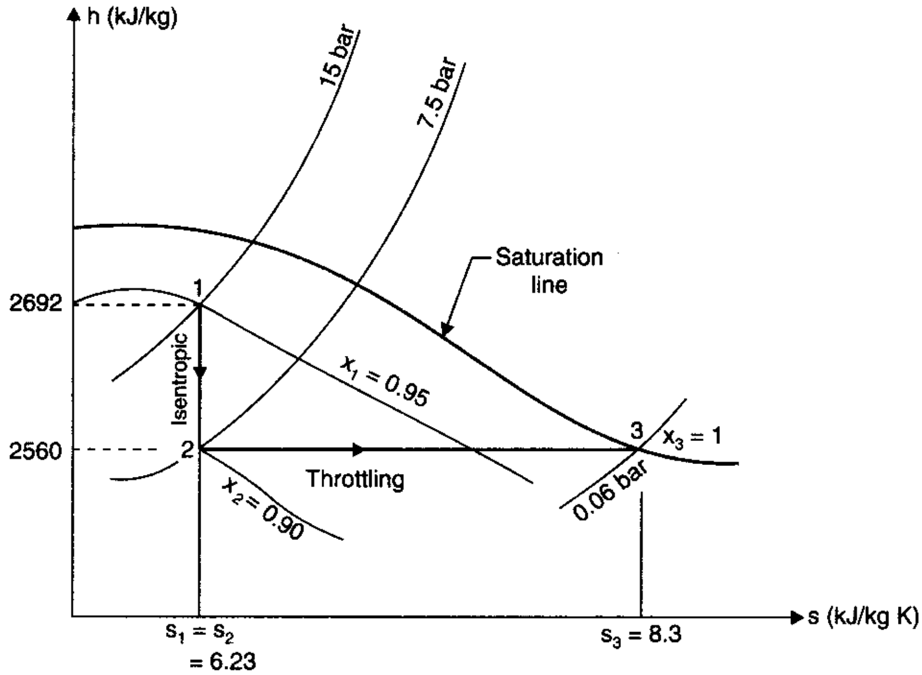


Fig. 4.77

- Locate point 1 at an intersection of 15 bar pressure line and 0.95 dryness fraction line.
- Draw vertical line from point 1 intersecting 7.5 bar pressure line at point 2. Line 1-2 represents *isentropic expansion.*
- From point 2 draw a horizontal line intersecting at the saturation line at point 3. Line 2-3 then represents *throttling expansion.*

From *Mollier chart* :

h_1 = 2692 kJ/kg, h_2 = 2560 kJ/kg

$s_1 = s_2$ = 6.23 kJ/kg, s_3 = 8.3 kJ/kg K

∴ (*i*) **Change in entropy** $= s_3 - (s_1 \text{ or } s_2)$

= 8.3 – 6.23 = **2.07 kJ/kg K (increase). (Ans.)**

(*ii*) **Change in enthalpy** $= h_2 \text{ (or } h_3) - h_1$

= 2560 – 2692 = – 132 kJ/kg

= **132 kJ/kg (decrease). (Ans.)**

4.15. UNSTEADY FLOW PROCESSES

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) *flow process.*

Following two cases only will be discussed :

1. Filling a tank.
2. Emptying a tank or tank discharge.

1. Filling a tank :

Let m_1 = Initial mass of fluid,
p_1 = Initial pressure,
v_1 = Initial specific volume,
T_1 = Initial temperature,
u_1 = Initial specific internal energy,

and m_2 = Final mass of fluid,
p_2 = Final pressure,

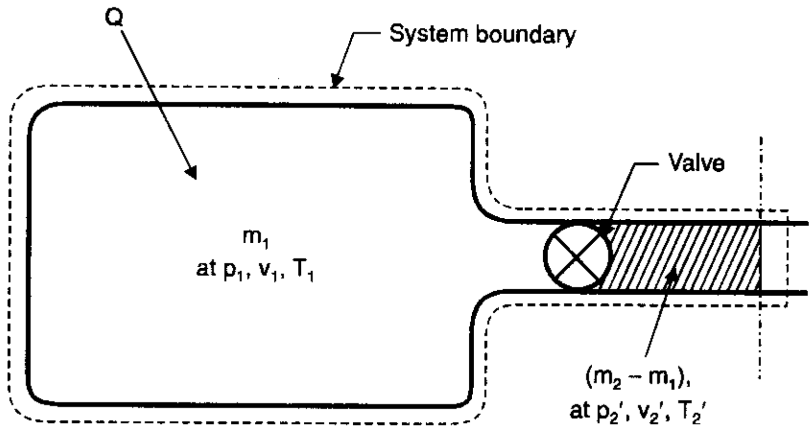


Fig. 4.78

v_2 = Final specific volume,
T_2 = Final temperature,
u_2 = Final specific internal energy,

Also, let p' = Entering fluid pressure,
v' = Entering fluid specific volume,
T' = Entering fluid temperature,
C' = Entering fluid velocity,
u' = Entering specific internal energy of fluid, and
h' = Entering specific enthalpy of fluid.

The quantity of fluid entering

$$= m_2 - m_1$$

Energy of entering fluid

$$= (m_2 - m_1)\left(u' + p'v' + \frac{C'^2}{2}\right) \quad ...(4.82)$$

$$= (m_2 - m_1)\left(h' + \frac{C'^2}{2}\right) \quad ...(4.83)$$

If Q = Heat transferred into the control volume, we have

$$(m_2 - m_1)\left(h' + \frac{C'^2}{2}\right) + Q = m_2u_2 - m_1u_1 \quad ...(4.84)$$

When the tank is fully insulated and thus no heat transfer takes place,

$$Q = 0$$

and
$$(m_2 - m_1)\left(h' + \frac{C'^2}{2}\right) = m_2u_2 - m_1u_1 \qquad ...(4.85)$$

Also, if the tank is empty initially and fully insulated for heat transfer,

$$m_1 = 0$$

Thus
$$h' + \frac{C'^2}{2} = u_2 \qquad ..(4.86)$$

Also, if kinetic energy in the pipe line is neglected

$$h' = u_2 \qquad ...(4.87)$$

2. Emptying a tank :

Analogous to the filling of the tank, the equation can be written as

$$(m_1 - m_2)\left(h' + \frac{C'^2}{2}\right) - Q = m_1u_1 - m_2u_2 \qquad ...(4.88)$$

where h' = Specific enthalpy of leaving fluid, and

C' = Velocity of leaving fluid.

For fully emptying the tank and no heat transfer and negligible exit velocity,

$$h' = u_1 \qquad ...(4.89)$$

Example 4.64. *An air receiver of volume 5.5 m³ contains air at 16 bar and 42°C. A valve is opened and some air is allowed to blow out to atmosphere. The pressure of the air in the receiver drops rapidly to 12 bar when the valve is then closed.*

Calculate the mass of air which has left the receiver.

Solution. Initial volume of air, $V_1 = 5.5 \text{ m}^3$

Initial pressure of air, $p_1 = 16$ bar

Initial temperature of air, $T_1 = 42 + 273 = 315$ K

Final volume of air, $V_2 = V_1 = 5.5 \text{ m}^3$

Final pressure of air, $p_2 = 12$ bar

Mass of air which left the receiver :

Mass of air in the *initial* condition,

$$m_1 = \frac{p_1V_1}{RT_1} = \frac{16 \times 10^5 \times 5.5}{(0.287 \times 10^3) \times 315} = 97.34 \text{ kg.}$$

Assuming that the mass in the receiver undergoes a reversible adiabatic process, then

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}}$$

$$\frac{T_2}{315} = \left(\frac{12}{16}\right)^{\frac{1.4 - 1}{1.4}} = \left(\frac{12}{16}\right)^{0.286} \quad \text{or} \quad T_2 = 315 \times \left(\frac{12}{16}\right)^{0.286} = 290 \text{ K}$$

Now mass of air in the receiver in *final* condition,

$$m_2 = \frac{p_2V_2}{RT_2} = \frac{12 \times 10^5 \times 5.5}{(0.287 \times 10^3) \times 290} = 79.3 \text{ kg.}$$

∴ **Mass of air which left the receiver,**

$$m = m_1 - m_2 = 97.34 - 79.3 = \mathbf{18.04\ kg.}\quad \textbf{(Ans.)}$$

Example 4.65. *A 1.6 m³ tank is filled with air at a pressure of 5 bar and a temperature of 100°C. The air is then let off to the atmosphere through a valve. Assuming no heat transfer, determine the work obtainable by utilising the kinetic energy of the discharge air to run a frictionless turbine.*

Take : Atmospheric pressure = 1 bar ;

c_p for air = 1 kJ/kg K ;

c_v for air = 0.711 kJ/kg K.

Solution. Initial volume of air, $V_1 = 1.6\ m^3$

Initial pressure of air, $p_1 = 5\ bar = 5 \times 10^5\ N/m^2$

Initial temperature of air, $T_1 = 100 + 273 = 373\ K$

Final pressure of air, $p_2 = 1\ bar = 1 \times 10^5\ N/m^2$

Now, initial quantity of air in the tank before discharge,

$$m_1 = \frac{p_1V_1}{RT_1} = \frac{5 \times 10^5 \times 1.6}{(0.287 \times 10^3) \times 373} = 7.47\ kg.$$

Assuming that system undergoes a reversible adiabatic expansion

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}}$$

where T_2 is the final temperature of air in the tank.

$$\therefore \quad \frac{T_2}{373} = \left(\frac{1}{5}\right)^{\frac{1.4-1}{1.4}} = 0.631$$

$$T_2 = 373 \times 0.631 = 235.4\ K\ (\textit{i.e.}, \text{finally in the line})$$

The final quantity of air remaining in the tank is

$$m_2 = \frac{p_2V_2}{RT_2} = \frac{1 \times 10^5 \times 1.6}{(0.287 \times 10^3) \times 235.4} = 2.368\ kg.$$

With $Q = 0$, kinetic energy is found from,

$$(m_1 - m_2)\left(h' + \frac{C'^2}{2}\right) = m_1u_1 - m_2u_2$$

or
$$(m_1 - m_2)\,h' + (m_1 - m_2)\,\frac{C'^2}{2} = m_1u_1 - m_2u_2$$

∴ Kinetic energy,

$$(m_1 - m_2)\,\frac{C'^2}{2} = (m_1u_1 - m_2u_2) - (m_1 - m_2)\,h'$$

$$= m_1c_vT_1 - m_2c_vT_2 - (m_1 - m_2)\,c_pT_2$$

$$= 7.47 \times 0.771 \times 373 - 2.368 \times 0.711 \times 235.4 - (7.47 - 2.368) \times 1 \times 235.4$$

$$= 2148.24 - 396.33 - 1201 = \mathbf{550.9\ kJ.}\quad \textbf{(Ans.)}$$

☞**Example 4.66.** *A frictionless piston is free to move in a closed cylinder. Initially there is 0.035 m³ of oxygen at 4.5 bar, 60°C on one side of the piston and 0.07 m³ of methane at 4.5 bar* *and – 12°C on the other side. The cylinder walls and piston may be regarded as perfect thermal insulators but the oxygen may be heated electrically. Heating takes place so that the volume of oxygen doubles. Find :*

(i) Final state condition ; *(ii) Work done by the piston ;*

(iii) Heat transferred to oxygen.

Treat both gases as perfect and take :

For oxygen $c_p = 0.88$ *kJ/kg K,* $R = 0.24$ *kJ/kg K*

For methane $c_p = 1.92$ *kJ/kg K,* $R = 0.496$ *kJ/kg K.*

Solution. For oxygen :

Initial volume, $V_1 = 0.035 \text{ m}^3$

Initial pressure, $p_1 = 4.5$ bar

Initial temperature, $T_1 = 60 + 273 = 333$ K

For methane :

Initial volume, $V_1 = 0.07 \text{ m}^3$

Final volume, $V_2 = 0.035 \text{ m}^3$

Initial pressure, $p_1 = 4.5$ bar

Initial temperature of methane,

$$T_1 = -12 + 273 = 261 \text{ K.}$$

For Methane :

$$c_p = R \times \frac{\gamma}{\gamma - 1} \quad \text{or} \quad 1.92 = 0.496 \left(\frac{\gamma}{\gamma - 1}\right)$$

or $$\frac{1.92}{0.496} = \frac{\gamma}{\gamma - 1} \quad \text{or} \quad 1.92(\gamma - 1) = 0.496\,\gamma$$

$\therefore$ $$\gamma = \frac{1.92}{(1.92 - 0.496)} = 1.348 \text{ say } 1.35$$

For Oxygen :

$$c_v = c_p - R = 0.88 - 0.24 = 0.64 \text{ kJ/kg K.}$$

(*i*) According to problem ; for *methane*

$$pV^\gamma = \text{constant holds good}$$

$\therefore$ $$p_1 V_1^\gamma = p_2 V_2^\gamma$$

$$p_2 = p_1 \cdot \left(\frac{V_1}{V_2}\right)^\gamma = 4.5\,(2)^{1.35} = \mathbf{11.47 \text{ bar.}} \quad \textbf{(Ans.)}$$

Also, $$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

or $$T_2 = \frac{p_2 V_2 T_1}{p_1 V_1} = \frac{11.47 \times 0.035 \times 261}{4.5 \times 0.07} = \mathbf{332.6 \text{ K.}} \quad \textbf{(Ans.)}$$

$\therefore$ $$\text{Work done} = \frac{p_1 V_1 - p_2 V_2}{\gamma - 1} = \frac{4.5 \times 10^5 \times 0.07 - 11.47 \times 10^5 \times 0.035}{(1.35 - 1)} \text{ J}$$

$$= \frac{10^5 (4.5 \times 0.07 - 11.47 \times 0.035)}{0.35 \times 1000} \text{ kJ}$$

$$= -24.7 \text{ kJ}$$ (*done on the methane*)

(*ii*) **The piston will be in virtual equilibrium and hence zero work is effected by the piston. (Ans.)**

(*iii*) Work done by oxygen = work done on methane and expansion of oxygen is effected in the system

$\therefore \quad W_{oxygen} = +\ 24.7$ kJ

and $\quad Q = (U_2 - U_1) + W$

Amount of oxygen present $= \dfrac{p_1 V_1}{RT_1} = \dfrac{4.5 \times 10^5 \times 0.035}{0.24 \times 1000 \times 333} = 0.197$ kg

and $\quad T_2 = \dfrac{p_2 V_2}{p_1 V_1} \times T_1 = \dfrac{11.47 \times 0.07 \times 333}{4.5 \times 0.035} =$ **1697.5 K. (Ans.)**

(As the piston is free, the final pressure of oxygen and methane will be **same**).

$$\therefore \quad Q = (U_2 - U_1) + W$$
$$= mc_v (T_2 - T_1) + W$$
$$= 0.197 \times 0.64\ (1697.5 - 333) + 24.7 = \textbf{196.7 kJ.} \quad \textbf{(Ans.)}$$

HIGHLIGHTS

1. *Internal energy* is the heat energy stored in a gas. The internal energy of a perfect gas is a function of *temperature* only.
2. First law of thermodynamics states :
   — Heat and work are mutually convertible but since energy can neither be created nor destroyed, the total energy associated with an energy conversion remains constant.

   Or

   — No machine can produce energy without corresponding expenditure of energy, *i.e.*, it is impossible to construct a perpetual motion machine of first kind.

   First law can be expressed as follows :

   $Q = \Delta E + W$

   $Q = \Delta U + W$ ... if electric, magnetic, chemical energies are absent and changes in potential and kinetic energies are neglected.
3. There can be no machine which would continuously supply mechanical work without some form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of the first kind, or in brief, PMM1. A PMM1 is thus impossible.
4. The energy of an isolated system is always constant.
5. In case of

   (*i*) **Reversible constant volume process** (v = constant)

   $$\Delta u = c_v(T_2 - T_1)\ ;\ W = 0\ ;\ Q = c_v\,(T_2 - T_1)$$

   (*ii*) **Reversible constant pressure process** (p = constant)

   $$\Delta u = c_v(T_2 - T_1)\ ;\ W = p(v_2 - v_1)\ ;\ Q = c_p\,(T_2 - T_1)$$

   (*iii*) **Reversible temperature or isothermal process** (pv = constant)

   $$\Delta u = 0,\ W = p_1 V_1 \log_e r,\ Q = W$$

   where r = expansion or compression ratio.

   (*iv*) **Reversible adiabatic process** (pv^γ = constant)

   $$\pm \Delta u = \mp\ W = \frac{R(T_1 - T_2)}{\gamma - 1}\ ;\ Q = 0\ ;\ \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}}$$

(*v*) **Polytropic reversible process** (pv^n = constant)

$$\Delta u = c_v (T_2 - T_1) \; ; \; W = \frac{R(T_1 - T_2)}{n-1} \; ; \; Q = \Delta u + W \; ;$$

and $$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{n-1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \quad \text{and} \quad Q = \left(\frac{\gamma - n}{n-1}\right) \times W.$$

6. Steady flow equation can be expressed as follows :

$$u_1 + \frac{C_1^2}{2} + Z_1 g + p_1 v_1 + Q = u_2 + \frac{C_2^2}{2} + Z_2 g + p_2 v_2 + W \quad ...(i)$$

or $$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W, \text{ neglecting } Z_1 \text{ and } Z_2 \quad ...(ii)$$

where, Q = Heat supplied per kg of fluid ; W = Work done by 1 kg of fluid ;
C = Velocity of fluid ; Z = Height above datum ;
p = Pressure of the fluid ; u = Internal energy per kg of fluid ;
pv = Energy required per kg of fluid.

This equation is applicable to any medium in any steady flow.

7. During adiabatic *throttling process* enthalpy remains constant. The slope of a constant enthalpy line on a p-T diagram is called Joule-Thompson co-efficient, μ.
8. In unsteady-flow processes, the rates at which mass and energy enter the control volume may not be the same as the rate of flow of mass and energy moving out of the control volume. The filling of a tank is an example of unsteady flow process.

OBJECTIVE TYPE QUESTIONS

Choose the Correct Answer :

1. If all the variables of a stream are independent of time it is said to be in
(*a*) steady flow (*b*) unsteady flow
(*c*) uniform flow (*d*) closed flow
(*e*) constant flow.
2. A control volume refers to
(*a*) a fixed region in space (*b*) a specified mass
(*c*) an isolated system (*d*) a reversible process only
(*e*) a closed system.
3. Internal energy of a perfect gas depends on
(*a*) temperature, specific heats and pressure (*b*) temperature, specific heats and enthalpy
(*c*) temperature, specific heats and entropy (*d*) temperature only.
4. In reversible polytropic process
(*a*) true heat transfer occurs (*b*) the entropy remains constant
(*c*) the enthalpy remains constant (*d*) the internal energy remains constant
(*e*) the temperature remains constant.
5. An isentropic process is always
(*a*) irreversible and adiabatic (*b*) reversible and isothermal
(*c*) frictionless and irreversible (*d*) reversible and adiabatic
(*e*) none of the above.

6. The net work done per kg of gas in a polytropic process is equal to

(a) $p_1v_1 \log_e \frac{v_2}{v_1}$ (b) $p_1(v_1 - v_2)$

(c) $p_2\left(v_2 - \frac{v_1}{v_2}\right)$ (d) $\frac{p_1v_1 - p_2v_2}{n-1}$

(e) $\frac{p_2v_1 - p_2v_2}{n-1}$.

7. Steady flow occurs when

(a) conditions do not change with time at any point

(b) conditions are the same at adjacent points at any instant

(c) conditions change steadily with the time

(d) $\left(\frac{\partial v}{\partial t}\right)$ is constant.

8. A reversible process requires that

(a) there be no heat transfer (b) newton's law of viscosity be satisfied

(c) temperature of system and surroundings be equal

(d) there be no viscous or coloumb friction in the system

(e) heat transfer occurs from surroundings to system only.

9. The first law of thermodynamics for steady flow

(a) accounts for all energy entering and leaving a control volume

(b) is an energy balance for a specified mass of fluid

(c) is an expression of the conservation of linear momentum

(d) is primarily concerned with heat transfer

(e) is restricted in its application to perfect gases.

10. The characteristic equation of gases $pV = mRT$ holds good for

(a) monoatomic gases (b) diatomic gas

(c) real gases (d) ideal gases

(e) mixture of gases.

11. A gas which obeys kinetic theory perfectly is known as

(a) monoatomic gas (b) diatomic gas

(c) real gas (d) pure gas

(e) perfect gas.

12. Work done in a free expansion process is

(a) zero (b) minimum

(c) maximum (d) positive

(e) negative.

13. Which of the following is not a property of the system ?

(a) Temperature (b) Pressure

(c) Specific volume (d) Heat

(e) None of the above.

14. In the polytropic process equation pv^n = constant, if $n = 0$, the process is termed as

(a) constant volume (b) constant pressure

(c) constant temperature (d) adiabatic

(e) isothermal.

15. In the polytropic process equation pv^n = constant, if n is infinitely large, the process is termed as

(a) constant volume (b) constant pressure

(c) constant temperature (d) adiabatic

(e) isothermal.

16. The processes or systems that do not involve heat are called
(*a*) isothermal processes
(*b*) equilibrium processes
(*c*) thermal processes
(*d*) steady processes
(*e*) adiabatic processes.

17. In a reversible adiabatic process the ratio (T_1/T_2) is equal to
(*a*) $\left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}}$
(*b*) $\left(\frac{v_1}{v_2}\right)^{\frac{\gamma-1}{\gamma}}$
(*c*) $(v_1 v_2)^{\frac{\gamma-1}{2\gamma}}$.
(*d*) $\left(\frac{v_2}{v_1}\right)^{\gamma}$.

18. In isothermal process
(*a*) temperature increases gradually
(*b*) volume remains constant
(*c*) pressure remains constant
(*d*) enthalpy change is maximum
(*e*) change in internal energy is zero.

19. During throttling process
(*a*) internal energy does not change
(*b*) pressure does not change
(*c*) entropy does not change
(*d*) enthalpy does not change
(*e*) volume change is negligible.

20. When a gas is to be stored, the type of compression that would be ideal is
(*a*) isothermal
(*b*) adiabatic
(*c*) polytropic
(*d*) constant volume
(*e*) none of the above.

21. If a process can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states, it is known as
(*a*) adiabatic process
(*b*) isothermal process
(*c*) ideal process
(*d*) frictionless process
(*e*) energyless process.

22. The state of a substance whose evaporation from its liquid state is complete, is known as
(*a*) vapour
(*b*) perfect gas
(*c*) air
(*d*) steam.

23. In SI units, the value of the universal gas constant is
(*a*) 0.8314 J/mole/K
(*b*) 8.314 J/mole/K
(*c*) 83.14 J/mole/K
(*d*) 831.4 J/mole/K
(*e*) 8314 J/mole/K.

24. When the gas is heated at constant pressure, the heat supplied
(*a*) increases the internal energy of the gas
(*b*) increases the temperature of the gas
(*c*) does some external work during expansion
(*d*) both (*b*) and (*c*)
(*e*) none of the above.

25. The gas constant (R) is equal to the
(*a*) sum of two specific heats
(*b*) difference of two specific heats
(*c*) product of two specific heats
(*d*) ratio of two specific heats.

26. The heat absorbed or rejected during a polytropic process is
(*a*) $\left(\frac{\gamma-n}{\gamma-1}\right) \times$ work done
(*b*) $\left(\frac{\gamma-n}{\gamma-1}\right)^2 \times$ work done
(*c*) $\left(\frac{\gamma-n}{\gamma-1}\right)^{1/2} \times$ work done
(*d*) $\left(\frac{\gamma-n}{\gamma-1}\right)^3 \times$ work done.

Answers

1. (*a*)	**2.** (*a*)	**3.** (*d*)	**4.** (*a*)	**5.** (*d*)	**6.** (*d*)	**7.** (*a*)
8. (*d*)	**9.** (*a*)	**10.** (*c*)	**11.** (*e*)	**12.** (*a*)	**13.** (*d*)	**14.** (*b*)
15. (*a*)	**16.** (*e*)	**17.** (*a*)	**18.** (*e*)	**19.** (*d*)	**20.** (*a*)	**21.** (*c*)
22. (*b*)	**23.** (*e*)	**24.** (*d*)	**25.** (*b*)	**26.** (*a*).		

THEORETICAL QUESTIONS

1. Define 'internal energy' and prove that it is a property of a system.
2. Explain the First Law of Thermodynamics as referred to closed systems undergoing a cyclic change.
3. State the First Law of Thermodynamics and prove that for a non-flow process, it leads to the energy equation $Q = \Delta U + W$.
4. What is the mechanical equivalent of heat ? Write down its value when heat is expressed in kJ and work is expressed in N-m.
5. What do you mean by "Perpetual motion machine of first kind-PMM 1" ?
6. Why only in constant pressure non-flow process, the enthalpy change is equal to heat transfer ?
7. Prove that the rate of change of heat interchange per unit change of volume when gas is compressed or expanded is given by $\frac{\gamma - n}{\gamma - 1} \times \frac{pdv}{J}$.
8. Write down the general energy equation for steady flow system and simplify when applied for the following systems :
   (*i*) Centrifugal water pump
   (*ii*) Reciprocating air compressor
   (*iii*) Steam nozzle
   (*iv*) Steam turbine
   (*v*) Gas turbine.
9. Explain clearly the difference between a non-flow and a steady flow process.
10. For isothermal flow and non-flow steady processes, prove that

$$\int_1^2 pdv = -\int_1^2 v \, . \, dp$$

Also state the assumptions made.

UNSOLVED EXAMPLES

Closed Systems

1. In a cyclic process, heat transfers are + 14.7 kJ, – 25.2 kJ, – 3.56 kJ and + 31.5 kJ. What is the net work for this cyclic process ? **[Ans.** 17.34 kJ]
2. A domestic refrigerator is loaded with food and the door closed. During a certain period the machine consumes 1 kWh of energy and the internal energy of the system drops by 5000 kJ. Find the net heat transferred in the system. **[Ans.** – 8.6 MJ]
3. 1.5 kg of liquid having a constant specific heat of 2.5 kJ/kg°C is stirred in a *well-insulated* chamber causing the temperature to rise by 15°C. Find :
   (*i*) Change in internal energy, and
   (*ii*) Work done for the process. **[Ans.** (*i*) 56.25 kJ, W = – 56.25 kJ]
4. A system is composed of a stone having a mass of 10 kg and a bucket containing 100 kg of water. Initially the stone and water are at the same temperature, the stone then falls into the water. Determine ΔU, ΔKE, ΔPE, ΔQ and ΔW for the following cases :
   (*i*) At the instant the stone is about to enter the water.

(*ii*) Just after the stone comes to rest in the bucket.

[**Ans.** (*i*) $\Delta Q = \Delta W = \Delta E = 0$, $\Delta KE = 4.184$ kJ, $\Delta PE = -4.184$ kJ ;
(*ii*) $\Delta Q = 0$, $\Delta W = 0$, $\Delta KE = 0$, $\Delta U = +4.184$ kJ, $\Delta PE = -4.184$ kJ]

5. A closed system of constant volume experiences a temperature rise of 20°C when a certain process occurs. The heat transferred in the process is 18 kJ. The specific heat at constant volume for the pure substance comprising the system is 1.2 kJ/kg°C, and the system contains 2 kg of this substance. Determine the change in internal energy and the work done. [**Ans.** $\Delta U = 48$ kJ ; $W = -30$ kJ]

6. A stationary mass of gas is compressed without friction from an initial state of 2 m^3 and 2×10^5 N/m^2 to a final state of 1 m^3 and 2×10^5 N/m^2, the pressure remaining the same. There is a transfer of 360 kJ of heat from the gas during the process. How much does the internal energy of the gas change ?[**Ans.** $\Delta U = -160$ kJ]

7. The internal energy of a certain substance is given by the following equation :

$$u = pv + 84$$

where u is given in kJ/kg, p is in kPa and v is in m^3/kg.

A system composed of 3 kg of this substance expands from an initial pressure of 500 kPa and a volume of 0.22 m^3 to a final pressure 100 kPa in a process in which pressure and volume are related by $pv^{1.2}$ = constant.

(*i*) If the expansion is quasi-static, find Q, ΔU and W for the process.

(*ii*) In another process the same system expands according to the same pressure-volume relationship as in part (*i*) and from the same initial state to the same final state as in part (*i*) but the heat transfer in this case is 30 kJ. Find the work transfer for this process.

(*iii*) Explain the difference in work transfer in parts (*i*) and (*ii*).

[**Ans.** (*i*) $\Delta U = -91$ kJ, $W = 127.5$ kJ, $Q = 36.5$ kJ
(*ii*) $W = 121$ kJ, (*iii*) The work in (*ii*) in not equal
to $\int pdV$ since the process is not quasi-static.]

8. A fluid is contained in a cylinder by a spring-loaded, frictionless piston so that the pressure in the fluid is linear function of the volume ($p = a + bV$). The internal energy of the fluid is given by the following equation

$$U = 34 + 3.15\,pV$$

where U is in kJ, p in kPa and V in cubic metre. If the fluid changes from an initial state of 170 kPa, 0.03 m^3 to a final state of 400 kPa, 0.06 m^3, with no work other than that done on the piston, find the direction and magnitude of the work and heat transfer.

[**Ans.** $W_{1-2} = 10.35$ kJ ;
$Q_{1-2} = 69.85$ kJ (heat flows into the system during the process)]

9. A piston cylinder arrangement has a gas in the cylinder space. During a constant pressure expansion to a larger volume the work effect for the gas are 1.6 kJ, the heat added to the gas and cylinder arrangement is 3.2 kJ and the friction between the piston and cylinder wall amounts to 0.24 kJ. Determine the change in internal energy of the entire apparatus (gas, cylinder, piston). [**Ans.** 1.84 kJ]

10. A system receives 42 kJ of heat while expanding with volume change of 0.123 m^3 against an atmosphere of 12 N/cm^2. A mass of 80 kg in the surroundings is also lifted through a distance of 6 metres.

(*i*) Find the change in energy of the system.

(*ii*) The system is returned to its initial volume by an adiabatic process which requires 100 kJ of work. Find the change in energy of system.

(*iii*) Determine the total change in energy of the system. [**Ans.** (*i*) 22.54 kJ, (*ii*) 100 kJ, (*iii*) 122.54 kJ]

11. A thermally insulated battery is being discharged at atmospheric pressure and constant volume. During a 1 hour test it is found that a current of 50 A and 2 V flows while the temperature increases from 20°C to 32.5°C. Find the change in internal energy of the cell during the period of operation. [**Ans.** -36×10^4 J]

12. In a certain steam plant the turbine develops 1000 kW. The heat supplied to the steam in the boiler is 2800 kJ/kg, the heat received by the system from cooling water in the condenser is 2100 kJ/kg and the feed pump work required to pump the condensate back into the boiler is 5 kW. Calculate the steam flow round the cycle in kg/s. [**Ans.** 1.421 kg/s]

13. In the compression stroke of an internal-combustion engine the heat rejected to the cooling water is 45 kJ/kg and the work input is 90 kJ/kg. Calculate the change in internal energy of the working fluid stating whether it is a gain or a loss. **[Ans.** 45 kJ/kg (gain)]

14. 85 kJ of heat are supplied to a system at constant volume. The system rejects 90 kJ of heat at constant pressure and 20 kJ of work is done on it. The system is brought to its original state by adiabatic process. Determine the adiabatic work. Determine also the value of internal energy at all end states if initial value is 100 kJ. **[Ans.** W = 15 kJ ; U_1 = 100 kJ, U_2 = 185 kJ ; U_3 = 115 kJ]

15. A closed system undergoes a reversible process at a constant pressure process of 3.5 bar and its volume changes from 0.15 m^3 to 0.06 m^3. 25 kJ of heat is rejected by the system during the process. Determine the change in internal energy of the system. **[Ans.** 6.5 kJ (increase)]

16. An air compressor takes in air at 10^5 Pa and 27°C having volume of 1.5 m^3/kg and compresses it to 4.5×10^5 Pa. Find the work done, heat transfer and change in internal energy if the compression is isothermal.

[Ans. – 225 kJ ; – 225 kJ ; $\Delta U = 0$]

17. A cylinder fitted with piston contains 0.2 kg of N_2 at 100 kPa and 30°C. The piston is moved compressing N_2 until the pressure becomes 1 MPa and temperature becomes 150°C. The work done during the process is 20 kJ. Determine the heat transferred from N_2 to the surroundings. Take c_v = 0.75 kJ/kg K for N_2.

[Ans. – 2 kJ]

18. A closed system consisting of 1 kg of gaseous CO_2 undergoes a reversible process at constant pressure causing a decrease of 30 kJ in internal energy. Determine the work done during the process. Take c_p = 840 J/kg°C and c_v = 600 J/kg°C. **[Ans.** – 12 kJ]

19. The specific heat at constant pressure of one kg fluid undergoing a non-flow constant pressure process is given by

$$c_p = \left[2.5 + \frac{40}{T + 20}\right] \text{ kg/kg°C}$$

where T is in °C.

The pressure during the process is maintained at 2 bar and volume changes from 1 m^3 to 1.8 m^3 and temperature changes from 50°C to 450°C. Determine :

(*i*) Heat added (*ii*) Work done

(*iii*) Change in internal energy (*iv*) Change in enthalpy.

[Ans. (*i*) 1076 kJ ; (*ii*) 160 kJ ; (*iii*) 916 kJ ; (*iv*) 1076 kJ]

20. 1 kg of nitrogen (molecular weight 28) is compressed reversibly and isothermally from 1.01 bar, 20°C to 4.2 bar. Calculate the work done and the heat flow during the process. Assume nitrogen to be a perfect gas.

[Ans. W = 124 kJ/kg ; Q = – 124 kJ/kg]

21. Air at 1.02 bar, 22°C, initially occupying a cylinder volume of 0.015 m^3, is compressed reversibly and adiabatically by a piston to a pressure of 6.8 bar. Calculate :

(*i*) The final temperature (*ii*) The final volume

(*iii*) The work done on the mass of air in the cylinder. **[Ans.** (*i*) 234.5°C, (*ii*) 0.00388 m^3 ; (*iii*) 2.76 kJ]

22. 1 kg of a perfect gas is compressed from 1.1 bar, 27°C according to a law $pv^{1.3}$ = constant, until the pressure is 6.6. bar. Calculate the heat flow to or from the cylinder walls,

(*i*) When the gas is ethane (molecular weight 30), which has

$$c_p = 1.75 \text{ kJ/kg K.}$$

(*ii*) When the gas is argon (molecular weight 40), which has

$$c_p = 0.515 \text{ kJ/kg K.}$$

[Ans. (*i*) 84.5 kJ/kg, (*ii*) – 59.4 kJ/kg]

23. 1 kg of air at 1 bar, 15°C is compressed reversibly and adiabatically to a pressure of 4 bar. Calculate the final temperature and the work done on the air. **[Ans.** 155°C ; 100.5 kJ/kg]

24. A certain perfect gas is compressed reversibly from 1 bar, 17°C to a pressure of 5 bar in a perfectly thermally insulated cylinder, the final temperature being 77°C. The work done on the gas during the compression is 45 kJ/kg. Calculate γ, c_v, R and the molecular weight of the gas.

[Ans. 1.132 ; 0.75 kJ/kg K ; 0.099 kJ/kg K ; 84]

25. 1 kg of air at 1.02 bar, 20°C is compressed reversibly according to a law $pv^{1.3}$ = constant, to a pressure of 5.5 bar. Calculate the work done on the air and heat flow to or from the cylinder walls during the compression. [**Ans.** 133.5 kJ/kg ; – 33.38 kJ/kg]

26. 0.05 kg of carbon dioxide (molecular weight 44), occupying a volume of 0.03 m^3 at 1.025 bar, is compressed reversibly until the pressure is 6.15 bar. Calculate final temperature, the work done on the CO_2, the heat flow to or from the cylinder walls,

(*i*) When the process is according to law $pv^{1.4}$ = constant,

(*ii*) When the process is isothermal,

(*iii*) When the process takes place in a perfectly thermally insulated cylinder.

Assume CO_2 to be a perfect gas, and take γ = 1.3. [**Ans.** 270°C ; 5.138 kJ ; 1.713 kJ ; 52.6°C ; 5.51 kJ ; – 5.51 kJ ; 219°C ; 5.25 kJ ; 0 kJ]

27. Oxygen (molecular weight 32) is compressed reversibly and polytropically in a cylinder from 1.05 bar, 15°C to 4.2 bar in such a way that one-third of the work input is rejected as heat to the cylinder walls. Calculate the final temperature of the oxygen.

Assume oxygen to be a perfect gas and take c_v = 0.649 kJ/kg K. [**Ans.** 113°C]

28. A cylinder contains 0.5 m^3 of a gas at 1 × 10^5 N/m^2 and 90°C. The gas is compressed to a volume of 0.125 m^3, the final pressure being 6 × 10^5 N/m^2. Determine :

(*i*) The mass of gas.

(*ii*) The value of index '*n*' for compression.

(*iii*) The increase in internal energy of gas.

(*iv*) The heat received or rejected by the gas during compression.

(γ = 1.4, R = 294.2 Nm/kg°C). [**Ans.** 0.468 kg ; 1.292 ; 62.7 kJ ; – 22.67 kJ]

Steady Flow Systems

29. 12 kg of a fluid per minute goes through a reversible steady flow process. The properties of fluid at the inlet are p_1 = 1.4 bar, ρ_1 = 25 kg/m^3, C_1 = 120 m/s and u_1 = 920 kJ/kg and at the exit are p_2 = 5.6 bar, ρ_2 = 5 kg/m^3, C_2 = 180 m/s and u_2 = 720 kJ/kg. During the passage, the fluid rejects 60 kJ/s and rises through 60 metres. Determine : (*i*) the change in enthalpy (Δh) and (*ii*) work done during the process (W).

[**Ans.** Δh = – 93.6 kJ/kg ; W = – 44.2 kW]

30. In the turbine of a gas turbine unit the gases flow through the turbine is 17 kg/s and the power developed by the turbine is 14000 kW. The enthalpies of the gases at inlet and outlet are 1200 kJ/kg and 360 kJ/kg respectively, and the velocities of the gases at inlet and outlet are 60 m/s and 150 m/s respectively. Calculate the rate at which the heat is rejected from the turbine. Find also the area of the inlet pipe given that the specific volume of the gases at inlet is 0.5 m^3/kg. [**Ans.** 119.3 kW (heat rejected) ; 0.142 m^3]

31. Air flows steadily at the rate of 0.4 kg/s through an air compressor, entering at 6 m/s with a pressure of 1 bar and a specific volume of 0.85 m^3/kg, and leaving at 4.5 m/s with a pressure of 6.9 bar and a specific volume of 0.16 m^3/kg. The internal energy of air leaving is 88 kJ/kg greater than that of the air entering. Cooling water in a jacket surrounding the cylinder absorbs heat from the air at the rate of 59 kJ/s. Calculate the power required to drive the compressor and the inlet and outlet pipe cross-sectional areas.

[**Ans.** 104.4 kW ; 0.057 m^2 ; 0.014 m^2]

32. A turbine operating under steady flow conditions receives steam at the following state : pressure 13.8 bar ; specific volume 0.143 m^3/kg ; internal energy 2590 kJ/kg ; velocity 30 m/s. The state of the steam leaving the turbine is : pressure 0.35 bar ; specific volume 4.37 m^3/kg ; internal energy 2360 kJ/kg ; velocity 90 m/s. Heat is lost to the surroundings at the rate of 0.25 kJ/s. If the rate of steam flow is 0.38 kg/s, what is the power developed by the turbine ? [**Ans.** 102.8 kW]

33. A nozzle is a device for increasing the velocity of a steadily flowing stream of fluid. At the inlet to a certain nozzle the enthalpy of the fluid is 3025 kJ/kg and the velocity is 60 m/s. At the exit from the nozzle the enthalpy is 2790 kJ/kg. The nozzle is horizontal and there is negligible heat loss from it.

(*i*) Find the velocity at the nozzle exit.

(*ii*) If the inlet area is 0.1 m^2 and specific volume at inlet is 0.19 m^3/kg, find the rate of flow of fluid.

(*iii*) If the specific volume at the nozzle exit is 0.5 m^3/kg, find the exit area of the nozzle.

[**Ans.** 688 m/s ; 31.6 kg/s ; 0.0229 m^2]

34. A gas flows steadily through a rotary compressor. The gas enters the compressor at a temperature of 16°C, a pressure of 100 kPa, and an enthalpy of 391.2 kJ/kg. The gas leaves the compressor at a temperature of 245°C, a pressure of 0.6 MPa and an enthalpy of 534.5 kJ/kg. There is no heat transfer to or from the gas as it flows through the compressor.

(*i*) Evaluate the external work done per unit mass of gas assuming the gas velocities at entry and exit to be negligible.

(*ii*) Evaluate the external work done per unit mass of gas when the gas velocity at entry is 80 m/s and that at exit is 160 m/s. [**Ans.** 143.3 kJ/kg, 152.9 kJ/kg]

35. A turbine, operating under steady-flow conditions, receives 5000 kg of steam per hour. The steam enters the turbine at a velocity of 3000 m/min, an elevation of 5 m and a specific enthalpy of 2787 kJ/kg. It leaves the turbine at a velocity of 6000 m/min, an elevation of 1 m and a specific enthalpy of 2259 kJ/kg. Heat losses from the turbine to the surroundings amount to 16736 kJ/h.

Determine the power output of the turbine. [**Ans.** 723 kW]

36. In a steady flow process, the working fluid flows at a rate of 240 kg/min. The fluid rejects 120 kJ/s passing through the system. The conditions of fluid at inlet and outlet are given as : C_1 = 300 m/s, p_1 = 6.2 bar, u_1 = 2100 kJ/kg, v_1 = 0.37 m^3/kg and C_2 = 150 m/s, p_2 = 1.3 bar, u_2 = 1500 kJ/kg, v_2 = 1.2 m^3/kg. The suffix 1 indicates the conditions at inlet and 2 indicates at outlet of the system. Neglecting the change in potential energy, determine the power capacity of the system in MW. [**Ans.** 2.7086 MW]

37. Steam enters a turbine at 20 m/s and specific enthalpy of 3000 kJ/kg and leaves the turbine at 40 m/s and specific enthalpy of 2500 kJ/kg. Heat lost to the surroundings is 25 kJ/kg of steam as the steam passes through the turbine. If the steam flow rate is 360000 kg/h, determine the output from the turbine in MW.

[**Ans.** 47.44 MW]

38. A stream of gases at 7.5 bar, 800°C and 150 m/s is passed through a turbine of a jet engine. The stream comes out of the turbine at 2.0 bar, 600°C and 300 m/s. The process may be assumed adiabatic. The enthalpies of gas at the entry and exit of the turbine are 960 kJ/kg and 700 kJ/kg gas respectively.

Determine the capacity of the turbine if the gas flow is 4 kg/s. [**Ans.** 905 kW]

39. In a steam power plant 1.5 kg of water is supplied per second to the boiler. The enthalpy and velocity of water entering into the boiler are 800 kJ/kg and 10 m/s. Heat at the rate of 2200 kJ per kg of water is supplied to the water. The steam after passing through the turbine comes out with a velocity of 50 m/s and enthalpy of 2520 kJ/kg. The boiler inlet is 5 m above the turbine exit. The heat loss from the boiler is 1800 kJ/min and from the turbine 600 kJ/min.

Determine the power capacity of the turbine, considering boiler and turbine as single unit.

[**Ans.** 678 kW]

40. 15 kg of air per minute is delivered by a centrifugal compressor. The inlet and outlet conditions of air are : C_1 = 10 m/s, p_1 = 1 bar, v_1 = 0.5 m^3/kg and C_2 = 80 m/s, p_2 = 7 bar, v_2 = 0.15 m^3/kg. The increase in enthalpy of air passing through the compressor is 160 kJ/kg, and heat loss to the surroundings is 720 kJ/min. Assuming that inlet and discharge lines are at the same level, find :

(*i*) Motor power required to drive the compressor.

(*ii*) Ratio of inlet to outlet pipe diameter. $\left[\textbf{Ans.}\ (i)\ 52.78\text{ kW}\ (ii)\ \dfrac{d_1}{d_2} = 5.16\right]$

41. A centrifugal air compressor used in gas turbine receives air at 100 kPa and 300 K and it discharges air at 400 kPa and 500 K. The velocity of air leaving the compressor is 100 m/s. Neglecting the velocity at the entry of the compressor, determine the power required to drive the compressor if the mass flow rate is 15 kg/s. Take c_p (air) = 1 kJ/kg K and assume that there is no heat transfer from the compressor to the surroundings.

[**Ans.** 3075 kW]

42. In a water cooled compressor 0.5 kg of air is compressed per second. A shaft input of 60 kW is required to run the compressor. Heat lost to the cooling water is 30 per cent of input and 10 per cent of the input is lost in bearings and other frictional effects. Air enters the compressor at 1 bar and 20°C. Neglecting the changes in kinetic energy and potential energy, determine the exit air temperature. Take c_p = 1 kJ/kg°C air.

Consider steady flow process. [**Ans.** 92°C]

43. Steam at 7 bar and 200°C enters an insulated convergent divergent nozzle with a velocity of 60 m/s. It leaves the nozzle at a pressure of 1.4 bar and enthalpy of 2600 kJ/kg.

Determine the velocity of the steam at exit. [**Ans.** 701 m/s]

44. A petrol engine develops 50 kW brake power. The fuel and air-flow rates are 10 kg and 107 kg/h. The temperature of fuel-air mixture entering the engine is 20°C and temperature of gases leaving the engine is 500°C. The heat transfer rate from the engine to the jacket cooling water is 50 kJ/s and that to the surroundings is 10 kJ/s.

Evaluate the increase in the specific enthalpy of the mixture as it flows through the engine.

[**Ans.** – 110 kJ/s]

45. A compressor takes air at 100 kN/m^2 and delivers the same at 550 kN/m^2. The compressor discharges 16 m^3 of free air per minute. The densities of air at inlet and exit are 1.25 kg/m^3 and 5 kg/m^3. The power of the motor driving the compressor is 40 kW. The heat lost to the cooling water circulated around the compressor is 30 kJ/kg of air passing through the compressor.

Neglecting changes in P.E. and K.E. determine the change in specific internal energy. [**Ans.** 60 kJ/kg]

46. A centrifugal pump operating under steady flow conditions delivers 3000 kg of water per minute at 20°C. The suction pressure is 0.8 bar and delivery pressure is 3 bar. The suction pipe diameter is 15 cm and discharge pipe diameter is 10 cm. Find the capacity of the drive motor.

Neglect the change in internal energy and assume that the suction and discharge are at same level.

[**Ans.** 11.8 kW]

47. 60 kg of water is delivered by a centrifugal pump per second. The inlet and outlet pressures are 1 bar and 4 bar respectively. The suction is 2 m below the centre of the pump and delivery is 8 m above the centre of the pump. Determine the capacity of the electric motor to run the pump. The suction and delivery pipe diameters are 20 cm and 10 cm and respectively. [**Ans.** 27.15 kW]

48. The air speed of a turbojet engine in flight is 270 m/s. Ambient air temperature is – 15°C. Gas temperature outlet of the nozzle is 600°C. Corresponding enthalpy values for air and gas are respectively 260 and 912 kJ/kg. Fuel air ratio is 0.0190. Chemical energy of the fuel is 44.5 MJ/kg. Owing to incomplete combustion 5% of the chemical energy is not released in the reaction. Heat loss from the engine is 21 kJ/kg of air.

Calculate the velocity of exhaust jet. [**Ans.** 560 m/s]

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

Take the enthalpy of air as $h = c_p t$, where c_p is the specific heat equal to 1.005 kJ/kg°C and t the temperature.

[**Ans.** 1580 kJ/s ; 298.8 kW ; 554 m/s]

Vapour (Steam)

50. 0.05 kg of steam is heated at a constant pressure of 2 bar until the volume occupied is 0.0658 m^3. Calculate the heat supplied and work done. [**Ans.** 18.25 kJ ; 4.304 kJ]

51. Steam at 7 bar and dryness fraction 0.9 expands in a cylinder behind a piston isothermally and reversibly to a pressure of 1.5 bar. Calculate the change of internal energy and the change of enthalpy per kg of steam. The heat supplied during the process is found to be 400 kJ/kg. Calculate the work done per kg of steam.

[**Ans.** 217.5 kJ/kg (gain) ; 245.7 kJ/kg ; 182.5 kJ/kg]

52. 1 kg of steam at 100 bar and 375°C expands reversibly in a perfectly thermally insulated cylinder behind a piston until pressure is 38 bar and the steam is then saturated.

Calculate the work done by the steam. [**Ans.** 169.7 kJ/kg]

53. In a steam engine the steam at the beginning of the expansion process is at 7 bar, dryness fraction 0.95, and the expansion follows the law $pv^{1.1}$ = constant, down to a pressure of 0.34 bar. Calculate the work done per kg of steam during the expansion, and the heat flow per kg of steam to or from the cylinder walls during the expansion. [**Ans.** 436 kJ/kg ; 155.6 kJ/kg (heat supplied)]

54. Steam at 19 bar is throttled to 1 bar and the temperature after throttling is found to be 150°C. Calculate the initial dryness fraction of the steam. [**Ans.** 0.989]

55. 1 kg of steam at 7 bar, entropy 6.5 kJ/kg K, is heated reversibly at constant pressure until the temperature is 250°C. Calculate the heat supplied, and show on a T-s diagram the area which represents the heat flow. **[Ans.** 283 kJ/kg]

56. 1 kg of steam at 20 bar, dryness fraction 0.9, is heated reversibly at constant pressure to a temperature of 300°C.
Calculate the heat supplied and change of entropy and show the process on a T-s diagram, indicating the area which represents the heat flow. **[Ans.** 415 kJ/kg ; 0.8173 kJ/kg K]

57. Steam at 0.05 bar, 100°C is to be condensed completely by a reversible constant pressure process.
Calculate the heat to be removed per kg of steam and the change of entropy. Sketch the process on a T-s diagram and shade in the area which represents the heat flow. **[Ans.** 2550 kJ/kg ; 8.292 kJ/kg K]

58. 0.05 kg of steam at 10 bar, dryness fraction 0.84, is heated reversibly in a rigid vessel until the pressure is 20 bar.
Calculate the change of entropy and the heat supplied. Show the area which represents the heat supplied on a T-s diagram. **[Ans.** 0.0704 kJ/kg K ; 36.85 kJ]

59. 1 kg of steam undergoes a reversible isothermal process from 20 bar and 250°C to a pressure of 30 bar. Calculate the heat flow, stating whether it is supplied or rejected and sketch the process on a T-s diagram. **[Ans.** – 135 kJ/kg]

60. Steam at 5 bar, 250°C, expands isentropically to a pressure of 0.7 bar. Calculate the final condition of steam. **[Ans.** 0.967]

61. Steam expands reversibly in a cylinder behind a piston from 6 bar dry saturated, to a pressure of 0.65 bar. Assuming that the cylinder is perfectly thermally insulated, calculate the work done during the expansion per kg of steam. Sketch the process on a T-s diagram. **[Ans.** 323.8 kJ/kg]

62. A steam engine receives steam at 4 bar, dryness fraction 0.8, and expands it according to a law $pv^{1.05}$ = constant to a condenser pressure of 1 bar. Calculate the change of entropy per kg of steam during the expansion, and sketch the process on a T-s diagram. **[Ans.** 0.381 kJ/kg K]

63. Steam at 15 bar is throttled to 1 bar and a temperature of 150°C. Calculate the initial dryness fraction and the change of entropy. Sketch the process on a T-s diagram and state the assumptions made in the throttling process. **[Ans.** 0.992, 1.202 kJ/kg K]

64. Steam enters a turbine at 70 bar, 500°C and leaves at 2 bar in a dry saturated state. Calculate the isentropic efficiency and effectiveness of the process. Neglect changes of kinetic and potential energy and assume that the process is adiabatic.
The atmospheric temperature is 17°C. **[Ans.** 84.4% ; 88%]

65. Steam at 10 bar and 250°C expands until the pressure becomes 2.75 bar. The dryness fraction of the steam at the end of expansion is 0.95. Determine the change in internal energy. **[Ans.** – 273 kJ/kg]

66. Calculate the quantity of heat required to form 2.5 kg of dry steam at 11 bar from water at 20°C. Also determine the amount of heat removed at constant pressure to cause the steam to become 0.95 dry. Calculate the specific volume at the respective conditions
[Ans. 6740 kJ ; 250 kJ ; 0.1775 m^3/kg ; 0.167 m^3/kg]

67. Steam at 10 bar and 0.95 dryness is available. Determine the final condition of steam in each of the following operations :
(*i*) 160 kJ of heat is removed at constant pressure ;
(*ii*) It is cooled at constant volume till the temperature inside falls to 140°C.
(*iii*) Steam expands isentropically in a steam turbine developing 300 kJ of work per kg of steam when the exit pressure of steam is 0.5 bar. **[Ans.** (*i*) 0.874 ; (*ii*) 0.367 ; (*iii*) 0.882]

68. Calculate the internal energy of 0.3 m^3 of steam at 4 bar and 0.95 dryness. If this steam is superheated at constant pressure through 30°C, determine the heat added and change in internal energy.
[Ans. 2451 kJ/kg ; 119 kJ ; 107.5 kJ/kg]

69. 1 kg of water at 30°C and 1 bar is heated at constant pressure until it becomes saturated vapour. Determine the change in volume, and internal energy during the process. **[Ans.** 1.694 m^3/kg (app.) ; 2380.6 kJ/kg]

70. Water is supplied to the boiler at 15 bar and 80°C and steam is generated at the same pressure at 0.9 dryness. Determine the heat supplied to the steam in passing through the boiler and change in entropy.
[Ans. 2260.5 kJ/kg ; 4.92 kJ/kg K]

71. A cylindrical vessel of 5 m^3 capacity contains wet steam at 1 bar. The volume of vapour and liquid in the vessel are 4.95 m^3 and 0.05 m^3 respectively. Heat is transferred to the vessel until the vessel is filled with saturated vapour. Determine the heat transfer during the process. [**Ans.** 104.93 MJ]

72. A closed vessel of 0.5 m^3 capacity contains dry saturated steam at 3.5 bar. The vessel is cooled until the pressure is reduced to 2 bar. Calculate :

(*i*) The mass of steam in the vessel.

(*ii*) Final dryness fraction of the steam, and

(*iii*) The amount of heat transferred during the process. [**Ans.** (*i*) 0.955 kg ; (*ii*) 0.582 ; (*iii*) – 828 kJ]

73. A closed vessel of 0.3 m^3 capacity contains steam at 8 bar and 200°C ;

(*i*) Determine the mass of the steam in the vessel.

(*ii*) The vessel is cooled till the steam becomes just dry and saturated. What will be the pressure of the steam in the vessel at this stage ?

(*iii*) The vessel is further cooled till the temperature drops to 158.85°C. Determine the pressure and condition of the steam. [**Ans.** (*i*) 1.2 kg ; (*ii*) 7.362 bar ; (*iii*) 6 bar, 0.826]

74. 0.5 kg of steam at 4 bar is contained in a cylinder fitted with a piston. The initial volume of steam is 0.1 m^3. Heat is transferred to the steam at constant pressure until the temperature becomes 300°C. Determine the heat transfer and work done during the process. [**Ans.** 771 kJ ; 91 kJ]

75. A quantity of steam at 13 bar and 0.8 dryness occupies 0.1 m^3. Determine the heat supplied to raise the temperature of the steam to 250°C at constant pressure and percentage of this heat which appears as external work. Take specific heat for superheated steam as 2.2 kJ/kg K. [**Ans.** 423 kJ/kg ; 15.3%]

76. A certain quantity of dry and saturated steam at 1.5 bar occupies initially a volume of 2.32 m^3. It is compressed until the volume is halved :

(*i*) Isothermally,

(*ii*) As per the law pv = constant, determine the final condition of steam in each case.

Also determine the heat rejected during the isothermal compression process.

[**Ans.** (*i*) 0.5, 2226.5 kJ ; (*ii*) 0.956]

77. Steam enters a turbine at a pressure of 10 bar and 300°C with a velocity of 50 m/s. The steam leaves the turbine at 1.5 bar and with a velocity of 200 m/s. Assuming the process to be reversible adiabatic and neglecting the change in potential energy, determine the work done per kg of steam flow through the turbine. [**Ans.** 375.55 kJ/kg]

78. Steam at 10 bar and 300°C passing through a convergent divergent nozzle expands reversibly and adiabatically till the pressure falls to 2 bar. If the velocity of steam entering into the nozzle is 50 m/s, determine the exit velocity of the steam. [**Ans.** 832 m/s]

Unsteady Flow Processes

79. An air receiver of volume 6 m^3 contains air at 15 bar and 40.5°C. A valve is opened and some air is allowed to blow out to atmosphere. The pressure of the air in the receiver drops rapidly to 12 bar when the valve is then closed. Calculate the mass of air which has left the receiver. [**Ans.** 14.7 kg]

80. The internal energy of air is given, at ordinary temperatures, by $u = u_0 + 0.718t$

where u is in kJ/kg, u_0 is any arbitrary value of u at 0°C, kJ/kg and t is temperature in °C.

Also for air, $pv = 0.287\ (t + 273)$, where p is in kPa and v is in m^3/kg.

(*i*) An evacuated bottle is fitted with a valve through which air from the atmosphere, at 760 mm Hg and 25°C, is allowed to flow slowly to fill the bottle. If no heat is transferred to or from the air in the bottle, what will its temperature be when the pressure in the bottle reaches 760 mm Hg ?

(*ii*) If the bottle initially contains 0.03 m^3 of air at 400 mm Hg and 25°C, what will the temperature be when the pressure in the bottle reaches 760 mm of Hg ? [**Ans.** (*i*) 144.2°C ; (*ii*) 71.6°C]