LECTURE FIVE

FIRST LAW APPLIED TO FLOW PROCESSES (OPEN SYSTEM)

Lecture content:

1. Steady and Unsteady Flow Process
2. Assumptions in Steady Flow Process
3. Mass and energy analysis of control volumes
4. Engineering Applications of Steady Flow Energy Equation

Lecture content:

At the end of this lecture, you will be able to:

- Develop the conservation of mass principle.
- Apply the conservation of mass principle to various systems including steady control volumes.
- Apply the first law of thermodynamics as the statement of the conservation of energy principle to control volumes.
- Solve energy balance problems for common steady-flow devices such as nozzles, compressors, turbines, throttling valves, mixing chambers, and heat exchangers.

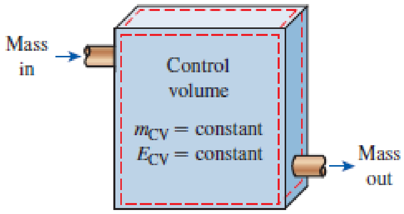
1. STEADY AND UNSTEADY FLOW PROCESS

The **flow processes** are those processes which occur in an open system (also called control volume) which permit the transfer of mass as well as energy to/from the system *i.e.*, across its boundaries.

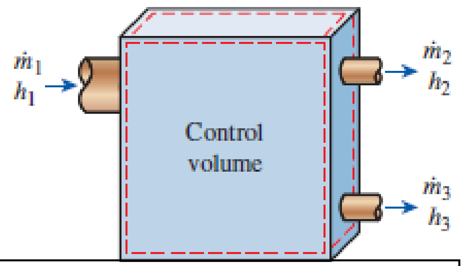
- ***Steady flow process*:**
  - The state of the working substance in the neighborhood of a given point remains constant with time.
  - The flow rate in and out of the system is equal and remains constant with time.
  - There is no change of stored energy within the system.
- ***Unsteady flow process*:**
  - The state of the working substance at the boundary of the system varies with time and mass inflow and outflow are not balanced.
  - There is a change of energy stored within the system during this process. The filling of a tank is an example of unsteady flow process.

2. ASSUMPTIONS IN STEADY FLOW PROCESS

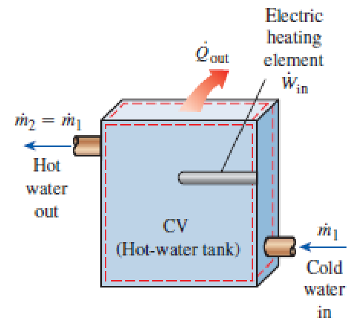
1. The mass flow through the system remains constant.
2. The rate of heat and work transfer is constant.
3. The working substance is uniform in composition.
4. The state of the working substance at any point remains constant with time.
5. Potential, kinetic and flow energies are considered.



$$\sum_{in} \dot{m} = \sum_{out} \dot{m}$$



Under steady-flow conditions, the substance properties at an inlet or exit remain constant (do not change with time).

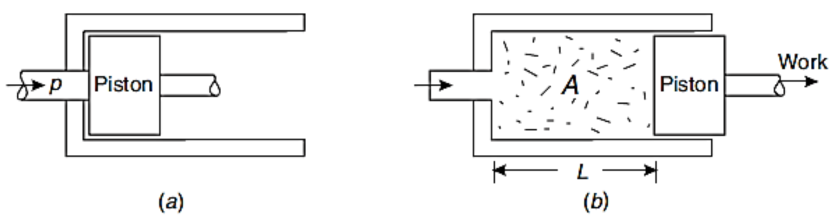


A water heater in steady operation.

3. MASS AND ENERGY ANALYSIS OF CONTROL VOLUMES (steady flow process)

The energy required to flow or move the working substance across the open system, is termed as flow energy or displacement energy. It is also known as **flow work.**

Let the working substance with pressure p (in N/m^2) pushes the piston of cross-sectional area A (in m2) through a distance L (in meters), as shown in Fig. shown. The magnitude of the flow energy must be exactly equal to the work done by the piston.



$\therefore$ Flow energy = Workdone by the system = Force × Distance moved

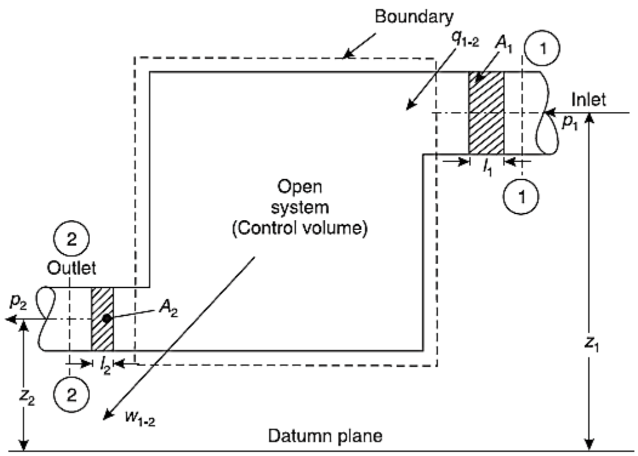
$= pA \times L$ (in N-m or J) $= pv$

where v = Volume of the working substance.

For 1 kg mass of the working substance,

Flow energy $= p\,v_s$ (in N-m/kg or J/kg)

where v_s = Specific volume of the working substance in m^3/kg.



Energy balance: for one kg of the working substance total energy entering the system at section 1-1= total energy entering the system at section 2-2

$$\sum e_{in} = \sum e_{out}$$

$$u_1 + gz_1 + \frac{1}{2}V_1^2 + p_1v_1 + q_{1-2} = u_2 + gz_2 + \frac{1}{2}V_2^2 + p_2v_2 + w_{1-2}$$

We know that; $u + pv = h$,

$$h_1 + gz_1 + \frac{1}{2}V_1^2 + q_{1-2} = h_2 + gz_2 + \frac{1}{2}V_2^2 + w_{1-2}$$

$$q_{1-2} - w_{1-2} = \left(h_2 + gz_2 + \tfrac{1}{2}V_2^2\right) - \left(h_1 + gz_1 + \tfrac{1}{2}V_1^2\right) \text{.........(SFEE) or}$$

$$q_{1-2} - w_{1-2} = g(z_2 - z_1) + \tfrac{1}{2}(V_2^2 - V_1^2) + (h_2 - h_1) \text{...... (kJ/s)}$$

Q= rate of heat transfers between the control volume and its surroundings.

W = Work transfer (power), for steady-flow devices, work done per unit time.

Mass conversion: $\sum m_{in} = \sum m_{out}$

$$m_1 = m_2$$

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2 \text{ (single stream)}$$

$$\frac{V_1 A_1}{v_1} = \frac{V_2 A_2}{v_2}$$

Example 1// In a certain steady flow process, the properties of the fluid at inlet and outlet are as follows:

At inlet: Pressure = 1.5 bar; density = 26 kg/m^3; velocity = 110 m/s; internal energy = 910 kJ/ kg.
At exit: Pressure = 5.5 bar; density = 5.5 kg / m^3; velocity = 190 m/s; internal energy = 710 kJ/kg. During the process, the fluid rejects 55 kJ/s of heat and rises through 55metres. The mass flow rate of the fluid is 10 kg / min. Determine:

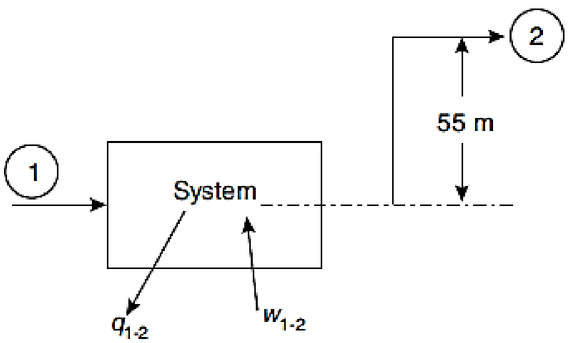
1. Change in enthalpy; and
2. Power developed during the process.

Solution:

Properties of the fluid at inlet	Properties of the fluid at outlet
$p_1 = 1.5\ bar = 150 \times 10^3 N/m^2$	$p_2 = 5.5\ bar = 550 \times 10^3 N/m^2$
$\rho_1 = 26 kg/m^3$	$\rho_2 = 5.5 kg/m^3$
$V_1 = 110\ m/s$	$V_2 = 190\ m/s$
$u_1 = 910\ kJ / kg$	$u_2 = 710\ kJ / kg$

Inlet specific volume, $v_{s1} = \frac{1}{\rho_1} = \frac{1}{26} = 0.0038 \frac{m^3}{kg}$

Outlet specific volume, $v_{s2} = \frac{1}{\rho_2} = \frac{1}{5.5} = 0.182\ m^3 / kg$



Heat rejected by fluid, $Q_{1-2} = 55\ kJ / s$

Rise in elevation = 55 m

Mass flow rate = $10\ kg/min = \frac{10}{60} = \frac{1}{6} kg/s$

1. *Change in enthalpy*

Enthalpy at inlet,

$$h_1 = u_1 + p_1 v_{s1} = 910 + 150 \times 0.038$$
$$= 915.7 \text{ kJ / kg}$$

Enthalpy at outlet,

$$h_2 = u_2 + p_2 v_{s2} = 710 + 550 \times 0.182 = 810.1 \text{ kJ / kg}$$

Change in enthalpy, $dh = h_2 - h_1 = 810.1 - 915.7 = -105.6$ kJ / kg

2. *Power developed during the process*

Let w_{1-2} = Work done or power developed during the process in kJ / kg.

We know that heat rejected by the fluid;

$$q_{1-2} = \frac{Q_{1-2}}{m} = \frac{55}{1/6} = -55 \times 6 = -330 \text{ kJ/kg}$$

The –ve sign is due to heat rejected.

Using the steady flow energy equation, we have

$$q - w = g(z_2 - z_1) + \frac{1}{2}({V_2}^2 - {V_1}^2) + (h_2 - h_1)$$

$$-330 - w_{1-2} = 9.81(55 - 0) + (\frac{(190)^2 - (110)^2}{2 \times 1000}) + (-105.6)$$

$$-330 - w_{1-2} = 0.54 + 12 - 105.6 = -93.06$$

$$w_{1-2} = -330 + 93.06 = -236.94\ kJ / kg$$

The –ve sign indicates that work is done on the system.

Since the mass flow rate is 1/6 kg / s, therefore work done or power developed during process,

$$W_{1-2} = m \times w_{1-2} = 39.5 \text{ kJ/s} = 39.54 \text{ kW}$$

4. STEADY FLOW ENERGY EQUATION APPLED TO VARIOUS PROCESSES:

The workdone for various steady flow processes, like non-flow processes are as follows:

(*a*) For constant volume process,

$$w_{1-2} = v(p_1 - p_2)$$

(*b*) For constant pressure process,

$$w_{1-2} = 0$$

(*c*) For constant temperature process,

$$w_{1-2} = 2.3\, p_1 v_1 \log\left(\frac{v_2}{v_1}\right)$$

(*d*) For adiabatic or isentropic process,

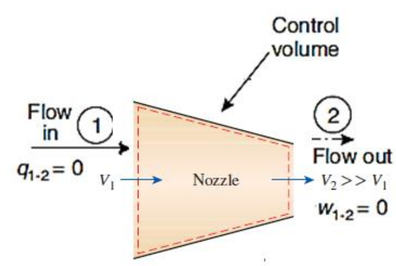
$$w_{1-2} = \frac{\gamma}{\gamma - 1}(p_1 v_1 - p_2 v_2)$$

(*e*) For polytropic process,

$$w_{1-2} = \frac{n}{n-1}(p_1 v_1 - p_2 v_2)$$

5. ENGINEERING APPLICATIONS OF STEADY FLOW ENERGY EQUATION

1. **Nozzle:** A nozzle is a passage of varying cross-section by means of which the pressure energy of the flowing fluid is converted into kinetic energy. The main use of the nozzle is to produce a jet of high velocity to drive a turbine and to produce thrust.



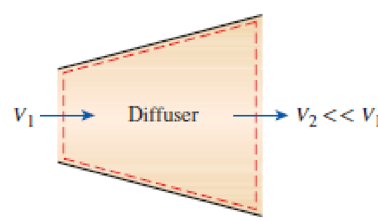
$$q_{1-2} - w_{1-2} = \left[\left(h_2 + gz_2 + \tfrac{1}{2}V_2^{\,2}\right) - \left(h_1 + gz_1 + \tfrac{1}{2}V_1^{\,2}\right)\right]$$

$$z_1 = z_2$$

In case V_1 is very small as compared to V_2, then V_1 may be neglected. $q_{1-2} - w_{1-2} = 0$

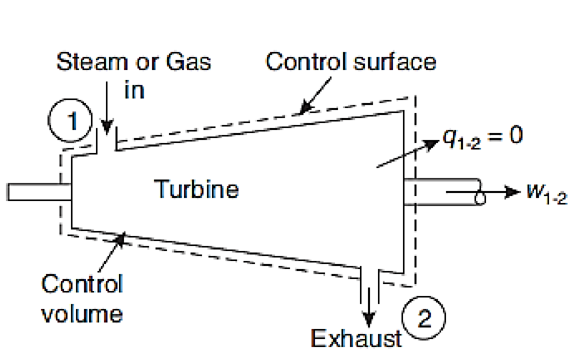
Thus; $V_2 = \sqrt{2(h_1 - h_2)}$

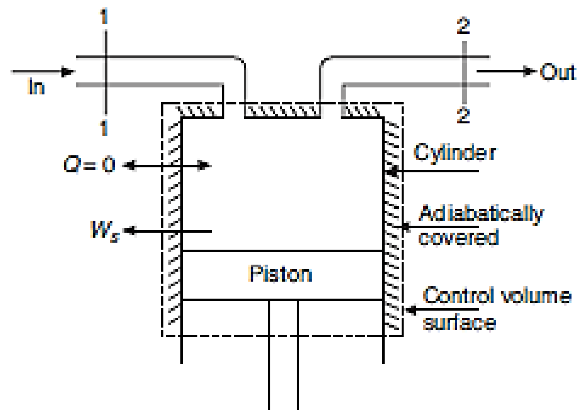
2. **Diffuser:** A diffuser is a passage of varying cross-section by means of which the kinetic energy of the flowing fluid is changed into pressure energy. The energy equation for steady flow may be applied in the similar way as for the nozzle but



$$V_1 = \sqrt{2(h_2 - h_1)}$$

3. **Steam or Gas turbine (Or IC engines)**: A turbine is used to convert the heat energy of steam or gas into useful work. $z_1 = z_2$, $V_1 = V_2$, and $q_{1-2} = 0$ (insulated i.e., adiabatic flow)





$$q_{1-2} + \left(h_1 + gz_1 + \tfrac{1}{2}{V_1}^2\right) = \left(h_2 + gz_2 + \tfrac{1}{2}{V_2}^2\right) + w_{1-2}$$

$$W_{1-2} = m(h_1 - h_2)$$

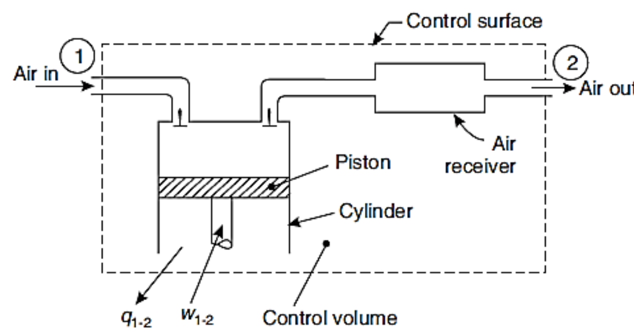
4. Compressors:

- **Reciprocating compressor:** A reciprocating compressor is used to compress air or gas from low pressure to high pressure with the help of work input (w_{1-2}). $z_1 = z_2$, $V_1 = V_2$

$$q_{1-2} - (-w_{1-2}) = (h_2 - h_1)$$

$$w_{1-2} = (h_1 - h_2) - q_{1-2}$$

"Work done on the system (-ve) & heat rejection (-ve)"



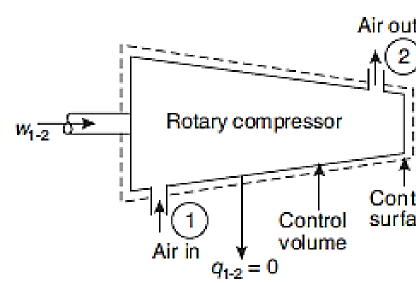
- **Rotary compressor:**

Adiabatic process, insulated system so $q_{1-2} = 0$

$$w_{1-2} = -(h_1 - h_2)$$

$$W = -m(h_1 - h_2)$$

"Work done on the system"

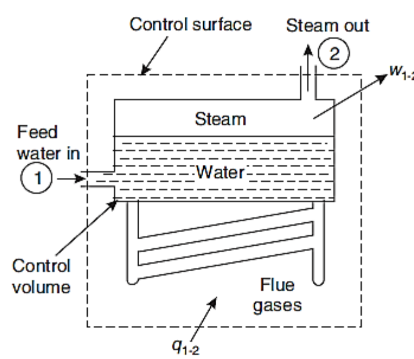


6. **Boiler:** A boiler is used to generate steam from feed water by heating due to burning of a fuel. The steam may be used to drive steam engine or a steam turbine.

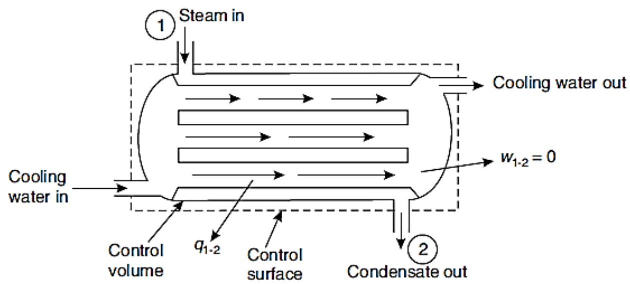
$z_1 = z_2$, $V_1 = V_2$, and $w_{1-2} = 0$,

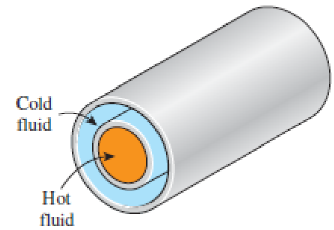
$$q_{1-2} = (h_2 - h_1)$$

$$Q = m(h_2 - h_1)$$



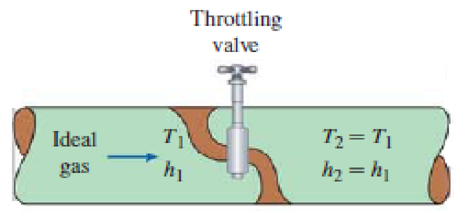
7. **Condensers & heat exchangers:** A condenser (or a heat exchanger) is a device used to condense steam by rejecting heat from the steam to the cooling water.





$$q_{1-2} = -(h_2 - h_1) \quad , \quad Q = -m(h_2 - h_1)$$

8. **Throttling process:** A process that takes place in such a way that the fluid expands through a *minute aperture such as a narrow throat or a slightly opened valve in the line of flow, is known as *throttling process*. In this case, shaft work done, $w_{1-2} = 0$, adiabatically covered, $q_{1-2} = 0$. Changes in K.E. = 0 and P.E. = 0. Applying SFEE for single stream and 1 for inlet and 2 for exit.



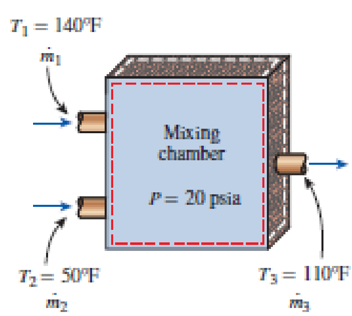
$$q_{1-2} - w_{1-2} = \left(h_2 + gz_2 + \frac{1}{2}V_2{}^2\right) - \left(h_1 + gz_1 + \frac{1}{2}V_1{}^2\right)$$

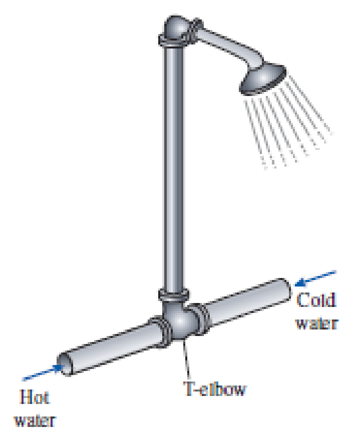
$m_1 = m_2$, $h_1 = h_2$ so,

$T_1 = T_2$ 'for gases only'

9. **Mixing chamber:**

Combining the mass and energy balances,





$$w_{1-2} = 0, \quad PE = 0, \quad KE = 0, \quad q_{1-2} = 0$$

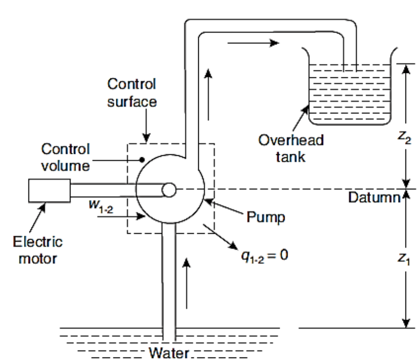
$$m_1 h_1 + m_2 h_2 = (m_1 + m_2)\, h_3$$

10. **Centrifugal pump.**

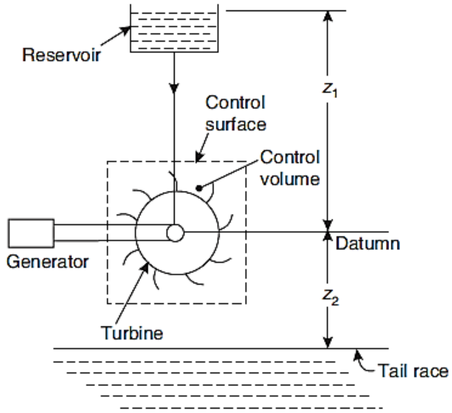
$$q_{1-2} = 0\,,\, u_1 = u_2$$

$$-gz_1 + \frac{1}{2}V_1{}^2 + p_1 v_{s1}$$

$$= gz_2 + \frac{1}{2}V_2{}^2 + p_1 v_{s2} - w_{1-2}$$



11. Water turbine.



$$gz_1 + \frac{1}{2}{V_1}^2 + p_1 v_{s1} = -gz_2 + \frac{1}{2}{V_2}^2 + p_1 v_{s2} + w_{1-2}$$

Example 2// A perfect gas flows through a nozzle where it expands in a reversible adiabatic manner. The inlet conditions are 22 bar, 500°C and 38 m/s. At exit, the pressure is 2 bar. Determine the exit temperature and velocity, if the flow rate is 4 kg / s. Take R = 190 J/kg. K and γ = 1.35.

Solution.

Inlet	**Outlet (exit)**
$p_1 = 22\ bar = 2200 \times 10^3\ N/m^2$	$p_2 = 2\ bar = 200 \times 10^3\ N/m^2$
$T_1 = 500°C = 500 + 273 = 773\ K$	T_2 = ?
$V_1 = 38\ m/s$	V_2 = ?

Mass, $m = 4\ kg/s$, Gas constant, $R = 190$ J/kg K and $\gamma = 1.35$

We know that for a reversible adiabatic process,

$$\frac{T_2}{T_1} = \left[\frac{p_2}{p_1}\right]^{\frac{\gamma-1}{\gamma}} = \left[\frac{2}{22}\right]^{\frac{1.35-1}{1.35}} = \left(\frac{1}{11}\right)^{0.259} = 0.537$$

$$T_2 = T_1 \times 0.537 = 773 \times 0.537 = 415.1\ K$$

and change in enthalpy from inlet to exit,

$$h_1 - h_2 = c_p\,(T_1 - T_2) = \frac{R\gamma}{\gamma - 1} = \frac{190 \times 1.35}{1.35 - 1}(773 - 415.1)$$

$$= 262.3 \times 103\ J/kg$$

Using the steady flow energy equation, we have

$$V_2 = \sqrt{V_1^2 + 2(h_1 - h_2)} = \sqrt{(38)^2 + 2(262.3 \times 10^3)} = 725.3\ m/s$$

* NOTE

We know that $c_p - c_v = R$

or $\frac{c_p - c_v}{c_v} = \frac{R}{c_v}$

or $\gamma - 1 = \frac{R}{c_v}$

Multiplying by c_p on both sides,

$c_p(\gamma - 1) = \frac{R}{c_v} \times c_p = R\gamma$ or $c_p = \frac{R\gamma}{\gamma - 1}$

Example 3// In a gas turbine, the gas enters at the rate of 5 kg / s with a velocity of 50 m / s and enthalpy of 900 kJ / kg and leaves the turbine with a velocity of 150 m/s and enthalpy of 400 kJ / kg. The loss of heat from the gases to the surroundings is 25 kJ / kg. Assume for gas, R = 0.285 kJ / kg K and c_p = 1.004 kJ/kg K. The inlet condition is at 100 kPa and 27°C. Determine the power output of the turbine and diameter of inlet pipe.

Solution.

Inlet	**Exit**
$V_1 = 50\, m / s$	$V_2 = 150\, m / s$
$h_1 = 900\, kJ / kg$	$h_2 = 400\, kJ / kg$
$p_1 = 100\, kPa$	
$T_1 = 27°C = 27 + 273 = 300\, K$	

Mass of the gas $m = 5\, kg / s$

Loss of heat to the surrounding, $q_{1-2} = -\ 25\, kJ / kg$ (– sign due to loss of heat)

Gas constant, $R = 0.285\, kJ / kg\, K, \quad c_p = 1.004\, kJ / kg\, K$

Now;

Let w_{1-2} = Workdone or power output of the turbine.

Using the steady flow energy equation for a unit mass, we have

$$h_1 + gz_1 + \frac{V_1^2}{2} + q_{1-2} = h_2 + gz_2 + \frac{V_2^2}{2} + w_{1-2}$$

$$z_1 = z_2$$

$$h_1 + \frac{V_1^2}{2} + q_{1-2} = h_2 + \frac{V_2^2}{2} + w_{1-2}$$

$$900 + \frac{50^2}{2 \times 1000} + (-25) = 400 + \frac{150^2}{2 \times 1000} + w_{1-2}$$

$$1.25 + 900 - 25 = 11.25 + 400 + w_{1-2}$$

$$876.25 = 411.25 + w_{1-2}$$

$$w_{1-2} = 876.25 - 411.25 = 465\, kJ/kg$$

Since the mass of gas is 5 kg / s; therefore, power output of the turbine,

$$W_{1-2} = 5 \times 465 = 2325\, kJ/s = 2325\, kW\ Ans.... (1\, kJ/s = 1\, kW)$$

Example 4// Air at a temperature of 20°C passes through a heat exchanger at a velocity of 40 m / s, where its temperature is raised to 820°C. It then enters a turbine with the same velocity of 40 m/s and expands till the temperature falls to 620°C. On leaving the turbine, the air is taken at a velocity of 55 m / s to a nozzle where it expands until the temperature has fallen to 510°C. If the air flow rate is 2.5 kg / s; calculate:

1. Rate of heat transfer to the air in the heat exchanger;
2. The power output from the turbine, assuming no heat loss; and
3. The velocity at exit from the nozzle, assuming no heat loss.

Take enthalpy of air as $h = c_p\, dT$, where c_p is the specific heat at constant pressure and taken as 1.005 kJ / kg K and $dT = T_2 - T_1$, is the change in temperature.

Solution.

Given: Temperature of air entering the heat exchanger,

$$T_1 = 20°C = 20 + 273 = 293\ K$$

Velocity of air, V_1 = 40 m / s

Temperature of air leaving the heat exchanger,

$$T_2 = 820°C = 820 + 273 = 1093\ K$$

Velocity of air entering the turbine,

$$V_2 = V_1 = 40\ m/s$$

Temperature of air leaving the turbine,

$$T_3 = 620°C = 620 + 273 = 893\ K$$

Velocity of air leaving the turbine or entering the nozzle,

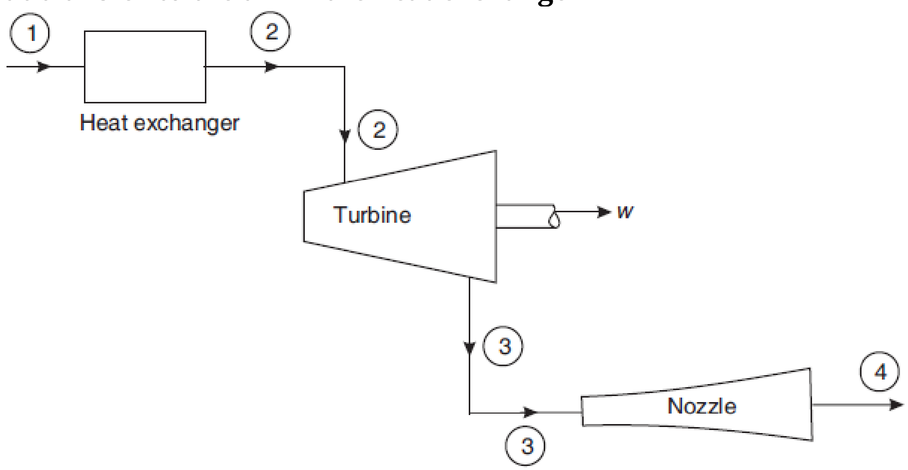
$$V_3 = 55\ m/s$$

Temperature of air leaving the nozzle,

$$T_4 = 510°C = 510 + 273 = 783\ K$$

Air flow rate, $m = 2.5\ kg/s$

1. **Rate of heat transfer to the air in the heat exchanger**



First of all, let us consider heat transfer through a heat exchanger.

Applying the steady flow energy equation, we have

$$h_1 + gz_1 + \frac{V_1^2}{2} + q_{1-2} = h_2 + gz_2 + \frac{V_2^2}{2} + w_{1-2}$$

$z_1 = z_2$, $V_2 = V_1$ and $w_{1-2} = 0$, for a heat exchanger, therefore,

$$q_{1-2} = h_2 - h_1 = c_p\,(T_2 - T_1) = 1.005\,(1093 - 293) = 804\ \text{kJ/kg}$$

Since the air flow rate (m) is 2.5 kg / s, therefore rate of heat transfer,

$Q_{1-2} = m \times q_{1-2} = 2.5 \times 804 = 2010\ kJ/s\ or\ kW$ ... (1 kJ /s = 1 kW)

2. **Power output from the turbine**

Let W_{1-2}= Workdone or power output from the turbine in kW.

Applying the steady flow energy equation, we have

$$h_2 + gz_2 + \frac{V_2^2}{2} + q_{2-3} = h_3 + gz_3 + \frac{V_3^2}{2} + w_{2-3}$$

$z_2 = z_3$ and $q_{2-3} = 0$

$$h_2 + \frac{{V_2}^2}{2} = h_3 + \frac{{V_3}^2}{2} + w_{2-3}$$

$$w_{2-3} = \left(\frac{{V_2}^2 - {V_3}^2}{2 \times 1000}\right) + (h_2 - h_3) = \left(\frac{{V_2}^2 - {V_3}^2}{2 \times 1000}\right) + c_p\,(T_2 - T_3)$$

$= \left[\frac{40^2 - 55^2}{2 \times 1000}\right]$+1.005 (1093 – 893) = – 0.7125 + 201 = 200.2875 kJ/ kg

Since the air flow rate (m) is 2.5 kg / s, therefore power output from the turbine.

$$W_{1-2} = m \times w_{1-2} = 2.5 \times 200.2875 = 500.72\ kJ\,/\,s\ or\ kW$$

3. ***Velocity at exit from the nozzle***

Let $V4$ = Velocity at exit from the nozzle in $m\,/\,s$.

$$h_3 + gz_3 + \frac{{V_3}^2}{2} + q_{3-4} = h_4 + gz_4 + \frac{{V_4}^2}{2} + w_{3-4}$$

$z_3 = z_4$, $q_{3-4} = 0$, and $w_{3-4} = 0$

$$h_3 + \frac{{V_3}^2}{2} = h_4 + \frac{{V_4}^2}{2}$$

$$V_4 = \sqrt{V_3^2 + 2(h_3 - h_4)} = \sqrt{V_3^2 + 2c_p\,(T_3 - T_4)} = \sqrt{(55)^2 + 2 \times 1.005(893 - 783)} =$$

$$= 473.43\ m/s$$

ASSIGNMENTS

1. In a steam 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. The heat losses from the boiler and turbine to the surroundings are 20 kJ / s. Calculate the power developed by the turbine considering boiler and turbine as single system.
2. In a water turbine, the water head measured from the center of the turbine is 1500 m and the flow rate is 500 kg / s. The tail race is 3 m below the turbine center line and outlet velocity is 10 m / s. Determine the power developed by the turbine.
3. Air enters an air compressor at 8 m/s velocity, 100 kPa pressure and 0.95 m3/ kg volume. It flows steadily at the rate of 0.6 kg / s and leaves at 6 m/s, 700 kPa and 0.19 m^3/ kg. The internal energy of the air leaving is 90 kJ / kg greater than that of air entering. The cooling water in the compressor jackets absorbs heat from the air at the rate of 60 kW. Find: 1. The ratio of the inlet pipe diameter to outlet pipe diameter; and 2. The rate of shaft work input to the air in kW.
4. A centrifugal pump delivers water at the rate of 45.5 kg/s by increasing the pressure from 80 kN/m2 to 280 kN/m2. The suction is 2 m below the centre of the pump and delivery is 5 m above the center of the pump. The suction and delivery pipe diameters are 150 mm and 100 mm respectively. Determine the power required to drive the pump.

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