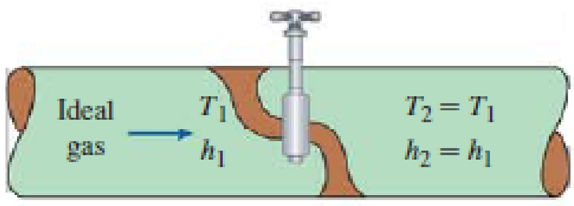
Lecture nine

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.

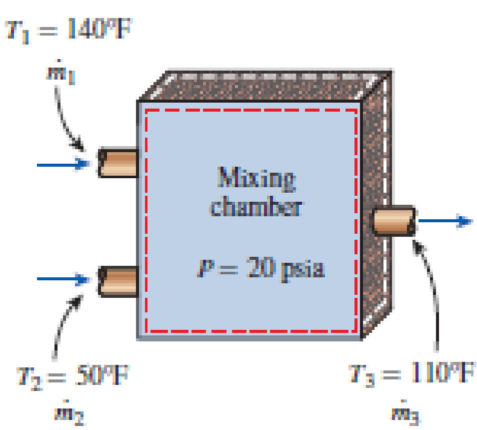
$$q_{1-2} - w_{1-2} = \left(h_2 + gz_2 + \frac{1}{2}V_2^2\right) - \left(h_1 + gz_1 + \frac{1}{2}V_1^2\right)$$

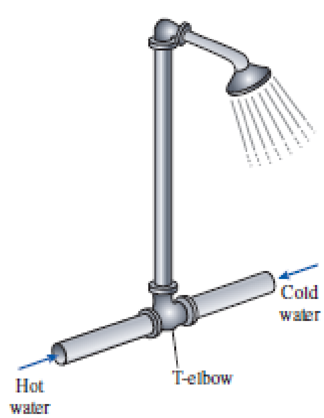
$$m_1 = m_2\,, \qquad h_1 = h_2 \qquad \text{so, } T_1 = T_2 \text{ 'for gases only'}$$



9. Mixing chamber:

Combining the mass and energy balances,





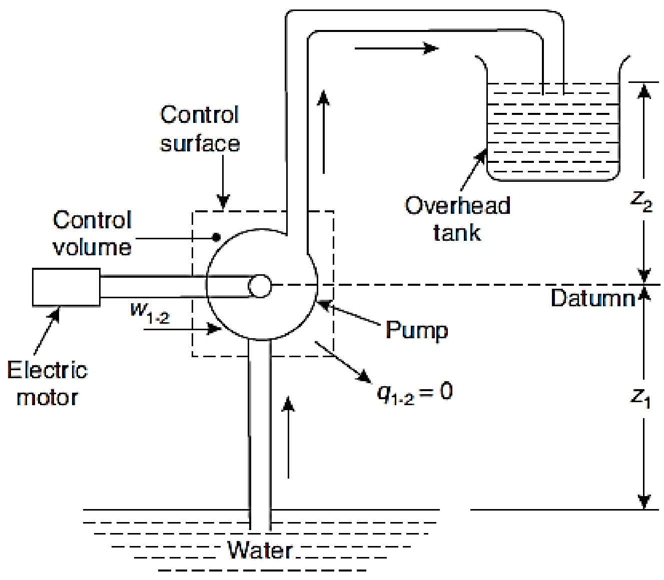
$w_{1-2}=0, \quad PE=0, \quad KE=0, \quad q_{1-2}=0$

$m_1h_1 + m_2h_2 = (m_1 + m_2)\, h_3$

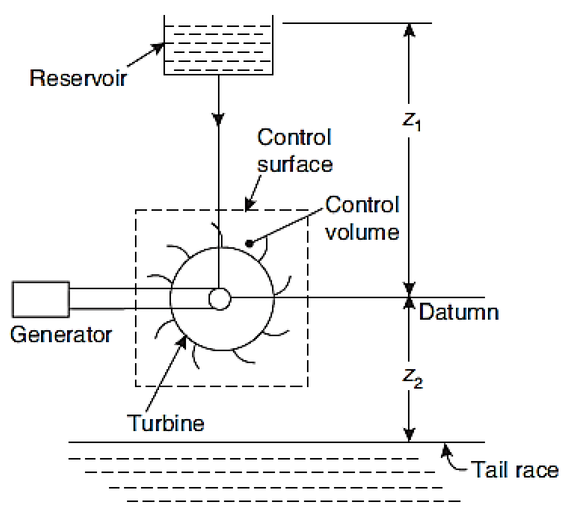
10. Centrifugal pump.

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

$$-gz_1+\frac{1}{2}V_1^2+p_1v_{s1}=gz_2+\frac{1}{2}V_2^2+p_1v_{s2}-w_{1-2}$$



11. Water turbine.



$$gz_1+\frac{1}{2}V_1^2+p_1v_{s1}=-gz_2+\frac{1}{2}V_2^2+p_1v_{s2}+w_{1-2}$$

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 × 10^3 N/m^2	p_2 = 2 bar = 200 ×10^3 $N/m2$
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 γ=1.35

We know that for a reversible adiabatic process:

$$\frac{T_2}{T_1}=[\frac{P_2}{P_1}]^{\frac{\gamma-1}{\gamma}} = [\frac{2}{22}]^{\frac{1.35-1}{1.35}} = (\frac{1}{11})^{0.259}=0.537$$

$T_2=T_1\times0.537=773 \times 0.537 = 415.1\ K$

and change in enthalpy from inlet to exit,

$$h_1-h_2 = cp\ (T_1-T_2)=\frac{R.\gamma}{\gamma-1}=190\times[\frac{1.35}{1.35-1}]\times(773 - 415.1) =$$

262.3 × 103 J / kg

Using the steady flow energy equation, we have

$$V_2=\sqrt{V_1^2+2(h_1-h_2)} = \sqrt{(38)^2 + 2(262.3 \times10^3\ )} = 725.3\ m/s$$

NOTE:

We know that C_p-C_v =R

or $\frac{C_p-C_v}{C_v} = \frac{R}{Cv}$

or γ-1=$\frac{R}{Cv}$

Multiply by C_p on both sides,

$C_p(\gamma-1)=\frac{R}{Cv}\times C_p = R\times\gamma$ or $C_p = \frac{R\times\gamma}{\gamma-1}$

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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 cp = 1.004 kJ/kg K. The inlet condition is at 100 kPa and 27°C. Determine the power output of the turbine.

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, $R = 0.285\ kJ/kg\ K$, $cp = 1.004\ kJ/kg\ K$

Now;

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

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

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

$$z_1 = z_2$$

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

$$900 + \frac{50^2}{2\times1000} + (-25) = 400 + \frac{150^2}{2\times1000} + w_{1-2}$$

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

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

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

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

$W_{1-2} = 5 \times 465 = 2325\ kJ/s = 2325\ kW$ $\quad$ *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 $h = cp\ dT$, where $cp$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, $V1$ = 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, $m = 2.5\ kg\ /\ s$.

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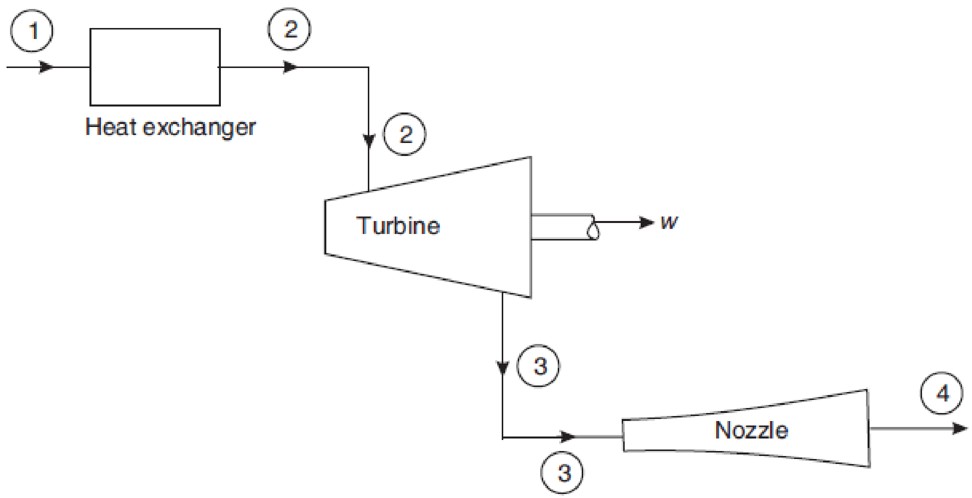
1. Rate of heat transfer to the air in the heat exchanger



First of all, let us consider heat transfer through a heat exchanger.
Applying the steady flow energy equation, we have

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

$z_1=z_2$, $V_2=V_1$ 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 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}= Work done or power output from the turbine in kW.
Applying the steady flow energy equation, we have

$$h_2+gz_2+\frac{1}{2}V_2^2+q_{2-3}=h_3+gz_3+\frac{1}{2}V_3^2+w_{2-3}$$

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

$$h_2+\frac{1}{2}V_2^2=h_3+\frac{1}{2}V_3^2+w_{2-3}$$

$$w_{2-3}=\left(\frac{V_2^2-V_3^2}{2\times1000}\right)+(h_2-h_3)=\left(\frac{V_2^2-V_3^2}{2\times1000}\right)+cp\ (T_2-T_3)$$

$$=\left[\frac{40^2-55^2}{2\times1000}\right]+1.005\ (1093-893)=-0.7125+201=200.2875\ \text{kJ/ kg}$$

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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 V_4 = Velocity at exit from the nozzle in m / s.

$$h_3 + gz_3 + \frac{1}{2} V_3^2 + q_{3-4} = h_4 + gz_4 + \frac{1}{2} V_4^2 + w_{3-4}$$

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

$$h_3 + \frac{1}{2} V_3^2 = h_4 \frac{1}{2} V_4^2$$

$V_4 = \sqrt{V_3^2 + 2(h_3 - h_4)} = \sqrt{V_3^2 + 2c_p\,(T_3 - T_4)} = \sqrt{(55)^2 + 2 \times 1.005(893 - 783)}$
$= = 473.43\ m/s$

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 m^3/ 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/m^2 to 280 kN/m^2. 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.