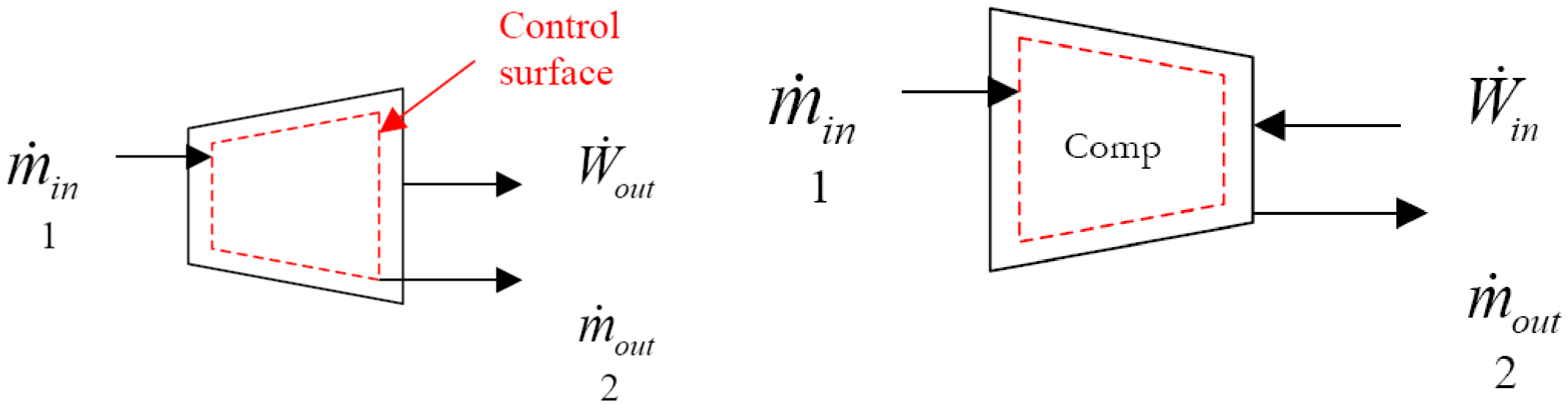
CHAPTER

7

MEC Thermodynamics

Turbine & Compressor



Turbine control volume

Steady-Flow Compressor

- Turbine – a work producing device through the expansion of a fluid.
- Compressor (as well as pump and fan) - device used to increase pressure of a fluid and involves work input.
- Q = 0 (well insulated), ΔPE = 0, ΔKE = 0 (very small compare to Δenthalpy).

- Energy balance: for turbine

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} + gz_{in} \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out} \right)$$

$$\dot{m}_{in}\left(h_{in}\right) = \dot{W}_{out} + \dot{m}_{out}\left(h_{out}\right)$$

$$\dot{W}_{out} = \dot{m}\left(h_1 - h_2\right)$$

- Energy balance: for compressor, pump and fan

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out}\right)$$

$$\dot{W}_{in} + \dot{m}_{in}\left(h_{in}\right) = \dot{m}_{out}\left(h_{out}\right)$$

$$\dot{W}_{in} = \dot{m}\left(h_2 - h_1\right)$$

Example 3.8

The power output of an adiabatic steam turbine is 5 MW. Compare the magnitudes of Δh, Δke, and Δpe. Then determine the work done per unit mass of the steam flowing through the turbine and calculate the mass flow rate of the steam.

Data	:	Inlet (P = 2 MPa, T = 400ºC,v = 50 m/s, z = 10 m)
		Exit (P = 15 kPa, x = 90%, v = 180 m/s, z = 6m)

Solution:

$\boxed{State\,1}$

$$\left.\begin{aligned} p_1 &= 2\,MPa \\ T_1 &= 400^o C \end{aligned}\right\} \begin{aligned} &\text{sup}\,erheated \\ &h_1 = 3248.4\,\tfrac{kJ}{kg} \end{aligned}$$

$\boxed{State\,2}$

$$\left.\begin{aligned} P_2 &= 15\,kPa \\ x_2 &= 0.9 \end{aligned}\right\} sat.mixture$$

$$\begin{aligned} h_2 &= h_{f2} + x_2 h_{fg2} \\ &= 225.94 + 0.9\ (2372.3) \\ &= 2361.01\,\tfrac{kJ}{kg} \end{aligned}$$

❖ From energy balance:

$$\cancel{\dot{Q}_{in}} + \cancel{\dot{W}_{in}} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{\ 2}}{2} + gz_{in}\right) =$$

$$\dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{\ 2}}{2} + gz_{out}\right)$$

❖ Solve the equation:

$$\Delta h \quad = h_2 - h_1 = \text{-}887.39\ \tfrac{kJ}{kg}$$

$$\Delta KE = \frac{V_2^{\ 2} - V_1^{\ 2}}{2000} = 14.95\,\tfrac{kJ}{kg}$$

$$\Delta PE = \frac{g\left(z_2 - z_1\right)}{1000} = -0.04\,\tfrac{kJ}{kg}$$

- the work done per unit mass

$$W_{out} = \left[\left(h_1 - h_2 \right) + \left(\frac{V_1^{\ 2} - V_2^{\ 2}}{2000} \right) + \left(\frac{g\left(z_1 - z_2 \right)}{1000} \right) \right]$$

$$= 887.39 - 14.95 + 0.04$$

$$= \underline{\underline{872.48 \ \tfrac{kJ}{kg}}}$$

- The mass flow rate

$$\dot{m} = \frac{\dot{W}_{out}}{W_{out}} = \frac{5000}{872.48} = \underline{\underline{5.73 \ \frac{kg}{s}}}$$

Example 3.9

Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s, and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor.

Solution:

- simplified energy balance:

$$\dot{W}_{in} = \dot{m}\left(h_2 - h_1\right) + \dot{Q}_{out}$$
$$= \dot{m}\left(h_2 - h_1\right) + \dot{m}q_{out}$$

$\boxed{State\,1}$

$$\left.\begin{array}{l} P_1 = 100\,kPa \\ T_1 = 280\,K \end{array}\right\} \begin{array}{c} air \\ h_1 = 280.13\,\frac{kJ}{kg} \end{array}$$

$\boxed{State\,2}$

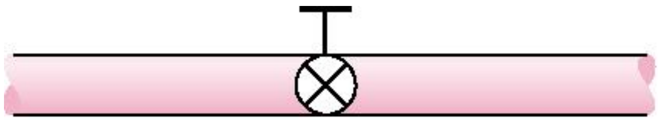
$$\left.\begin{array}{l} P_2 = 600\,kPa \\ T_2 = 400\,K \end{array}\right\} \begin{array}{c} air \\ h_2 = 400.98\,\frac{kJ}{kg} \end{array}$$

- Thus

$$\dot{W}_{in} = 0.02\left[\left(400.98 - 280.13\right) + 16\right]$$

$$= \underline{\underline{2.74\,kW}}$$

Throttling Valve


(*a*) An adjustable valve


(*b*) A porous plug


(*c*) A capillary tube

Flow-restricting devices that cause a significant pressure drop in the fluid.

Some familiar examples are ordinary adjustable valves and capillary tubes.

Example 3.10

Steam enters a throttling valve at 8000 kPa and 300°C and leaves at a pressure of 1600 kPa. Determine the final temperature and specific volume of the steam.

$\boxed{State\,1}$

$$\left.\begin{array}{r} P_1 = 8000\,kPa \\ T_1 = 300^o C \end{array}\right\} \begin{array}{l} \text{superheated} \\ h_1 = 2786.5\,\tfrac{kJ}{kg} \end{array}$$

$\boxed{State\,2}$

$$\left.\begin{array}{r} P_2 = 1600\,kPa \\ h_2 = h_1 \end{array}\right\} \text{make interpolation}$$

$P(kPa)$	$T(^oC)$	v_f	v_g	h_f	h_g
1500	198.29	0.001154	0.131710	844.55	2791
1600	T_2	v_{f2}	v_{g2}	h_{f2}	h_{g2}
1750	205.72	0.001166	0.113440	878.16	2795.2

- At state 2, the region is sat. mixture

$$T_2 = T_{sat} = \underline{\underline{201.3^o C}}$$

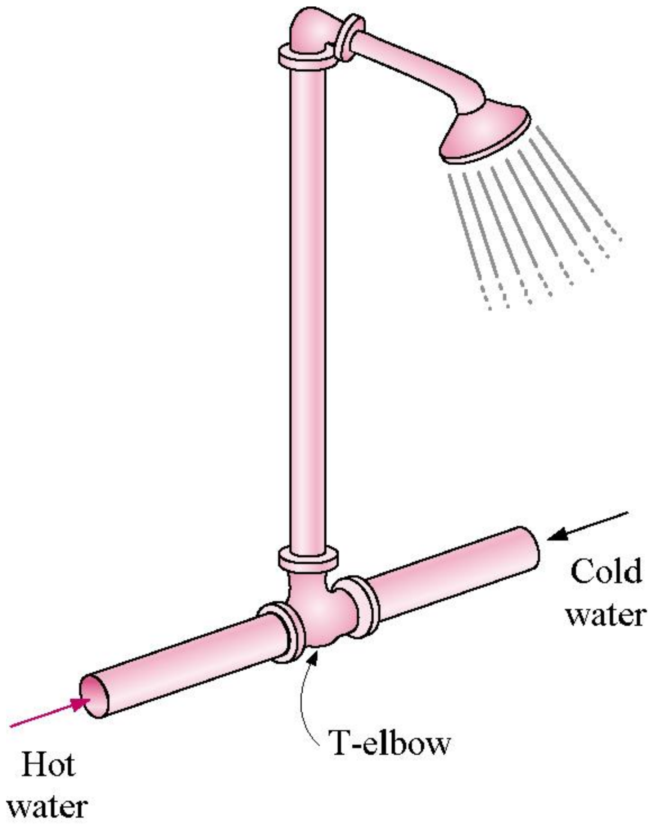
- Getting the quality at state 2

$$x_2 = \frac{h_2 - h_{f2}}{h_{g2} - h_{f2}}$$
$$= \frac{2786.5 - 857.994}{2792.68 - 857.994}$$
$$= 0.997$$

- Specific volume at state 2

$$v_2 = v_{f2} + x_2 v_{fg2}$$
$$= 0.0011588 +$$
$$0.997\left(0.124402 - 0.0011588\right)$$
$$= \underline{\underline{0.1240 \tfrac{m^3}{kg}}}$$

Mixing Chamber



The section where the mixing process takes place.

An ordinary T-elbow or a Y-elbow in a shower, for example, serves as the mixing chamber for the cold- and hot-water streams.

Mixing Chamber

- Energy Balance:

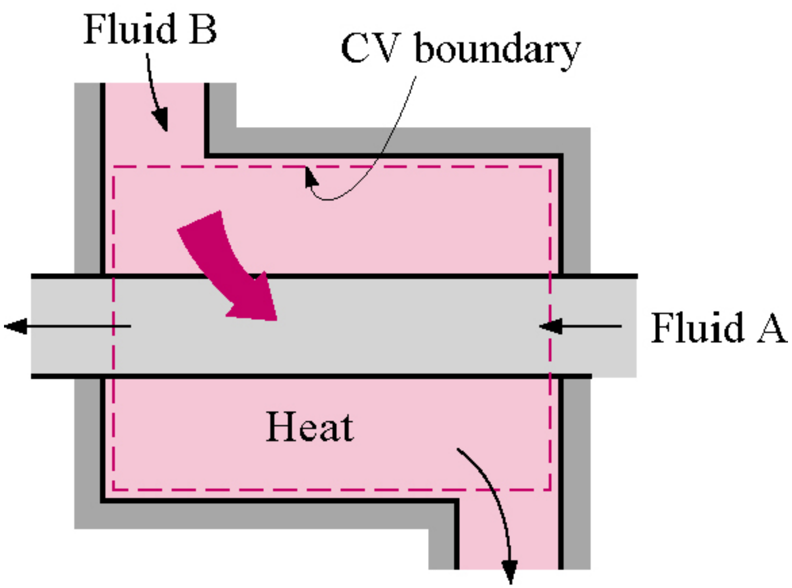
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

$$\dot{m}_1 h_1 + \left(\dot{m}_3 - \dot{m}_1\right) h_2 = \dot{m}_3 h_3$$

$$\dot{m}_1 \left(h_1 - h_2\right) = \dot{m}_3 \left(h_3 - h_2\right)$$

$$\dot{m}_1 = \dot{m}_3 \left(\frac{h_3 - h_2}{h_1 - h_2}\right)$$

Heat Exchanger



(*a*) System: Entire heat exchanger ($Q_{CV} = 0$)

Devices where two moving fluid streams exchange heat without mixing.

Heat exchangers typically involve no work interactions (w = 0) and negligible kinetic and potential energy changes for each fluid stream.

Example 3.11

Liquid sodium, flowing at 100 kg/s, enters a heat exchanger at 450°C and exits at 350°C. The specific heat of sodium is 1.25 kJ/kg.°C. Water enters at 5000 kPa and 20°C. Determine the minimum mass flux of the water so that the water does not completely vaporize. Neglect the pressure drop through the exchanger. Also, calculate the rate of heat transfer.

Solution:

- simplified energy balance:

$$\dot{m}_s h_{1s} + \dot{m}_w h_{1w} = \dot{m}_s h_{2s} + \dot{m}_w h_{2w}$$

$$\dot{m}_s \left(h_{1s} - h_{2s}\right) = \dot{m}_w \left(h_{2w} - h_{1w}\right)$$

$$\dot{m}_s C_{p,s} \left(T_{1s} - T_{2s}\right) = \dot{m}_w \left(h_{2w} - h_{1w}\right)$$

$$\underline{State\,1: water}$$

$$\left.\begin{aligned} P_1 &= 5000\,kPa \\ T_1 &= 20^o C \end{aligned}\right\} \begin{aligned} &comp.liquid \\ &h_{1w} = 88.61\,\tfrac{kJ}{kg} \end{aligned}$$

$$\underline{State\,2: water}$$

$$P_2 = 5000\,kPa$$

$$h_{2w} = 2794.2\,\tfrac{kJ}{kg}$$

Assume a sat. vapor state to obtain the max. allowable exiting enthalpy.

- the minimum mass flux of the water so that the water does not completely vaporize

$$\dot{m}_w = \frac{m_s C_{p,s}\left(T_{1s} - T_{2s}\right)}{\left(h_{2w} - h_{1w}\right)}$$

$$= \frac{100(1.25)(450-350)}{2794.2-88.61}$$

$$= \underline{\underline{4.62\,\tfrac{kg}{s}}}$$

- the rate of heat transfer

$$\dot{Q}_w = \dot{m}_w\left(h_{2w} - h_{1w}\right)$$

$$= 4.62(2794.2-88.61)$$

$$= \underline{\underline{12.5\,MW}}$$

Supplementary Problems 3

1. Air flows through the supersonic nozzle . The inlet conditions are 7 kPa and 420°C. The nozzle exit diameter is adjusted such that the exiting velocity is 700 m/s. Calculate (a) the exit temperature, (b)the mass flux, and (c) the exit diameter. Assume an adiabatic quasiequilibrium flow.

2. Steam at 5 MPa and 400°C enters a nozzle steadily velocity of 80 m/s, and it leaves at 2 MPa and 300°C. The inlet area of the nozzle is 50 cm^2, and heat is being lost at a rate of 120 kJ/s. Determine (a) the mass flow rate of the steam, (b) the exit velocity of the steam, and (c) the exit area nozzle.

3. Steam enters a turbine at 4000 kPa and 500^{o}C and leaves as shown in Fig A below. For an inlet velocity of 200 m/s, calculate the turbine power output. (a)Neglect any heat transfer and kinetic energy change (b)Show that the kinetic energy change is negligible.

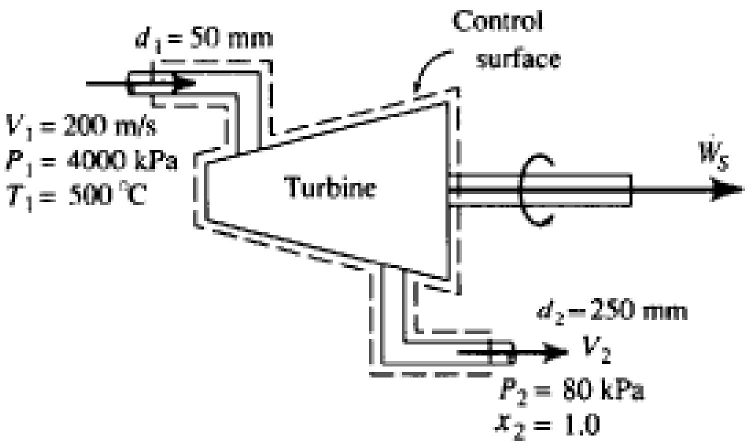


Figure A

4. Consider an ordinary shower where hot water at 60°C is mixed with cold water at 10°C. If it is desired that a steady stream of warm water at 45°C be supplied, determine the ratio of the mass flow rates of the hot to cold water. Assume the heat losses from the mixing chamber to be negligible and the mixing to take place at a pressure of 150 kPa.

5. Refrigerant-134a is to be cooled by water in a condenser. The refrigerant enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70ºC and leaves at 35°C. The cooling water enters at 300 kPa and 15°C and leaves at 25ºC. Neglecting any pressure drops, determine (a) the mass flow rate of the cooling water required and (b) the heat transfer rate from the refrigerant to water.