ESO201A

Lecture#21

(Class Lecture)

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By

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Example Problem #2

The power output of an adiabatic steam turbine is 5 MW, and the inlet and exit conditions of the steam are as indicated in Fig. 1.

(a) Compare the magnitudes of Δh, Δke and Δpe.

(b) Determine the work done per unit mass of steam flowing through the turbine.

(c) Calculate the mass flow rate of steam.

Solution

Assumptions

1. Steady-flow process ($\Delta m_{cv} = 0$, $\Delta E_{cv} = 0$).
2. The system is adiabatic and thus there is no heat transfer.

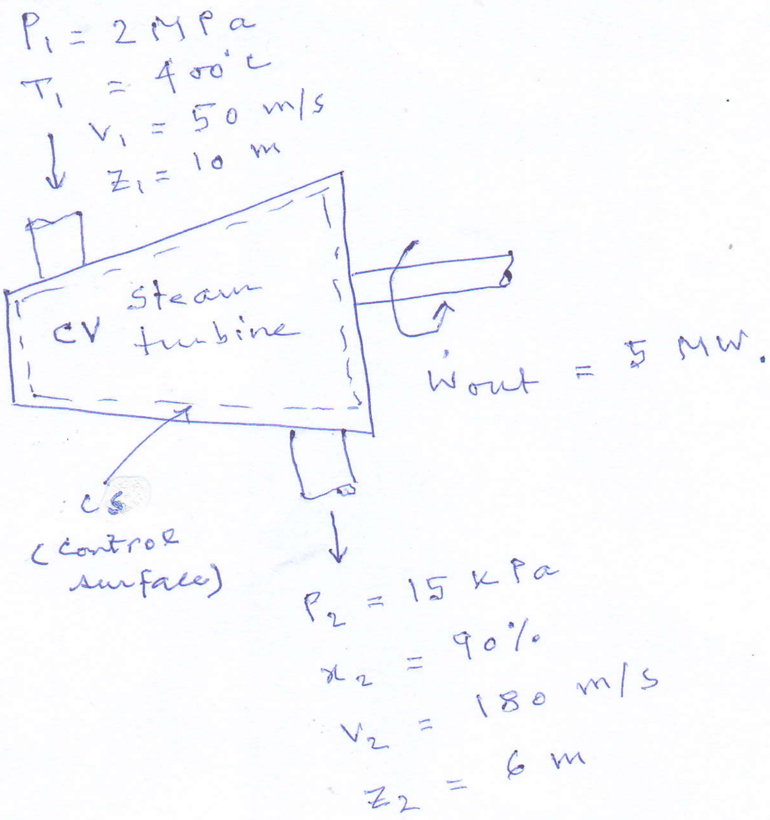


Fig. 1

We take the turbine as the system which is a control volume since mass crosses the system boundary during the process.

(a) At the inlet,

$P_1 = 2$ MPa (i.e. 2000 kPa)

$T_1 = 400°C$

From Table A-5 we see that

$T_{sat@2MPa} = 212.38°C$

Since $T_{1@2MPa} > T_{sat@2MPa}$, the steam is superheated.

At the inlet, from Table A-6, we get

$$h_1 = 3248.4 \text{ kJ/kg}$$

At the turbine exit we have a saturated liquid-vapour mixture at P = 15 kPa since $x_2 = 0.9$.

From Table A-5,

$$h_{fg@15kPa} = 2372.3 \text{ kJ/kg}$$

$$h_{f@15kPa} = 225.94 \text{ kJ/kg}$$

Hence,

$$h_2 = h_f + x_2 h_{fg}$$

$$= 225.94 + 0.9(2372.3)$$

$$= 225.94 + 2135.07$$

$$= 2361.01 \text{ kJ/kg}$$

Then,

$$\Delta h = h_2 - h_1$$

$$= 2361.01 - 3248.4$$

$$= \boxed{-887.39 \text{ kJ/kg}}$$

$$\Delta ke = \frac{V_2^2 - V_1^2}{2}$$

$$= \frac{(180)^2 - (50)^2}{2} \cdot \frac{1}{1000}$$

(since 1000 m^2/s^2 = 1 kJ/kg)

$$= \frac{32400 - 2500}{2000}$$

$$= \boxed{14.95 \text{ kJ/kg}}$$

$$\Delta Pe = g(z_2 - z_1) = \frac{(9.8)(6-10)}{1000}$$

$$= \boxed{-0.0392 \text{ kJ/kg}}$$

$$\approx \boxed{-0.04 \text{ kJ/kg}}$$

Thus, we see $|\Delta Pe| << |\Delta h|$
$|\Delta Pe| << |\Delta ke|$.

This is typical of most engineering devices.

Second, as a result of low pressure and thus high specific volume, the steam velocity at the turbine exit can be very high. Yet the $|\Delta ke|$ is a small fraction of $|\Delta h|$ (1.68% in this case) and is therefore, often neglected.

(b) The energy balance for the steady-flow system is:

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\Rightarrow \dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right)$$

$$= \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

(since $\dot{Q} = 0$)

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

$$= -\left[\Delta h + \Delta ke + \Delta pe\right]$$

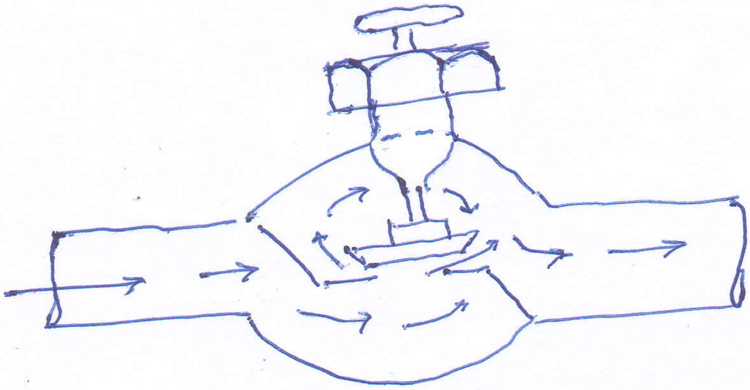
$$= -\left[-887.39 + 14.95 - 0.04\right]$$

$$= \boxed{872.48 \text{ kJ/kg}}$$

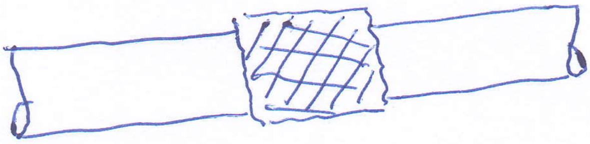
Throttling

- Throttling valves are any kind of flow-restricting devices that cause a significant pressure drop in the fluid.
- Examples: Ordinary adjustable valves, capillary tubes, and porous plugs.
- Unlike turbines, they produce a pressure drop without involving any work.
- The pressure drop in the fluid is often accompanied by a large drop in temperature, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications.

- The magnitude of the temperature drop (or sometimes, the temperature rise) during a throttling process is governed by a property called the Joule-Thomson coefficient, $(\partial T/\partial P)_h$.



(a) Flow through a valve



(b) A porous plug

(c) A capillary tube

Fig. 1 Examples of throttling devices

- Throttling devices are usually small and the flow through them may be assumed adiabatic ($\dot{Q}=0$) since there is neither sufficient time nor large enough area for any effective heat transfer to take place.

- Also, there is no work done ($\dot{W}=0$).

- Δke and Δpe are also very small and taken to be zero.

- Although the exit velocity is often considerably higher than the inlet velocity, $|\Delta ke| << |\Delta h|$.

Conservation of Energy

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m} h_1 + \dot{m} \frac{V_1^2}{2} + \dot{m} g z_1 = \dot{Q}_{out} + \dot{W}_{out} + \dot{m} h_2 + \dot{m} \frac{V_2^2}{2} + \dot{m} g z_2$$

$$\Rightarrow \cancel{\dot{Q}_{in}}^{0} + \cancel{\dot{W}_{in}}^{0} + \dot{m} h_1 = \cancel{\dot{Q}_{out}}^{0} + \cancel{\dot{W}_{out}}^{0} + \cancel{\dot{m} \left(\frac{V_2^2}{2} - \frac{V_1^2}{2} \right)}^{0} + \cancel{\dot{m} g (z_2 - z_1)}^{0} + \dot{m} h_2$$

$$\Rightarrow \boxed{h_1 = h_2}$$

Thus,

$$u_1 + P_1 v_1 = u_2 + P_2 v_2$$

or internal energy + Flow energy = constant

If $P_2 v_2 > P_1 v_1$, then

$$u_2 < u_1$$

and thus exit temperature will be lower than the inlet temperature usually. This is the case in refrigeration and air-conditioning.

If $P_2 v_2 < P_1 v_1$, then

$$u_2 > u_1$$

and there will be a temperature rise usually.

For ideal gases, since $h = f(T)$ only, $h_1 = h_2$ implies that

$$T_1 = T_2 .$$

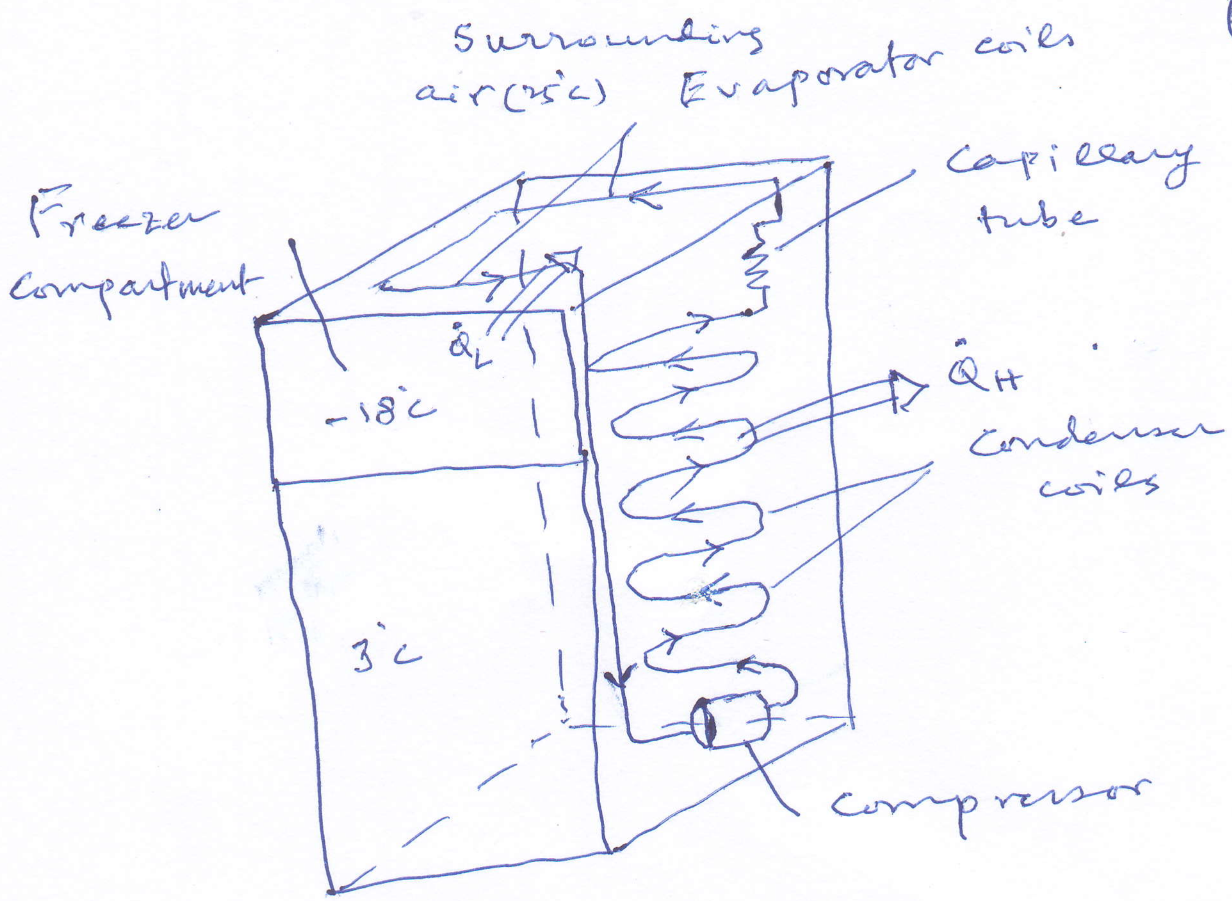


Fig. 2 An ordinary household refrigerator

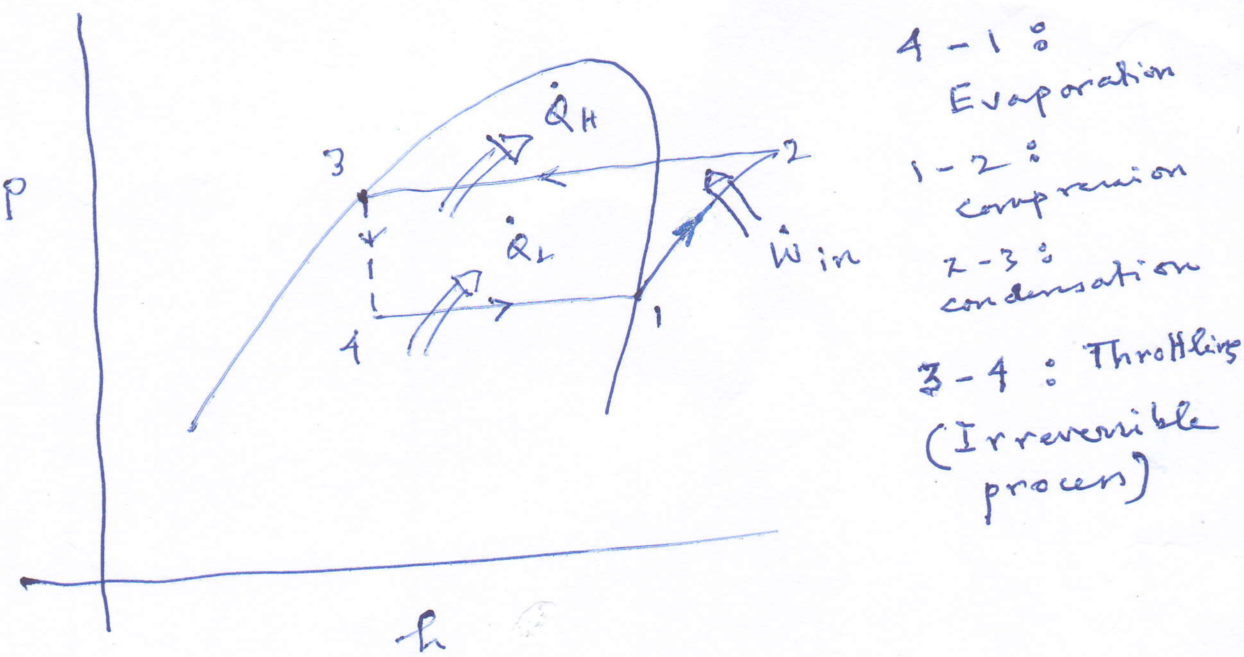


Fig. 3 P-h diagram of ideal vapour compression refrigeration cycle