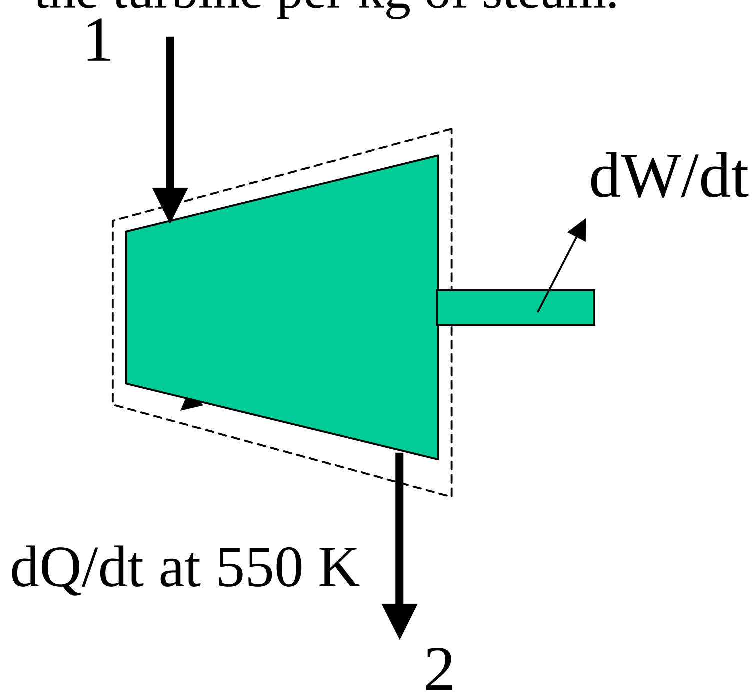
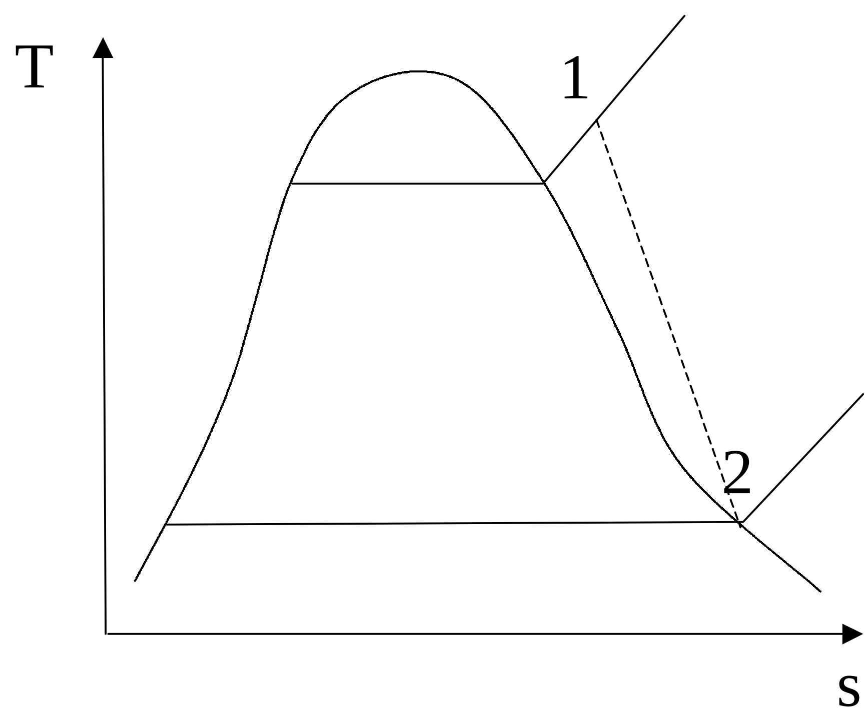
Example (A poorly maintained system)

- Following the same turbine example from previous lecture note. Let us consider that steam enters a turbine with the same pressure of 3 MPa, the same temp. of 400°C, and the same velocity of 150 m/s. The exit conditions remain the same as 100% saturated vapor exits at 100°C with velocity of 50 m/s. Due to poor maintenance, the turbine now develops less work than previously at 450 instead of 500 kJ per kg of steam. There is now more heat transfer between the turbine and its surroundings at an averaged surface temperature of 550 K. The higher temperature is reasonable since there should be more heat generation due to the imperfect operating condition. Determine the new rate at which entropy is produced within the turbine per kg of steam.





Solution

$$\text{Mass conservation}: \frac{dm}{dt} = 0 = \dot{m}_1 - \dot{m}_2, \;\; \dot{m} = \dot{m}_1 = \dot{m}_2$$

$$\text{Entropy balance analysis}: \frac{ds}{dt} = \int \frac{\dot{Q}}{T} + \dot{m}_1 s_1 - \dot{m}_2 s_2 + \dot{s}_{generation}$$

$$\text{Steady state}: 0 = \frac{ds}{dt} = \frac{\dot{Q}}{T} + \dot{m}_1 s_1 - \dot{m}_2 s_2 + \dot{s}_{gen}$$

$$\left(\frac{1}{\dot{m}}\right)\dot{s}_{gen} = -\left(\frac{1}{\dot{m}}\right)\frac{\dot{Q}}{T_b} + (s_2 - s_1), \text{ Need to determine } \dot{\mathrm{Q}}, \mathrm{s}_2, \text{ and } \mathrm{s}_1$$

$$\text{From table A-4, saturated table, } \mathrm{s}_2 = s_g = 7.356 (kJ/kgK)$$

$$\text{From table A-6, superheated table, } \mathrm{s}_1 = 6.922 (kJ/kgK)$$

$$\text{Question: How do we determine } \dot{\mathrm{Q}}?$$

Solution

Use Energy balance equation of course:

$$\frac{\mathrm{dE}}{\mathrm{dt}} = \frac{\mathrm{dE_g}}{\mathrm{dt}} + \dot{Q} + \dot{E}_1 - \dot{E}_2 - \frac{dW}{dt}, \quad \frac{\mathrm{dE}}{\mathrm{dt}} = \frac{\mathrm{dE_g}}{\mathrm{dt}} = 0$$

$$-\dot{Q} = \dot{m}_1\left(h_1 + \frac{V_1^2}{2}\right) - \dot{m}_2\left(h_2 + \frac{V_2^2}{2}\right) - \frac{dW}{dt}$$

$$\frac{-\dot{Q}}{\dot{m}} = \left(h_1 - h_2\right) + \frac{1}{2}\left(V_1^2 - V_2^2\right) - \frac{1}{\dot{m}}\frac{dW}{dt}$$

Table A-6, superheated vapor, $h_1 = 3230.8(kJ/kg)$

Table A-4, saturated table, $h_2 = h_g = 2676(kJ/kg)$

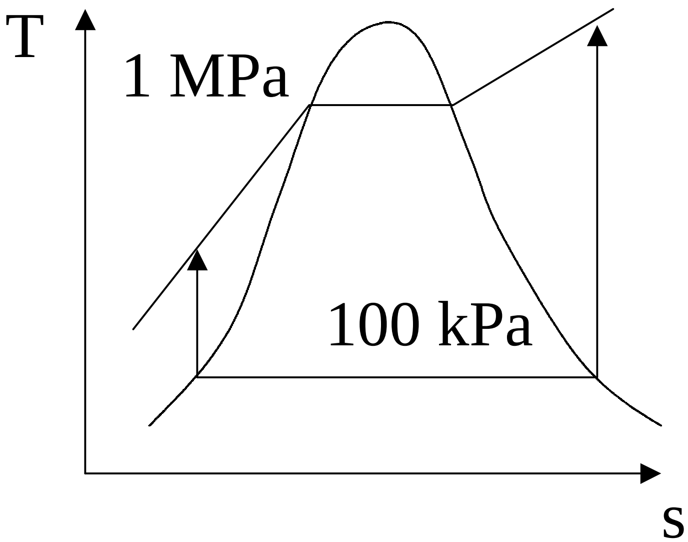
$$\frac{-\dot{Q}}{\dot{m}} = (3230.8 - 2676) + \frac{1}{2}(150^2 - 50^2)(1/1000) - 400 = 164.8(kJ/kg)$$

From previous page: $\left(\frac{1}{\dot{m}}\right)\dot{s}_{gen} = -\left(\frac{1}{\dot{m}}\right)\frac{\dot{Q}}{T_b} + (s_2 - s_1)$

$$= \frac{164.8}{550} + (7.356 - 6.922) = 0.734(kJ/kg\,K) > 0.564(kJ/kgK)$$

Example

- Determine the work required to compressed steam isentropically from 100 kPa to 1 MPa if the steam is (a) saturated liquid and (b) saturated vapor at the inlet state. Negelct change in KE and PE.



For a steady flow process with no generation and negligible KE & PE:

$\delta q - \delta W = dh$ (per unit mass flowing through)

For a reversible process $(\delta q)_{rev} = Tds = dh - vdP$

Therefore $(\delta W)_{rev} = (\delta q)_{rev} - dh = -vdP$

Integrating: $W_{rev} = -\int_1^2 vdP$, This is valid for a reversible process in a steady-flow device

(a) For an incompressible fluid such as the saturated liquid,

$v = v_{f@100kPa} = 0.001043(m^3/kg)$ is a constant, therefore

$$W_{rev} = -\int_1^2 vdP = v_1(P_1 - P_2) = (0.001043)(100 - 1000) = -0.94(kJ/kg)$$

Example(cont.)

If the steam is saturated vapor instead, its specific volume will not be a constant during compression and we need to derive its relation to the pressure variation in order to do the integration :

From the Tds equation : $\mathrm{Tds = dh - vdP}$, $\mathrm{-vdP} = Tds - dh$

If the process is an isentropic process, $\mathrm{ds = 0}$, $\mathrm{vdP = dh}$

$$W_{rev} = -\int_1^2 vdP = -\int_1^2 dh = h_1 - h_2$$

From saturated table A-5, $\mathrm{P_1 = 100\ kPa}$,

$\mathrm{h_1} = h_g = 2675.5(kJ/kg)$, $s_1 = s_g = 7.36(kJ/kg\,K)$

From superheated table A-6 : $\mathrm{P_2} = 1MPa$, and $\mathrm{s_2} = s_1$

$h_2 = 3195.5(kJ/kg)$

$W_{rev} = (2675.5 - 3195.5) = -520(kJ/kg)$

In conclusion, it is much more difficult to compress vapor than liquid and this is one of the reason a condenser is used to condense steam into liquid form before the pump delivers it back to the boiler