INDIAN INSTITUTE OF TECHNOLOGY KANPUR

ESO 201A: Thermodynamics

(2023-24 I Semester)

Instructor: Dr Avinash Kumar Agarwal

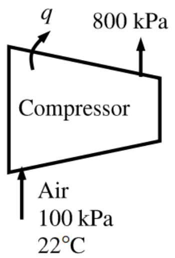
Tutorial 8

Question 1: Air enters a compressor steadily at the ambient conditions of 100 kPa and 22°C and leaves at 800 kPa. Heat is lost from the compressor in the amount of 120 kJ/kg, and the air experiences an entropy decrease of 0.40 kJ/kg.K. Using constant specific heats, determine (a) the exit temperature of the air, (b) the work input to the compressor, and (c) the entropy generation during this process. (**Answers: (a) 85.8 °C (b) 184.1 kJ/kg (c) 0.0068 kJ/kg.K)**

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with constant specific heats.

Properties The gas constant of air is R = 0.287 kPa.m^3/kg.K. Also, the specific heat at room temperature is c_p = 1.005 kJ/kg.K (Table A-2).

Analysis (*a*) The exit temperature of the air may be determined from the relation for the entropy change of air



$$\Delta S_{\text{air}} = c_p \ln\frac{T_2}{T_{al}} - R\ln\frac{P_2}{P_1}$$

$$-0.40 \text{ kJ/kg.K} = (1.005 \text{ kJ/kg.K})\ln\frac{T_2}{(22+273)\text{ K}} - (0.287 \text{ kJ/kg.K})\ln\frac{800 \text{ kPa}}{100 \text{ kPa}}$$

$$T_2 = 358.8 \text{ K} = \mathbf{85.8°C}$$

(*b*) The work input to the compressor is obtained from an energy balance on the compressor

$$w_{in} = c_p(T_2 - T_1) + q_{out} = (1.005 \text{ kJ/kg.°C})(85.8 - 22)\text{°C} + 120 \text{ kJ/kg} = \mathbf{184.1\,kJ/kg}$$

(*c*) The entropy generation associated with this process may be obtained by adding the entropy change of air as it is compressed in the compressor and the entropy change of the surroundings

$$\Delta s_{\text{surr}} = \frac{q_{\text{out}}}{T_{\text{surr}}} = \frac{120 \text{ kJ/kg}}{(22+273)\text{ K}} = 0.4068 \text{ kJ/kg.K}$$

$$s_{\text{gen}} = \Delta s_{\text{total}} = \Delta s_{\text{air}} + \Delta s_{\text{surr}} = -0.40 + 0.4068 = \mathbf{0.0068\,kJ/kg.K}$$

Question 2: Steam enters an adiabatic turbine steadily at 7 MPa, 500°C, and 45 m/s and leaves at 100 kPa and 75 m/s. If the power output of the turbine is 5 MW and the isentropic efficiency is 77 percent, determine (a) the mass flow rate of steam through the turbine, (b) the temperature at the turbine exit, and (c) the rate of entropy generation during this process. (**Answers: (a) 886 kg/s (b)103.7 ºC (c) 4.01 kW/K)**

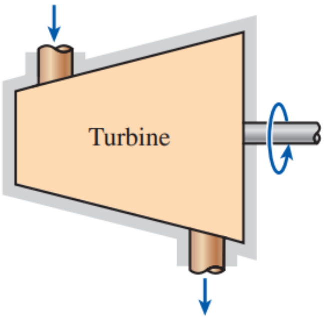
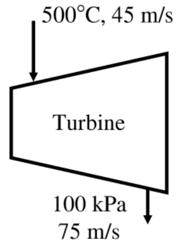


Fig. 1

Assumptions **1** Steady operating conditions exist. **2** Potential energy changes are negligible.

Analysis (*a*) The properties of the steam at the inlet of the turbine and the enthalpy at the exit for the isentropic case are (Table A-6)

$$\left.\begin{aligned} P_1 &= 7 \text{ MPa} \\ T_1 &= 500°\text{C} \end{aligned}\right\} \begin{aligned} h_1 &= 3411.4 \text{ kJ/kg} \\ s_1 &= 6.8000 \text{ kJ/kg.K} \end{aligned}$$



$$\left.\begin{aligned} P_2 &= 100 \text{ kPa} \\ s_2 &= s_1 = 6.8000 \text{ kJ/kg.K} \end{aligned}\right\} h_{2s} = 2466.6 \text{ kJ/kg}$$

The power output if the expansion was isentropic would be

$$\dot{W}_s = \frac{\dot{W}_a}{\eta_T} = \frac{5000 \text{ kW}}{0.77} = 6494 \text{ kW}$$

An energy balance on the turbine for the isentropic process may be used to determine the mass flow rate of the steam

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_{2s} + \frac{V_2^2}{2}\right) + \dot{W}_s$$

$$\dot{m}\left[3411.4 \text{ kJ/kg} + \frac{(45 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right] = \dot{m}\left[2466.6 \text{ kJ/kg} + \frac{(75 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right] + 6494 \text{ kW}$$

$$\dot{m} = \mathbf{6.886 \text{ kg/s}}$$

(*b*) An energy balance on the turbine for the actual process may be used to determine actual enthalpy at the exit

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) + \dot{W}_a$$

$$(6.886 \text{ kg/s})\left[3411.4 \text{ kJ/kg} + \frac{(45 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right] = (6.886 \text{ kg/s})\left[h_2 + \frac{(75 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right] + 5000 \text{ kW}$$

$$h_2 = 2683.5 \text{ kJ/kg}$$

Now, other properties at the exit state may be obtained

$$\left.\begin{aligned} P_2 &= 100 \text{ kPa} \\ h_2 &= 2683.5 \text{ kJ/kg} \end{aligned}\right\} \begin{aligned} T_2 &= \mathbf{103.7°C} \\ s_2 &= 7.3817 \text{ kJ/kg.K} \end{aligned}$$

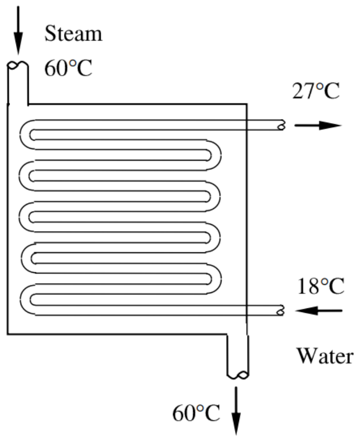
(*c*) Since the turbine is adiabatic, the entropy generation is the entropy change of steam as it flows in the turbine

$$\dot{S}_{\text{gen}} = \dot{m}(s_2 - s_1) = (6.886 \text{ kg/s})(7.3817 - 6.8000) \text{ kJ/kg.K} = \mathbf{4.01 \text{ kW/K}}$$

Question 3: Steam is to be condensed in the condenser of a steam power plant at a temperature of 60°C with cooling water from a nearby lake, which enters the tubes of the condenser at 18°C at a rate of 75 kg/s and leaves at 27°C. Assuming the condenser to be perfectly insulated, determine (a) the rate of condensation of the steam and (b) the rate of entropy generation in the condenser. (**Answers: (a) 1.20 kg/s (b) 1.06 kW/K)**

Properties The enthalpy and entropy of vaporization of water at 60°C are h_{fg} =2357.7 kJ/kg and s_{fg} = 7.0769 kJ/kg.K (Table A-4). The specific heat of water at room temperature is c_p = 4.18 kJ/kg.°C (Table A-3).

Analysis (*a*) We take the cold water tubes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as



$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{\text{system}}^{\nearrow 0\ \text{(steady)}}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0$$

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

$$\dot{Q}_{\text{in}} + \dot{m}h_1 = \dot{m}h_2 \quad (\text{since } \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

$$\dot{Q}_{\text{in}} = \dot{m}c_p(T_2 - T_1)$$

Then the heat transfer rate to the cooling water in the condenser becomes

$$\dot{Q} = [\dot{m}c_p(T_{\text{out}} - T_{\text{in}})]_{\text{cooling water}}$$
$$= (75\text{ kg/s})(4.18\text{ kJ/kg.°C})(27°\text{C} - 18°\text{C}) = 2822\text{ kJ/s}$$

The rate of condensation of steam is determined to be

$$\dot{Q} = (\dot{m}h_{fg})_{\text{steam}} \longrightarrow \dot{m}_{\text{steam}} = \frac{\dot{Q}}{h_{fg}} = \frac{2822\text{ kJ/s}}{2357.7\text{ kJ/kg}} = \mathbf{1.20\ kg/s}$$

(*b*) The rate of entropy generation within the condenser during this process can be determ the entropy balance on the entire condenser. Noting that the condenser is well-insulated a the entropy balance for this steady-flow system can be expressed as

$$\underbrace{\dot{S}_{\text{in}} - \dot{S}_{\text{out}}}_{\substack{\text{Rate of net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{\dot{S}_{\text{gen}}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{\Delta \dot{S}_{\text{system}}^{\nearrow 0\ \text{(steady)}}}_{\substack{\text{Rate of change}\\ \text{of entropy}}}$$

$$\dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{\text{gen}} = 0 \quad (\text{since } Q = 0)$$

$$\dot{m}_{\text{water}} s_1 + \dot{m}_{\text{steam}} s_3 - \dot{m}_{\text{water}} s_2 - \dot{m}_{\text{steam}} s_4 + \dot{S}_{\text{gen}} = 0$$

$$\dot{S}_{\text{gen}} = \dot{m}_{\text{water}}(s_2 - s_1) + \dot{m}_{\text{steam}}(s_4 - s_3)$$

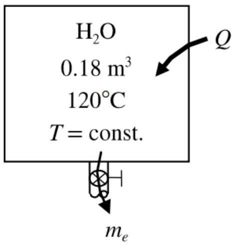
Noting that water is an incompressible substance and steam changes from saturated vapor entropy generation is determined to be

$$\dot{S}_{\text{gen}} = \dot{m}_{\text{water}} c_p \ln\frac{T_2}{T_1} + \dot{m}_{\text{steam}}(s_f - s_g) = \dot{m}_{\text{water}} c_p \ln\frac{T_2}{T_1} - \dot{m}_{\text{steam}} s_{fg}$$
$$= (75\text{ kg/s})(4.18\text{ kJ/kg}\cdot\text{K})\ln\frac{27+273}{18+273} - (1.20\text{ kg/s})(7.0769\text{ kJ/kg}\cdot\text{K})$$
$$= \mathbf{1.06\ kW/K}$$

Question 4: A 0.18-m3 rigid tank is filled with saturated liquid water at 120°C. A valve at the bottom of the tank is now opened, and one-half of the total mass is withdrawn from the tank in the liquid form. Heat is transferred to water from a source at 230°C so that the temperature in the tank remains constant. Determine (a) the amount of heat transfer and (b) the total entropy generation for this process. (**Answers: (a) 222.6 kJ (b) 0.1237 kJ/K)**

Assumptions **1** This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as a uniform-flow process since the state of fluid leaving the device remains constant. **2** Kinetic and potential energies are negligible. **3** There are no work interactions involved. **4** The direction of heat transfer is to the tank (will be verified).

Properties The properties of water are (Tables A-4 through A-6)



$$\left.\begin{array}{l} T_1 = 120°\text{C} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} v_1 = v_{f\,@\,120°\text{C}} = 0.001060 \text{ m}^3/\text{kg} \\ u_1 = u_{f\,@\,120°\text{C}} = 503.60 \text{ kJ/kg} \\ s_1 = s_{f\,@\,120°\text{C}} = 1.5279 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_e = 120°\text{C} \\ \text{sat. liquid} \end{array}\right\} \begin{array}{l} h_e = h_{f\,@\,120°\text{C}} = 503.81 \text{ kJ/kg} \\ s_e = s_{f\,@\,120°\text{C}} = 1.5279 \text{ kJ/kg}\cdot\text{K} \end{array}$$

Analysis (*a*) We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the microscopic energies of flowing and nonflowing fluids are represented by enthalpy *h* and internal energy *u*, respectively, the mass and energy balances for this uniform-flow system can be expressed as

Mass balance:

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \rightarrow m_e = m_1 - m_2$$

Energy balance:

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$Q_{\text{in}} = m_e h_e + m_2 u_2 - m_1 u_1 \quad (\text{since } W \cong \text{ke} \cong \text{pe} \cong 0)$$

The initial and the final masses in the tank are

$$m_1 = \frac{V}{v_1} = \frac{0.18 \text{ m}^3}{0.001060 \text{ m}^3/\text{kg}} = 169.76 \text{ kg}$$

$$m_2 = \frac{1}{2} m_1 = \frac{1}{2}(169.76 \text{ kg}) = 84.88 \text{ kg} = m_e$$

Now we determine the final internal energy and entropy,

$$v_2 = \frac{V}{m_2} = \frac{0.18 \text{ m}^3}{84.88 \text{ kg}} = 0.002121 \text{ m}^3/\text{kg}$$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.002121 - 0.001060}{0.8913 - 0.001060} = 0.001191$$

$$\left.\begin{array}{l} T_2 = 120°\text{C} \\ x_2 = 0.001191 \end{array}\right\} \begin{array}{l} u_2 = u_f + x_2 u_{fg} = 503.60 + (0.001191)(2025.3) = 506.01 \text{ kJ/kg} \\ s_2 = s_f + x_2 s_{fg} = 1.5279 + (0.001191)(5.6013) = 1.5346 \text{ kJ/kg}\cdot\text{K} \end{array}$$

The heat transfer during this process is determined by substituting these values into the energy balance equation,

$$\begin{aligned} Q_{\text{in}} &= m_e h_e + m_2 u_2 - m_1 u_1 \\ &= (84.88 \text{ kg})(503.81 \text{ kJ/kg}) + (84.88 \text{ kg})(506.01 \text{ kJ/kg}) - (169.76 \text{ kg})(503.60 \text{ kJ/kg}) \\ &= \mathbf{222.6 \text{ kJ}} \end{aligned}$$

(*b*) The total entropy generation is determined by considering a combined system that includes the tank and the heat source. Noting that no heat crosses the boundaries of this combined system and no mass enters, the entropy balance for it can be expressed as

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{gen}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{system}}_{\substack{\text{Change} \\ \text{in entropy}}} \longrightarrow -m_e s_e + S_{gen} = \Delta S_{tank} + \Delta S_{source}$$

Therefore, the total entropy generated during this process is

$$S_{gen} = m_e s_e + \Delta S_{tank} + \Delta S_{source} = m_e s_e + (m_2 s_2 - m_1 s_1) - \frac{Q_{source,out}}{T_{source}}$$

$$= (84.88 \text{ kg})(1.5279 \text{ kJ/kg}\cdot\text{K}) + (84.88 \text{ kg})(1.5346 \text{ kJ/kg}\cdot\text{K})$$

$$-(169.76 \text{ kg})(1.5279 \text{ kJ/kg}\cdot\text{K}) - \frac{222.6 \text{ kJ}}{(230+273) \text{ K}}$$

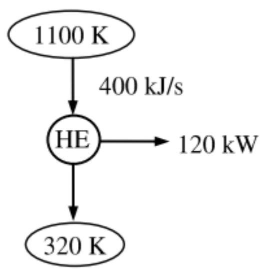
$$= \mathbf{0.1237 \text{ kJ/K}}$$

Question 5: A heat engine receives heat from a source at 1100 K at a rate of 400 kJ/s, and it rejects the waste heat to a medium at 320 K. The measured power output of the heat engine is 120 kW, and the environment temperature is 25°C. Determine (a) the reversible power, (b) the rate of irreversibility, and (c) the second-law efficiency of this heat engine. **(Answers: (a) 284 kW, (b) 164 kW, (c) 42.3 %)**

Analysis (a) The reversible power is the power produced by a reversible heat engine operating between the specified temperature limits,

$$\eta_{th,max} = \eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{320 \text{ K}}{1100 \text{ K}} = 0.7091$$

$$\dot{W}_{rev,out} = \eta_{th,rev}\dot{Q}_{in} = (0.7091)(400 \text{ kJ/s}) = \mathbf{283.6 \text{ kW}}$$



(b) The irreversibility rate is the difference between the reversible power and the actual power output:

$$\dot{I} = \dot{W}_{rev,out} - \dot{W}_{u,out} = 283.6 - 120 = \mathbf{163.6 \text{ kW}}$$

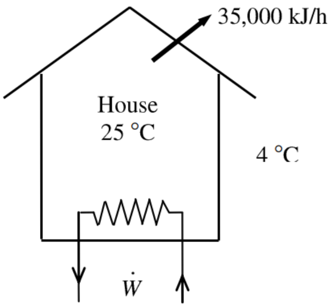
(c) The second law efficiency is determined from its definition,

$$\eta_{II} = \frac{W_{u,out}}{W_{rev,out}} = \frac{120 \text{ kW}}{283.6 \text{ kW}} = 0.423 = \mathbf{42.3\%}$$

Question 6: A house that is losing heat at a rate of 35,000 kJ/h when the outside temperature drops to 4°C is to be heated by electric resistance heaters. If the house is to be always maintained at 25°C, determine the reversible work input for this process and the irreversibility. (**Answers: (a) 0.685 kW (b) 9.04 kW)**

Analysis We consider a reversible heat pump operation as the reversible counterpart of the irreversible process of heating the house by resistance heaters. Instead of using electricity input for resistance heaters, it is used to power a reversible heat pump. The reversible work is the minimum work required to accomplish this process, and the irreversibility is the difference between the reversible work and the actual electrical work consumed. The actual power input is

$$\dot{W}_{\text{in}} = \dot{Q}_{\text{out}} = \dot{Q}_H = 35{,}000 \text{ kJ/h} = 9.722 \text{ kW}$$



The COP of a reversible heat pump operating between the specified temperature limits is

$$\text{COP}_{\text{HP,rev}} = \frac{1}{1 - T_L / T_H} = \frac{1}{1 - 277.15/298.15} = 14.20$$

Thus,

$$\dot{W}_{\text{rev,in}} = \frac{\dot{Q}_H}{\text{COP}_{\text{HP,rev}}} = \frac{9.722 \text{ kW}}{14.20} = \mathbf{0.685\ kW}$$

and

$$\dot{I} = \dot{W}_{\text{u,in}} - \dot{W}_{\text{rev,in}} = 9.722 - 0.658 = \mathbf{9.04\ kW}$$