INDIAN INSTITUTE OF TECHNOLOGY KANPUR

ESO 201A: Thermodynamics

(2023-24 I Semester)

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Tutorial 9

Question 1: Which has the capability to produce the most work in a closed system l kg of steam at 800 kPa and 180°C or 1 kg of R–134a at 800 kPa and 180°C? Take T_0 = 25°C and P_0 = 100 kPa. **(Ans: 623 kJ (steam), 71.23 kJ (R-134a))**

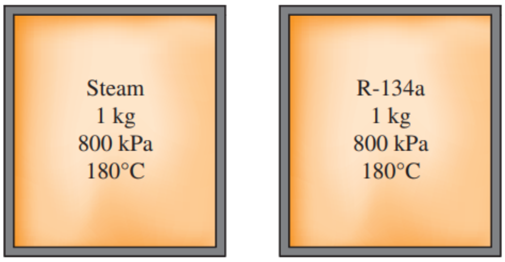


Fig. 1

Analysis The properties of water at the given state and at the dead state are

$$\left.\begin{array}{l} P = 800\text{ kPa} \\ T = 180°\text{C} \end{array}\right\} \begin{array}{l} u = 2594.7\text{ kJ/kg} \\ v = 0.24720\text{ m}^3\text{/kg} \quad \text{(Table A-6)} \\ s = 6.7155\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_0 = 25°\text{C} \\ P_0 = 100\text{ kPa} \end{array}\right\} \begin{array}{l} u_0 \cong u_{f@25°\text{C}} = 104.83\text{ kJ/kg} \\ v_0 \cong v_{f@25°\text{C}} = 0.001003\text{ m}^3\text{/kg} \quad \text{(Table A-4)} \\ s_0 \cong s_{f@25°\text{C}} = 0.3672\text{ kJ/kg}\cdot\text{K} \end{array}$$

The exergy of steam is

$$\Phi = m\left[u - u_0 + P_0(v - v_0) - T_0(s - s_0)\right]$$

$$= (1\text{ kg})\left[\begin{array}{l}(2594.7 - 104.83)\text{kJ/kg} + (100\text{ kPa})(0.24720 - 0.001003)\text{m}^3\text{/kg}\left(\dfrac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ -(298\text{ K})(6.7155 - 0.3672)\text{kJ/kg}\cdot\text{K}\end{array}\right]$$

$$= \mathbf{622.7\ kJ}$$

For R-134a;

$$\left.\begin{array}{l} P = 800\text{ kPa} \\ T = 180°\text{C} \end{array}\right\} \begin{array}{l} u = 386.99\text{ kJ/kg} \\ v = 0.044554\text{ m}^3\text{/kg} \quad \text{(Table A-13)} \\ s = 1.3327\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_0 = 25°\text{C} \\ P_0 = 100\text{ kPa} \end{array}\right\} \begin{array}{l} u_0 = 252.60\text{ kJ/kg} \\ v_0 = 0.001003\text{ m}^3\text{/kg} \quad \text{(from EES)} \\ s_0 = 1.1061\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\Phi = m\left[u - u_0 + P_0(v - v_0) - T_0(s - s_0)\right]$$

$$= (1\text{ kg})\left[\begin{array}{l}(386.99 - 252.60)\text{kJ/kg} + (100\text{ kPa})(0.044554 - 0.001003)\text{m}^3\text{/kg}\left(\dfrac{1\text{ kJ}}{1\text{ kPa}\cdot\text{m}^3}\right) \\ -(298\text{ K})(1.3327 - 1.1061)\text{kJ/kg}\cdot\text{K}\end{array}\right]$$

$$= \cancel{47.5\text{ kJ}}\ 71.23\text{ kJ}$$

The steam can therefore has more work potential than the R-134a.

Question 2: The radiator of a steam heating system has a volume of 20 L and is filled with superheated water vapor at 200 kPa and 200°C. At this moment both the inlet and the exit valves to the radiator are closed. After a while it is observed that the temperature of the steam drops to 80°C as a result of heat transfer to the room air, which is at 21°C. Assuming the surroundings to be at 0°C, determine (a) the amount of heat transfer to the room and (b) the maximum amount of heat that can be supplied to the room if this heat from the radiator is supplied to a heat engine that is driving a heat pump. Assume the heat engine operates between the radiator and the surroundings. **(Ans: (a) 30.3 kJ, (b) 116 kJ))**

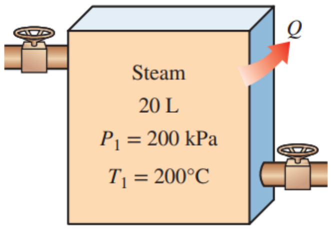
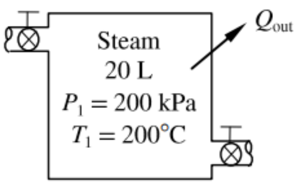


Fig. 2

Assumptions Kinetic and potential energies are negligible.

Properties From the steam tables (Tables A-4 through A-6),



$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 200°\text{C} \end{array}\right\} \begin{array}{l} v_1 = 1.0805 \text{ m}^3/\text{kg} \\ u_1 = 2654.6 \text{ kJ/kg} \\ s_1 = 7.5081 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_2 = 80°\text{C} \\ (v_2 = v_1) \end{array}\right\} \begin{array}{l} x_2 = \dfrac{v_2 - v_f}{v_{fg}} = \dfrac{1.0805 - 0.001029}{3.4053 - 0.001029} = 0.3171 \\ u_2 = u_f + x_2 u_{fg} = 334.97 + 0.3171 \times 2146.6 = 1015.6 \text{ kJ/kg} \\ s_2 = s_f + x_2 s_{fg} = 1.0756 + 0.3171 \times 6.5355 = 3.1479 \text{ kJ/kg}\cdot\text{K} \end{array}$$

Analysis (a) The mass of the steam is

$$m = \frac{V}{v_1} = \frac{0.020 \text{ m}^3}{1.0805 \text{ m}^3/\text{kg}} = 0.01851 \text{ kg}$$

The amount of heat transfer to the room is determined from an energy balance on the radiator expressed as

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

$$-Q_{\text{out}} = \Delta U = m(u_2 - u_1) \quad (\text{since } W = \text{KE} = \text{PE} = 0)$$

$$Q_{\text{out}} = m(u_1 - u_2)$$

or

$$Q_{\text{out}} = (0.01851 \text{ kg})(2654.6 - 1015.6) \text{ kJ/kg} = \mathbf{30.3 \ kJ}$$

(*b*) The reversible work output, which represents the maximum work output $W_{\text{rev,out}}$ in this case can be determined from the exergy balance by setting the exergy destruction equal to zero,

$$\underbrace{X_{\text{in}} - X_{\text{out}}}_{\substack{\text{Net exergy transfer}\\ \text{by heat, work, and mass}}} - \underbrace{X_{\text{destroyed}}^{\nearrow 0 \text{ (reversible)}}}_{\substack{\text{Exergy}\\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change}\\ \text{in exergy}}}$$

$$-W_{\text{rev,out}} = X_2 - X_1 \quad \rightarrow \quad W_{\text{rev,out}} = X_1 - X_2 = \Phi_1 - \Phi_2$$

Substituting the closed system exergy relation, the reversible work during this process is determined to be

$$\begin{aligned} W_{\text{rev,out}} &= m\left[(u_1 - u_2) - T_0(s_1 - s_2) + P_0(\upsilon_1^{\nearrow 0} - \upsilon_2)\right] \\ &= m\left[(u_1 - u_2) - T_0(s_1 - s_2)\right] \\ &= (0.01851 \text{ kg})\left[(2654.6 - 1015.6) \text{ kJ/kg} - (273 \text{ K})(7.5081 - 3.1479) \text{ kJ/kg}\cdot\text{K}\right] = 8.305 \text{ kJ} \end{aligned}$$

When this work is supplied to a reversible heat pump, it will supply the room heat in the amount of

$$Q_H = \text{COP}_{\text{HP,rev}} W_{\text{rev}} = \frac{W_{\text{rev}}}{1 - T_L / T_H} = \frac{8.305 \text{ kJ}}{1 - 273/294} = \mathbf{116 \text{ kJ}}$$

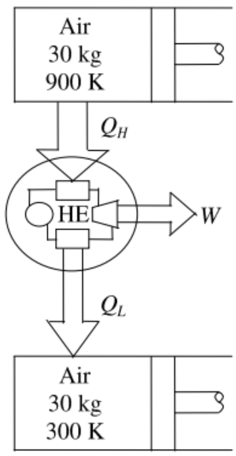
Discussion Note that the amount of heat supplied to the room can be increased by about 3 times by eliminating the irreversibility associated with the irreversible heat transfer process.

Question 3: Two constant-pressure devices, each filled with 30 kg of air, have temperatures of 900 K and 300 K. A heat engine placed between the two devices extracts heat from the high-temperature device, produces work, and rejects heat to the low-temperature device. Determine the maximum work that can be produced by the heat engine and the final temperature of the devices. Assume constant specific heats at room temperature. **(Ans: 4847 kJ, 519.6 K)**

Assumptions Air is an ideal gas with constant specific heats at room temperature.

Properties The gas constant of air is 0.287 kPa.m^3/kg.K (Table A-1). The constant pressure specific heat of air at room temperature is $c_p = 1.005$ kJ/kg.K (Table A-2).

Analysis For maximum power production, the entropy generation must be zero. We take the two cylinders (the heat source and heat sink) and the heat engine as the system. Noting that the system involves no heat and mass transfer and that the entropy change for cyclic devices is zero, the entropy balance can be expressed as



$$\underbrace{S_{\text{in}} - S_{\text{out}}}_{\substack{\text{Net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{S_{\text{gen}}^{\nearrow 0}}_{\substack{\text{Entropy}\\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change}\\ \text{in entropy}}}$$

$$0 + S_{\text{gen}}^{\nearrow 0} = \Delta S_{\text{cylinder,source}} + \Delta S_{\text{cylinder,sink}} + \Delta S_{\text{heat engine}}^{\nearrow 0}$$

$$\Delta S_{\text{cylinder,source}} + \Delta S_{\text{cylinder,sink}} = 0$$

$$\left(mc_p \ln \frac{T_2}{T_1} - mR \ln \frac{P_2}{P_1}^{\nearrow 0} \right)_{\text{source}} + 0 + \left(mc_p \ln \frac{T_2}{T_1} - mR \ln \frac{P_2}{P_1}^{\nearrow 0} \right)_{\text{sink}} = 0$$

$$\ln \frac{T_2}{T_{1A}} \frac{T_2}{T_{1B}} = 0 \longrightarrow T_2^2 = T_{1A} T_{1B}$$

where T_{1A} and T_{1B} are the initial temperatures of the source and the sink, respectively, and T_2 is the common final temperature. Therefore, the final temperature of the tanks for maximum power production is

$$T_2 = \sqrt{T_{1A} T_{1B}} = \sqrt{(900 \text{ K})(300 \text{ K})} = \mathbf{519.6 \text{ K}}$$

The energy balance $E_{in} - E_{out} = \Delta E_{\text{system}}$ for the source and sink can be expressed as follows:

Source:

$$-Q_{\text{source,out}} + W_{b,in} = \Delta U \;\rightarrow\; Q_{\text{source,out}} = \Delta H = mc_p(T_{1A} - T_2)$$

$$Q_{\text{source,out}} = mc_p(T_{1A} - T_2) = (30\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(900 - 519.6)\text{K} = 11{,}469\text{ kJ}$$

Sink:

$$Q_{\text{sink,in}} - W_{b,out} = \Delta U \;\rightarrow\; Q_{\text{sink,in}} = \Delta H = mc_p(T_2 - T_{1A})$$

$$Q_{\text{sink,in}} = mc_p(T_2 - T_{1B}) = (30\text{ kg})(1.005\text{ kJ/kg}\cdot\text{K})(519.6 - 300)\text{K} = 6621\text{ kJ}$$

Then the work produced becomes

$$W_{\text{max,out}} = Q_H - Q_L = Q_{\text{source,out}} - Q_{\text{sink,in}} = 11{,}469 - 6621 = \mathbf{4847\ \ kJ}$$

Therefore, a maximum of 4847 kJ of work can be produced during this process.

Question 4: A 0.8-m^3 insulated rigid tank contains 1.54 kg of carbon dioxide at 100 kPa. Now paddle-wheel work is done on the system until the pressure in the tank rises to 135 kPa. Determine (a) the actual paddle-wheel work done during this process and (b) the minimum paddle-wheel work with which this process (between the same end states) could be accomplished. Take T_0 = 298 K.

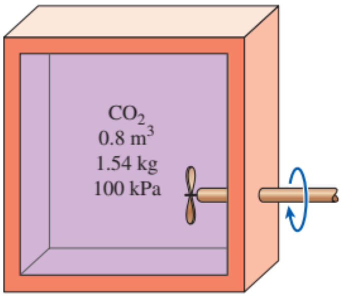


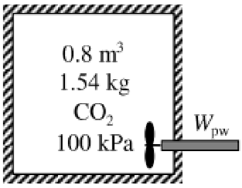
Fig. 3

Solution:

8-39 An insulated tank contains CO_2 gas at a specified pressure and volume. A paddle-wheel in the tank stirs the gas, and the pressure and temperature of CO_2 rises. The actual paddle-wheel work and the minimum paddle-wheel work by which this process can be accomplished are to be determined.

Assumptions **1** At specified conditions, CO_2 can be treated as an ideal gas with constant specific heats at the average temperature. **2** The surroundings temperature is 298 K.

Properties The gas constant of CO_2 is 0.1889 kJ/kg.K (Table A-1)



Analysis (a) The initial and final temperature of CO_2 are

$$T_1 = \frac{P_1 V_1}{mR} = \frac{(100 \text{ kPa})(0.8 \text{ m}^3)}{(1.54 \text{ kg})(0.1889 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})} = 275.0 \text{ K}$$

$$T_2 = \frac{P_2 V_2}{mR} = \frac{(135 \text{ kPa})(0.8 \text{ m}^3)}{(1.54 \text{ kg})(0.1889 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})} = 371.3 \text{ K}$$

$$T_{avg} = (T_1 + T_2)/2 = (275.0 + 371.3)/2 = 323.1 \text{ K} \longrightarrow c_{\upsilon,avg} = 0.680 \text{ kJ/kg}\cdot\text{K (Table A-2}b)$$

The actual paddle-wheel work done is determined from the energy balance on the CO_2 gas in the tank,

We take the contents of the cylinder as the system. This is a closed system since no mass enters or leaves. The energy balance for this stationary closed system can be expressed as

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

$$W_{pw,in} = \Delta U = mc_\upsilon(T_2 - T_1)$$

or

$$W_{pw,in} = (1.54 \text{ kg})(0.680 \text{ kJ/kg}\cdot\text{K})(371.3 - 275.0)\text{K} = \mathbf{100.8 \text{ kJ}}$$

(b) The minimum paddle-wheel work with which this process can be accomplished is the reversible work, which can be determined from the exergy balance by setting the exergy destruction equal to zero,

$$\underbrace{X_{in} - X_{out}}_{\substack{\text{Net exergy transfer}\\ \text{by heat, work, and mass}}} - \underbrace{X_{destroyed}^{\nearrow 0 \text{ (reversible)}}}_{\substack{\text{Exergy}\\ \text{destruction}}} = \underbrace{\Delta X_{system}}_{\substack{\text{Change}\\ \text{in exergy}}} \rightarrow W_{rev,in} = X_2 - X_1$$

Substituting the closed system exergy relation, the reversible work input for this process is determined to be

$$\begin{aligned} W_{rev,in} &= m\left[(u_2 - u_1) - T_0(s_2 - s_1) + P_0(\upsilon_2^{\nearrow 0} - \upsilon_1)\right] \\ &= m\left[c_{\upsilon,avg}(T_2 - T_1) - T_0(s_2 - s_1)\right] \\ &= (1.54 \text{ kg})[(0.680 \text{ kJ/kg}\cdot\text{K})(371.3 - 275.0) \text{ K} - (298 \text{ K})(0.2041 \text{ kJ/kg}\cdot\text{K})] \\ &= \mathbf{7.18 \text{ kJ}} \end{aligned}$$

since

$$s_2 - s_1 = c_{\upsilon,avg} \ln\frac{T_2}{T_1} + R\ln\frac{\upsilon_2}{\upsilon_1}^{\nearrow 0} = (0.680 \text{ kJ/kg}\cdot\text{K})\ln\left(\frac{371.3 \text{ K}}{275.0 \text{ K}}\right) = 0.2041 \text{ kJ/kg}\cdot\text{K}$$

Question 5: An insulated rigid tank is divided into two equal parts by a partition. Initially, one part contains 3 kg of argon gas at 300 kPa and 70°C, and the other side is evacuated. The partition is removed, and the gas fills the entire tank. Assuming the surroundings to be at 25°C, determine the exergy destroyed during this process.

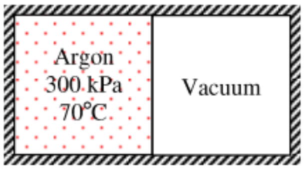
Solution:

8-43 One side of a partitioned insulated rigid tank contains argon gas at a specified temperature and pressure while the other side is evacuated. The partition is removed, and the gas fills the entire tank. The exergy destroyed during this process is to be determined.

Assumptions Argon is an ideal gas with constant specific heats, and thus ideal gas relations apply.

Properties The gas constant of argon is R = 0.2081 kJ/kg.K (Table A-1).

Analysis Taking the entire rigid tank as the system, the energy balance can be expressed as



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

$$0 = \Delta U = m(u_2 - u_1)$$

$$u_2 = u_1 \quad \rightarrow \quad T_2 = T_1$$

since $u = u(T)$ for an ideal gas.

The exergy destruction (or irreversibility) associated with this process can be determined from its definition $X_{\text{destroyed}} = T_0 S_{\text{gen}}$ where the entropy generation is determined from an entropy balance on the entire tank, which is an insulated closed system,

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

$$S_{\text{gen}} = \Delta S_{\text{system}} = m(s_2 - s_1)$$

where

$$\Delta S_{\text{system}} = m(s_2 - s_1) = m\left(c_{v,\text{avg}} \ln\frac{T_2}{T_1}^{\nearrow 0} + R\ln\frac{V_2}{V_1}\right) = mR\ln\frac{V_2}{V_1}$$

$$= (3\text{ kg})(0.2081\text{ kJ/kg}\cdot\text{K})\ln(2) = 0.433\text{ kJ/K}$$

Substituting,

$$X_{\text{destroyed}} = T_0 S_{\text{gen}} = mT_0(s_2 - s_1) = (298\text{ K})(0.433\text{ kJ/K}) = \mathbf{129\ \ kJ}$$

Question 6: Steam enters a turbine at 9 MPa, 600°C, and 60 m/s and leaves at 20 kPa and 90 m/s with a moisture content of 5 percent. The turbine is not adequately insulated, and it estimated that heat is lost from the turbine at a rate of 220 kW. The power output of the turbine is 4.5 MW. Assuming the surroundings to be at 25°C, determine (a) the reversible power output of the turbine, (b) the exergy destroyed within the turbine, and (c) the second-law efficiency of the turbine. (d) Also, estimate the possible increase in the power output of the turbine if the turbine were perfectly insulated.

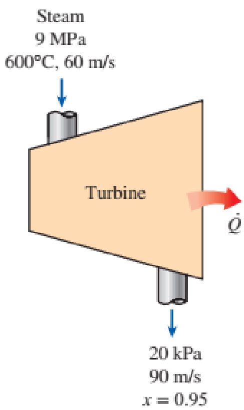


Fig. 4

Solution:

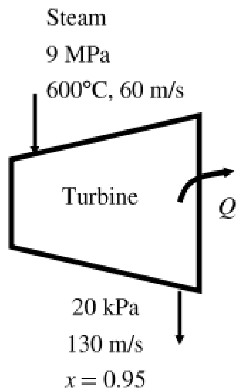
8-64 Steam expands in a turbine, which is not insulated. The reversible power, the exergy destroyed, the second-law efficiency, and the possible increase in the turbine power if the turbine is well insulated are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Potential energy change is negligible.

Analysis (*a*) The properties of the steam at the inlet and exit of the turbine are (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 9 \text{ MPa} \\ T_1 = 600°\text{C} \end{array}\right\} \begin{array}{l} h_1 = 3634.1 \text{ kJ/kg} \\ s_1 = 6.9605 \text{ kJ/kg.K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 20 \text{ kPa} \\ x_2 = 0.95 \end{array}\right\} \begin{array}{l} h_2 = 2491.1 \text{ kJ/kg} \\ s_2 = 7.5535 \text{ kJ/kg.K} \end{array}$$



The enthalpy at the dead state is

$$\left.\begin{array}{l} T_0 = 25°\text{C} \\ x = 0 \end{array}\right\} h_0 = 104.83 \text{ kJ/kg}$$

The mass flow rate of steam may be determined from an energy balance on the turbine

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

$$\dot{m}\left[3634.1 \text{ kJ/kg} + \frac{(60 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right] = \dot{m}\left[2491.1 \text{ kJ/kg} + \frac{(130 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right]$$

$$+220 \text{ kW} + 4500 \text{ kW} \longrightarrow \dot{m} = 4.137 \text{ kg/s}$$

The reversible power may be determined from

$$\dot{W}_{\text{rev}} = \dot{m}\left[h_1 - h_2 - T_0(s_1 - s_2) + \frac{V_1^2 - V_2^2}{2}\right]$$

$$= \overset{4.137}{\cancel{(2.693)}}\left[(3634.1 - 2491.1) - (298)(6.9605\text{-}7.5535) + \frac{(60 \text{ m/s})^2 - (130 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)\right]$$

$$= \mathbf{5451 \text{ kW}}$$

(b) The exergy destroyed in the turbine is

$$\dot{X}_{\text{dest}} = \dot{W}_{\text{rev}} - \dot{W}_a = 5451 - 4500 = \mathbf{951 \text{ kW}}$$

(*c*) The second-law efficiency is

$$\eta_{II} = \frac{\dot{W}_a}{\dot{W}_{\text{rev}}} = \frac{4500 \text{ kW}}{5451 \text{ kW}} = 0.826 = \mathbf{82.6\%}$$

(*d*) The energy of the steam at the turbine inlet in the given dead state is

$$\dot{Q} = \dot{m}(h_1 - h_0) = (4.137 \text{ kg/s})(3634.1\text{-}104.83)\text{kJ/kg} = 14{,}602 \text{ kW}$$

The fraction of energy at the turbine inlet that is converted to power is

$$f = \frac{\dot{W}_a}{\dot{Q}} = \frac{4500 \text{ kW}}{14{,}602 \text{ kW}} = 0.3082$$

Assuming that the same fraction of heat loss from the turbine could have been converted to work, the possible increase in the power if the turbine is to be well-insulated becomes

$$\dot{W}_{\text{increase}} = f\dot{Q}_{\text{out}} = (0.3082)(220 \text{ kW}) = \mathbf{67.8 \text{ kW}}$$

Question 7: Liquid water at 200 kPa and 15°C is heated in a chamber by mixing it with superheated steam at 200 kPa and 200°C. Liquid water enters the mixing chamber at a rate of 4 kg/s, and the chamber is estimated to lose heat to the surrounding air at 25°C at a rate of 600 kJ/min. If the mixture leaves the mixing chamber at 200 kPa and 80°C, determine (a) the mass flow rate of the superheated steam and (b) the wasted work potential during this mixing process.

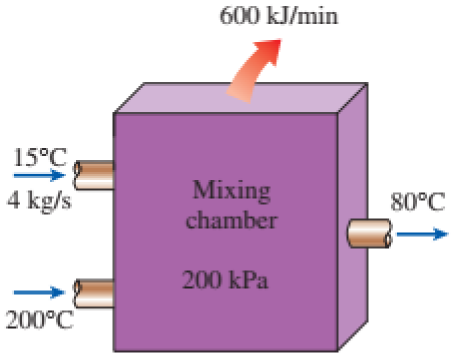


Fig. 5

Solution:

8-77 Liquid water is heated in a chamber by mixing it with superheated steam. For a specified mixing temperature, the mass flow rate of the steam and the rate of exergy destruction are to be determined.

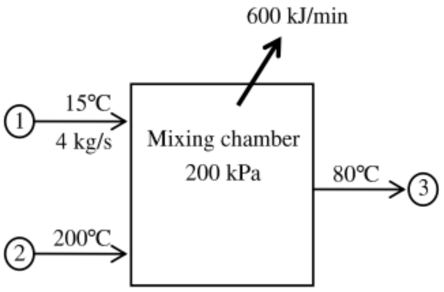
Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** There are no work interactions.

Properties Noting that $T < T_{sat\ @\ 200\ kPa} = 120.23°C$, the cold water and the exit mixture streams exist as a compressed liquid, which can be approximated as a saturated liquid at the given temperature. From Tables A-4 through A-6,

$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 15°\text{C} \end{array}\right\} \begin{array}{l} h_1 \cong h_{f\ @\ 15°C} = 62.98 \text{ kJ/kg} \\ s_1 \cong s_{f\ @\ 15°C} = 0.22447 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 200 \text{ kPa} \\ T_2 = 200°\text{C} \end{array}\right\} \begin{array}{l} h_2 = 2870.4 \text{ kJ/kg} \\ s_2 = 7.5081 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_3 = 200 \text{ kPa} \\ T_3 = 80°\text{C} \end{array}\right\} \begin{array}{l} h_3 \cong h_{f\ @\ 80°C} = 335.02 \text{ kJ/kg} \\ s_3 \cong s_{f\ @\ 80°C} = 1.0756 \text{ kJ/kg}\cdot\text{K} \end{array}$$



Analysis (a) We take the mixing chamber as the system, which is a control volume. The mass and energy balances for this steady-flow system can be expressed in the rate form as

Mass balance: $\dot{m}_{in} - \dot{m}_{out} = \Delta\dot{m}_{system}^{\nearrow 0\ (steady)} = 0 \longrightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy balance:

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

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

$$\dot{m}h_1 + \dot{m}_2 h_2 = \dot{Q}_{out} + \dot{m}_3 h_3$$

Combining the two relations gives

$$\dot{Q}_{out} = \dot{m}_1 h_1 + \dot{m}_2 h_2 - (\dot{m}_1 + \dot{m}_2) h_3 = \dot{m}_1 (h_1 - h_3) + \dot{m}_2 (h_2 - h_3)$$

Solving for $\dot{m}_2$ and substituting, the mass flow rate of the superheated steam is determined to be

$$\dot{m}_2 = \frac{\dot{Q}_{out} - \dot{m}_1 (h_1 - h_3)}{h_2 - h_3} = \frac{(600/60 \text{ kJ/s}) - (4 \text{ kg/s})(62.98 - 335.02) \text{ kJ/kg}}{(2870.4 - 335.02) \text{ kJ/kg}} = \mathbf{0.429\ kg/s}$$

Also,

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 = 4 + 0.429 = 4.429 \text{ kg/s}$$

(*b*) The exergy destroyed during a process can be determined from an exergy balance or directly from its definition $X_{destroyed} = T_0 S_{gen}$ where the entropy generation S_{gen} is determined from an entropy balance on an *extended system* that includes the mixing chamber and its immediate surroundings. It gives

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

$$\dot{m}_1 s_1 + \dot{m}_2 s_2 - \dot{m}_3 s_3 - \frac{\dot{Q}_{out}}{T_{b,surr}} + \dot{S}_{gen} = 0$$

$$\dot{S}_{gen} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2 + \frac{\dot{Q}_{out}}{T_0}$$

Substituting, the exergy destruction is determined to be

$$\begin{aligned} \dot{X}_{destroyed} &= T_0 \dot{S}_{gen} = T_0 \left(\dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_1 s_1 + \frac{\dot{Q}_{out}}{T_{b,surr}} \right) \\ &= (298 \text{ K})(4.429 \times 1.0756 - 0.429 \times 7.5081 - 4 \times 0.22447 + 10/298) \text{kW/K} \\ &= \mathbf{202\ kW} \end{aligned}$$

Question 8: An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 95 kPa and 27°C, and 750 kJ/kg of heat is transferred to air during the constant-volume heat-addition process. Taking into account the variation of specific heats with temperature, determine (a) the pressure and temperature at the end of the heat-addition process, (b) the net work output, (c) the thermal efficiency, and (d) the mean effective pressure for the cycle.

Solution:

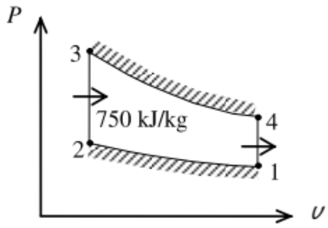
9-34 An ideal Otto cycle with air as the working fluid has a compression ratio of 8. The pressure and temperature at the end of the heat addition process, the net work output, the thermal efficiency, and the mean effective pressure for the cycle are to be determined.

Assumptions **1** The air-standard assumptions are applicable. **2** Kinetic and potential energy changes are negligible. **3** Air is an ideal gas with variable specific heats.

Properties The gas constant of air is $R = 0.287$ kJ/kg.K. The properties of air are given in Table A-17.

Analysis (*a*) Process 1-2: isentropic compression.

$$T_1 = 300\text{ K} \longrightarrow \begin{array}{l} u_1 = 214.07\text{ kJ/kg} \\ \upsilon_{r_1} = 621.2 \end{array}$$



$$\upsilon_{r_2} = \frac{\upsilon_2}{\upsilon_1}\upsilon_{r_1} = \frac{1}{r}\upsilon_{r_1} = \frac{1}{8}(621.2) = 77.65 \longrightarrow \begin{array}{l} T_2 = 673.1\text{ K} \\ u_2 = 491.2\text{ kJ/kg} \end{array}$$

$$\frac{P_2\upsilon_2}{T_2} = \frac{P_1\upsilon_1}{T_1} \longrightarrow P_2 = \frac{\upsilon_1}{\upsilon_2}\frac{T_2}{T_1}P_1 = (8)\left(\frac{673.1\text{ K}}{300\text{ K}}\right)(95\text{ kPa}) = 1705\text{ kPa}$$

Process 2-3: υ = constant heat addition.

$$q_{23,\text{in}} = u_3 - u_2 \longrightarrow u_3 = u_2 + q_{23,\text{in}} = 491.2 + 750 = 1241.2\text{ kJ/kg} \longrightarrow \begin{array}{l} T_3 = \mathbf{1539\text{ K}} \\ \upsilon_{r_3} = 6.588 \end{array}$$

$$\frac{P_3\upsilon_3}{T_3} = \frac{P_2\upsilon_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2}P_2 = \left(\frac{1539\text{ K}}{673.1\text{ K}}\right)(1705\text{ kPa}) = \mathbf{3898\text{ kPa}}$$

(*b*) Process 3-4: isentropic expansion.

$$\upsilon_{r_4} = \frac{\upsilon_1}{\upsilon_2}\upsilon_{r_3} = r\upsilon_{r_3} = (8)(6.588) = 52.70 \longrightarrow \begin{array}{l} T_4 = 774.5\text{ K} \\ u_4 = 571.69\text{ kJ/kg} \end{array}$$

Process 4-1: υ = constant heat rejection.

$$q_{\text{out}} = u_4 - u_1 = 571.69 - 214.07 = 357.62\text{ kJ/kg}$$

$$w_{\text{net,out}} = q_{\text{in}} - q_{\text{out}} = 750 - 357.62 = \mathbf{392.4\text{ kJ/kg}}$$

(*c*)
$$\eta_{\text{th}} = \frac{w_{\text{net, out}}}{q_{\text{in}}} = \frac{392.4\text{ kJ/kg}}{750\text{ kJ/kg}} = \mathbf{52.3\%}$$

(*d*)
$$\upsilon_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})}{95\text{ kPa}} = 0.906\text{ m}^3/\text{kg} = \upsilon_{\max}$$

$$\upsilon_{\min} = \upsilon_2 = \frac{\upsilon_{\max}}{r}$$

$$\text{MEP} = \frac{w_{\text{net,out}}}{\upsilon_1 - \upsilon_2} = \frac{w_{\text{net,out}}}{\upsilon_1(1-1/r)} = \frac{392.4\text{ kJ/kg}}{(0.906\text{ m}^3/\text{kg})(1-1/8)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{495.0\text{ kPa}}$$