INDIAN INSTITUTE OF TECHNOLOGY KANPUR

ESO 201A: Thermodynamics

(2023-24 I Semester)

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Tutorial 6

Question 1: Air (cp = 1.005 kJ/kg·°C) is to be preheated by hot exhaust gases in a cross-flow heat exchanger before it enters the furnace. Air enters the heat exchanger at 95 kPa and 20°C at a rate of 0.6 m3/s. The combustion gases (cp = 1.10 kJ/kg·°C) enter at 160°C at a rate of 0.95 kg/s and leave at 95°C. Determine the rate of heat transfer to the air and its outlet temperature. **(67.93 kW and 120°C)**

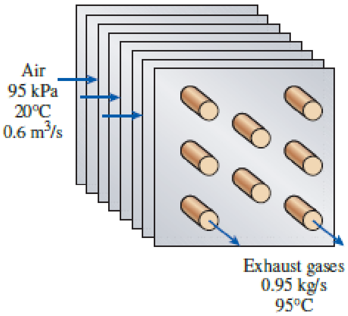


Figure 1.

Assumptions **1** Steady operating conditions exist. **2** The heat exchanger is well-insulated so that heat loss to the surroundings is negligible and thus heat transfer from the hot fluid is equal to the heat transfer to the cold fluid. **3** Changes in the kinetic and potential energies of fluid streams are negligible. **4** Fluid properties are constant.

Properties The specific heats of air and combustion gases are given to be 1.005 and 1.10 kJ/kg.°C, respectively.

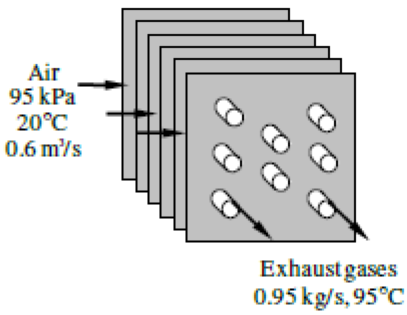
Analysis We take the exhaust pipes as the system, which is a control volume. The energy balance for this steady-flow system can be expressed in the rate form as

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

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

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

Then the rate of heat transfer from the exhaust gases becomes



$$\dot{Q} = [\dot{m}c_p(T_{in} - T_{out})]_{gas}$$
$$= (0.95 \text{ kg/s})(1.1 \text{ kJ/kg.°C})(160\text{°C} - 95\text{°C})$$
$$= \mathbf{67.93\ kW}$$

The mass flow rate of air is

$$\dot{m} = \frac{P\dot{V}}{RT} = \frac{(95 \text{ kPa})(0.6 \text{ m}^3/\text{s})}{(0.287 \text{ kPa.m}^3/\text{kg.K}) \times 293 \text{ K}} = 0.6778 \text{ kg/s}$$

Noting that heat loss by the exhaust gases is equal to the heat gain by the air, the outlet temperature of the air becomes

$$\dot{Q} = \dot{m}c_p(T_{c,\,out} - T_{c,\,in}) \longrightarrow T_{c,\,out} = T_{c,\,in} + \frac{\dot{Q}}{\dot{m}c_p} = 20\text{°C} + \frac{67.93 \text{ kW}}{(0.6778 \text{ kg/s})(1.005 \text{ kJ/kg.°C})} = \mathbf{120°C}$$

Question2: An air-conditioning system involves the mixing of cold air and warm outdoor air before the mixture is routed to the conditioned room in steady operation. Cold air enters the mixing chamber at 7°C and 105 kPa at a rate of 0.55 m3/s while warm air enters at 34°C and 105 kPa. The air leaves the room at 24°C. The ratio of the mass flow rates of the hot to cold airstreams is 1.6. Using variable specific heats, determine (a) the mixture temperature at the inlet of the room and (b) the rate of heat gain of the room. **(23.6ºC and 0.691 kW)**

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

Mass balance:

$$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{system}^{\nearrow 0 \text{ (steady)}} = 0 \rightarrow \dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 + 1.6\dot{m}_1 = \dot{m}_3 = 2.6\dot{m}_1 \quad \text{since} \quad \dot{m}_2 = 1.6\dot{m}_1$$

Energy balance:

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

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

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad (\text{since } \dot{Q} \cong \dot{W} \cong \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

Combining the two gives

$$\dot{m}_1 h_1 + 1.6\dot{m}_1 h_2 = 2.6\dot{m}_1 h_3 \quad or \quad h_3 = (h_1 + 1.6h_2)/2.6$$

Substituting,

$$h_3 = (280.13 + 1.6 \times 307.23)/2.6 = 296.81 \text{ kJ/kg}$$ **Table A17 (Interpolating)**

From air table at this enthalpy, the mixture temperature is

$$T_3 = T_{@ h = 296.81 \text{ kJ/kg}} = 296.6 \text{ K} = \mathbf{23.6°C}$$

(*b*) The mass flow rates are determined as follows

$$v_1 = \frac{RT_1}{P} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(7 + 273 \text{ K})}{105 \text{ kPa}} = 0.7654 \text{ m}^3/\text{kg}$$

$$\dot{m}_1 = \frac{\dot{V}_1}{v_1} = \frac{0.55 \text{ m}^3/\text{s}}{0.7654 \text{ m}^3/\text{kg}} = 0.7186 \text{ kg/s}$$

$$\dot{m}_3 = 2.6\dot{m}_1 = 2.6(0.7186 \text{ kg/s}) = 1.868 \text{ kg/s}$$

The rate of heat gain of the room is determined from

$$\dot{Q}_{gain} = \dot{m}_3(h_{room} - h_3) = (1.868 \text{ kg/s})(297.18 - 296.81) \text{ kJ/kg} = \mathbf{0.691 \text{ kW}}$$

Therefore, the room gains heat at a rate of 0.691 kW.

Question 3: A 2-m3 rigid insulated tank initially containing saturated water vapor at 1 MPa is connected through a valve to a supply line that carries steam at 400°C. Now the valve is opened, and steam is allowed to flow slowly into the tank until the pressure in the tank rises to 2 MPa. At this instant the tank temperature is measured to be 300°C. Determine the mass of the steam that has entered and the pressure of the steam in the supply line. **(5.645 kg and 8931 kPa)**

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 entering the tank remains constant. **2** Kinetic and potential energies are negligible.

Properties The initial and final properties of steam in the tank are (Tables A-5 and A-6)

$$\left.\begin{array}{l} P_1 = 1\text{ MPa} \\ x_1 = 1\text{ (sat. vap.)} \end{array}\right\} \begin{array}{l} v_1 = 0.19436\text{ m}^3\text{/kg} \\ u_1 = 2582.8\text{ kJ/kg} \end{array}$$

$$\left.\begin{array}{l} P_2 = 2\text{ MPa} \\ T_1 = 300°\text{C} \end{array}\right\} \begin{array}{l} v_2 = 0.12551\text{ m}^3\text{/kg} \\ u_2 = 2773.2\text{ kJ/kg} \end{array}$$

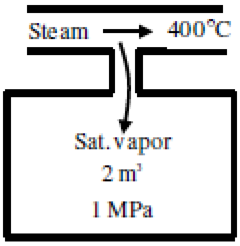
Analysis We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the microscopic energies of flowing and nonflowing fluids are represented by enthalpy h and internal energy u, respectively, the mass and energy balances for this uniform-flow system can be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

Mass balance: $m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \quad \rightarrow \quad m_i = m_2 - m_1$

Energy balance:

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

$$m_i h_i = m_2 u_2 - m_1 u_1 \quad (\text{since } Q \cong ke \cong pe \cong 0)$$



The initial and final masses and the mass that has entered are

$$m_1 = \frac{V}{v_1} = \frac{2\text{ m}^3}{0.19436\text{ m}^3\text{/kg}} = 10.29\text{ kg}$$

$$m_2 = \frac{V}{v_2} = \frac{2\text{ m}^3}{0.12551\text{ m}^3\text{/kg}} = 15.94\text{ kg}$$

$$m_i = m_2 - m_1 = 15.94 - 10.29 = \mathbf{5.645\text{ kg}}$$

Substituting,

$$(5.645\text{ kg})h_i = (15.94\text{ kg})(2773.2\text{ kJ/kg}) - (10.29\text{ kg})(2582.8\text{ kJ/kg}) \longrightarrow h_i = 3122.72\text{ kJ/kg}$$

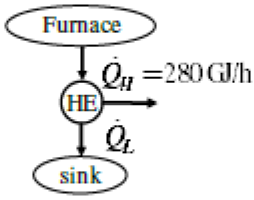
$h_i = 3122.72$ kJ/kg
$T_i = 400$ ºC
$P_i = 8.81$ MPa (From Table A-6)

Question 4: A steam power plant receives heat from a furnace at a rate of 280 GJ/h. Heat losses to the surrounding air from the steam as it passes through the pipes and other components are estimated to be about 8 GJ/h. If the waste heat is transferred to the cooling water at a rate of 165 GJ/h, determine (a) net power output and (b) the thermal efficiency of this power plant. **(29.7 MW and 38.2%)**

Assumptions **1** The plant operates steadily. **2** Heat losses from the working fluid at the pipes and other components are taken into consideration.

Analysis (*a*) The total heat rejected by this power plant is

$$\dot{Q}_L = 165 + 8 = 173 \text{ GJ/h}$$



Then the net power output of the plant becomes

$$\dot{W}_{\text{net,out}} = \dot{Q}_H - \dot{Q}_L = 280 - 173 = 107 \text{ GJ/h} = \mathbf{29.7\ MW}$$

(*b*) The thermal efficiency of the plant is determined from its definition,

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net, out}}}{\dot{Q}_H} = \frac{107 \text{ GJ/h}}{280 \text{ GJ/h}} = 0.382 = \mathbf{38.2\%}$$

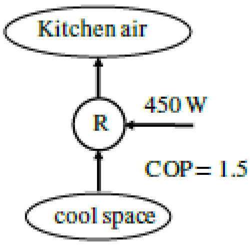
Question 5: A household refrigerator that has a power input of 450 W and a COP of 1.5 is to cool 5 large watermelons, 10 kg each, to 8°C. If the watermelons are initially at 28°C, determine how long it will take for the refrigerator to cool them. The watermelons can be treated as water whose specific heat is 4.2 kJ/kg·°C. Is your answer realistic or optimistic? **(104 min)**

Assumptions **1** The refrigerator operates steadily. **2** The heat gain of the refrigerator through its walls, door, etc. is negligible. **3** The watermelons are the only items in the refrigerator to be cooled.

Properties The specific heat of watermelons is given to be $c = 4.2$ kJ/kg°C.

Analysis The total amount of heat that needs to be removed from the watermelons is

$$Q_L = (mc\Delta T)_{\text{watermelons}} = 5 \times (10 \text{ kg})(4.2 \text{ kJ/kg}\cdot°\text{C})(28 - 8)°\text{C} = 4200 \text{ kJ}$$



The rate at which this refrigerator removes heat is

$$\dot{Q}_L = (\text{COP}_\text{R})(\dot{W}_{\text{net, in}}) = (1.5)(0.45 \text{ kW}) = 0.675 \text{ kW}$$

That is, this refrigerator can remove 0.675 kJ of heat per second. Thus the time required to remove 4200 kJ of heat is

$$\Delta t = \frac{Q_L}{\dot{Q}_L} = \frac{4200 \text{ kJ}}{0.675 \text{ kJ/s}} = 6222 \text{ s} = \mathbf{104\ min}$$

This answer is optimistic since the refrigerated space will gain some heat during this process from the surrounding air, which will increase the work load. Thus, in reality, it will take longer to cool the watermelons.

Question 6: A heat pump operates on a Carnot heat pump cycle with a COP of 12.5. It keeps a space at 24°C by consuming 2.15 kW of power. Determine the temperature of the reservoir from which the heat is absorbed and the heating load provided by the heat pump.

Assumptions The heat pump operates steadily.

Analysis The temperature of the low-temperature reservoir is

$$\text{COP}_{\text{HP,max}} = \frac{T_H}{T_H - T_L} \longrightarrow 12.5 = \frac{297 \text{ K}}{(297 - T_L)\text{ K}} \longrightarrow T_L = \mathbf{273\ K}$$

The heating load is

$$\text{COP}_{\text{HP,max}} = \frac{\dot{Q}_H}{\dot{W}_{in}} \longrightarrow 12.5 = \frac{\dot{Q}_H}{2.15 \text{ kW}} \longrightarrow \dot{Q}_H = \mathbf{26.9\ kW}$$

Question 7: A 30-kg iron block and a 40-kg copper block, both initially at 80°C, are dropped into a large lake at 15°C. Thermal equilibrium is established after a while as a result of heat transfer between the blocks and the lake water. Determine the total entropy change for this process. **(0.642 kJ/K)**

Assumptions **1** The water, the iron block and the copper block are incompressible substances with constant specific heats at room temperature. **2** Kinetic and potential energies are negligible.

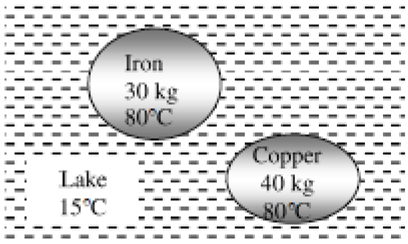
Properties The specific heats of iron and copper at room temperature are $c_{\text{iron}} = 0.45$ kJ/kg.°C and $c_{\text{copper}} = 0.386$ kJ/kg.°C (Table A-3).

Analysis The thermal-energy capacity of the lake is very large, and thus the temperatures of both the iron and the copper blocks will drop to the lake temperature (15°C) when the thermal equilibrium is established. Then the entropy changes of the blocks become

$$\Delta S_{\text{iron}} = mc_{\text{avg}} \ln\left(\frac{T_2}{T_1}\right) = (30 \text{ kg})(0.45 \text{ kJ/kg}\cdot\text{K})\ln\left(\frac{288 \text{ K}}{353 \text{ K}}\right) = -2.746 \text{ kJ/K}$$

$$\Delta S_{\text{copper}} = mc_{\text{avg}} \ln\left(\frac{T_2}{T_1}\right) = (40 \text{ kg})(0.386 \text{ kJ/kg}\cdot\text{K})\ln\left(\frac{288 \text{ K}}{353 \text{ K}}\right) = -3.141 \text{ kJ/K}$$

We take both the iron and the copper blocks, as the *system*. This is a *closed system* since no mass crosses the system boundary during the process. The energy balance for this system can be expressed as



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

$$-Q_{\text{out}} = \Delta U = \Delta U_{\text{iron}} + \Delta U_{\text{copper}}$$

or,

$$Q_{\text{out}} = [mc(T_1 - T_2)]_{\text{iron}} + [mc(T_1 - T_2)]_{\text{copper}}$$

Substituting,

$$Q_{\text{out}} = (30 \text{ kg})(0.45 \text{ kJ/kg}\cdot\text{K})(353 - 288)\text{K} + (40 \text{ kg})(0.386 \text{ kJ/kg}\cdot\text{K})(353 - 288)\text{K}$$
$$= 1881 \text{ kJ}$$

Thus,

$$\Delta S_{\text{lake}} = \frac{Q_{\text{lake, in}}}{T_{\text{lake}}} = \frac{1881 \text{ kJ}}{288 \text{ K}} = 6.528 \text{ kJ/K}$$

Then the total entropy change for this process is

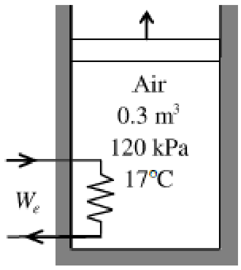
$$\Delta S_{\text{total}} = \Delta S_{\text{iron}} + \Delta S_{\text{copper}} + \Delta S_{\text{lake}} = (-2.746) + (-3.141) + 6.528 = \mathbf{0.642\ kJ/K}$$

Question 8: An insulated piston–cylinder device initially contains 300 L of air at 120 kPa and 17°C. Air is now heated for 15 min by a 200-W resistance heater placed inside the cylinder. The pressure of air is kept constant during this process. Determine the entropy change of air, assuming (a) constant specific heats and (b) variable specific heats. **(0.387 kJ/K and 0.387 kJ/K)**

Assumptions At specified conditions, air can be treated as an ideal gas.

Properties The gas constant of air is $R = 0.287$ kJ/kg.K (Table A-1).

Analysis The mass of the air and the electrical work done during this process are



$$m = \frac{P_1 V_1}{RT_1} = \frac{(120\ \text{kPa})(0.3\ \text{m}^3)}{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(290\ \text{K})} = 0.4325\ \text{kg}$$

$$W_{\text{e,in}} = \dot{W}_{\text{e,in}}\Delta t = (0.2\ \text{kJ/s})(15\times 60\ \text{s}) = 180\ \text{kJ}$$

The energy balance for this stationary closed system can be expressed as

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

$$W_{\text{e, in}} - W_{\text{b, out}} = \Delta U \longrightarrow W_{\text{e, in}} = m(h_2 - h_1) \cong c_p(T_2 - T_1)$$

since $\Delta U + W_b = \Delta H$ during a constant pressure quasi-equilibrium process.

(a) Using a constant c_p value at the anticipated average temperature of 450 K, the final temperature becomes

Thus,

$$T_2 = T_1 + \frac{W_{\text{e, in}}}{mc_p} = 290\ \text{K} + \frac{180\ \text{kJ}}{(0.4325\ \text{kg})(1.02\ \text{kJ/kg}\cdot\text{K})} = 698\ \text{K}$$

Then the entropy change becomes

$$\Delta S_{\text{sys}} = m(s_2 - s_1) = m\left(c_{p,\text{ avg}} \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}^{\nearrow 0}\right) = mc_{p,\text{ avg}} \ln\frac{T_2}{T_1}$$

$$= (0.4325\ \text{kg})(1.020\ \text{kJ/kg}\cdot\text{K})\ \ln\left(\frac{698\ \text{K}}{290\ \text{K}}\right) = \mathbf{0.387\ kJ/K}$$

(b) Assuming variable specific heats,

$$W_{\text{e,in}} = m(h_2 - h_1) \longrightarrow h_2 = h_1 + \frac{W_{\text{e,in}}}{m} = 290.16\ \text{kJ/kg} + \frac{180\ \text{kJ}}{0.4325\ \text{kg}} = 706.34\ \text{kJ/kg}$$

From the air table (Table A-17), we read $s_2^\circ = 2.5628$ kJ/kg·K corresponding to this h_2 value. Then,

$$\Delta S_{\text{sys}} = m\left(s_2^\circ - s_1^\circ + R\ln\frac{P_2}{P_1}^{\nearrow 0}\right) = m(s_2^\circ - s_1^\circ) = (0.4325\ \text{kg})(2.5628 - 1.66802)\ \text{kJ/kg}\cdot\text{K} = \mathbf{0.387\ kJ/K}$$