Thermodynamics (ME2121)
Tutorial 3

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Summary of Chapters 5&6

* The second law of Thermodynamics (P253, P262)

Kelvin-Planck Statement : It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

Clausius Statement: It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

* Principles of heat engines, Refrigerators and heat pumps (P257-260)

Heat engine: $$\eta_{th} = \frac{W_{net.out}}{Q_{in}}$$

Refrigerator: $$COP_R = \frac{Q_L}{W_{net.in}} = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L}$$

Heat pump: $$COP_{HP} = \frac{Q_H}{W_{net.in}} = \frac{Q_H}{Q_H - Q_L} = \frac{T_H}{T_H - T_L}$$

Summary of Chapters 5&6

* Reversible and irreversible processes (P265-269)

  Reversible process is a process that can be reversed without leaving any trace on the surroundings

  Typical irreversibilities:

  - Friction
  - Unrestrained expansion of a gas
  - Heat transfer through a finite difference
  - Mixing
  - Chemical reactions, etc.

* The Carnot cycle and its principles

  Reversible isothermal expansion

  Reversible adiabatic expansion (Isentropic)

  Reversible isothermal compression

  Reversible adiabatic expansion (Isentropic)

Summary of Chapters 5&6

* Definition of Entropy $dS = \left(\frac{\delta Q}{T}\right)_{\text{int},rev}$ a measure of molecular disorder or randomness of a system and it can be created but cannot be destroyed.

* Increases of entropy principle: The entropy of an isolated system during a process always increases or, in the limiting case of a reversible process, remains constant $S_{gen} \geq 0$

* property diagrams involving entropy (h-s, t-s) (p314), The Tds relations (p320)

  Tds = du + Pdv (Gibs equation)

  Tds = dh –vdP

* Entropy change of liquids and solids (small temperature change)

$$ds = \frac{du}{T} = \frac{CdT}{T} \Rightarrow s_2 - s_1 = C_{av} \ln \frac{T_2}{T_1}$$

* The entropy change of ideal gases (small temperature change)

$$ds = \frac{du}{T} + \frac{Pdv}{T} = C_v \frac{dT}{T} + R\frac{dv}{v} \Rightarrow s_2 - s_1 = C_{v,av} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

$$ds = \frac{dh}{T} + \frac{vdv}{T} P = C_p \frac{dT}{T} + R\frac{dP}{P} \Rightarrow s_2 - s_1 = C_{p,av} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

Summary of Chapters 5&6

* Reversible steady-flow work

$$w_{rev,in} = \int v dp + \Delta ke + \Delta pe$$

v should be smaller for work-consuming devices---pumps, compressors, etc.

v should be greater for work-producing devices---steam turbines, etc.

* Calculation of the compressor work (P337)

* Isentropic processes (internally irreversible, adiabatic, const Cp and Cv) (p313)

Isentropic process $Pv^k = const$

Polytropic process $Pv^n = const$

Isothermal process Pv = const

* Isentropic (or adiabatic) efficiencies of steady-flow devices (turbines, compressors and pumps, nozzles)

* Entropy balance (P347)

$$\underbrace{S_{in} - S_{out}}_{\text{Net entropy transfer by heat and mass}} + \underbrace{S_{gen}}_{\text{Entropy Generation}} = \underbrace{\Delta S_{system}}_{\text{Change in entropy}} = S_2 - S_1$$

The entropy change of a system during a process is equal to the net entropy transfer through the system and the entropy generated within the system.

Summary of Chapters 5&6

*Entropy transfer by Heat transfer

$$S_{heat} = \frac{Q}{T} (T = const)$$

$$S_{heat} = \int_1^2 \frac{Q}{T} \cong \sum \frac{Q_k}{T_k}$$

*Entropy transfer by Mass flow

$$S_{mass} = ms$$

$$S_{mass} = \int_{\Delta t} \dot{S}_{mass} dt$$

$$\dot{S}_{mass} \int_A s\rho V dA$$

* Entropy change for a closed system and its surroundings

$$S_{gen} = \sum \Delta S = \Delta S_{sys} + \Delta S_{sur}$$

Since any closed system and its surroundings can be treated as an adiabatic system in which the entropy generation equals the entropy change of the adiabatic system

Summary of Chapters 5&6

* Entropy balance for a closed system

$$\sum \frac{Q_k}{T_k} + S_{gen} = \Delta S_{sys}$$

* Entropy balance for a control volume

$$\sum \frac{Q_k}{T_k} + \sum m_i s_i - \sum m_e s_e + S_{gen} = \Delta S_{sys}$$

$$\Delta S_{sys} = S_{final} - S_{initial} = S_2 - S_1$$

* Entropy change for a general steady flow process

$$\dot{S}_{gen} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k} (\sin ce \Delta \dot{S}_{sys} = 0)$$

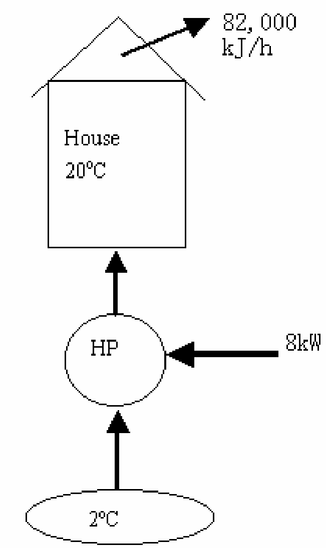
Typical processes operated steadily in such devices as turbines, compressors, nozzles, diffusers, heat exchangers, pipes, ducts, etc.

Problem 1

Problem C1 (Problem 5-107)

A Carnot heat pump is to be used to heat a house and maintain it at 20°C in winter. On a day when the average outdoor temperature remains at about 2°C, the house is estimated to lose heat at a rate of 82,200kJ/h. If the heat pump consumes 8kW of power while operating, determine (a) how long the heat pump ran on that day; (b) the total heating costs, assuming an average price of 8.5cents/kWh for electricity; and (c) the heating cost for the same day if resistance heating is used instead of a heat pump

Solution



(a) The coefficient of performance of this Carnot heat pump depends on the temperature limits in the cycle only, and is determined from

$$COP_{HP,rev} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(2+273)/(20+273)} = 16.3$$

The amount of heat the house lost that day is

$$Q_H = \dot{Q}_H(1day) = (82000kJ/h)(24h) = 1.968\times10^6\,kJ$$

Then the required work input to this Carnot heat pump is determined from the definition of the coefficient of performance to be

$$W_{net,in} = \frac{Q_H}{COP_{HP}} = \frac{1.968\times10^6\,kJ}{16.3} = 120736kJ$$

Problem 1

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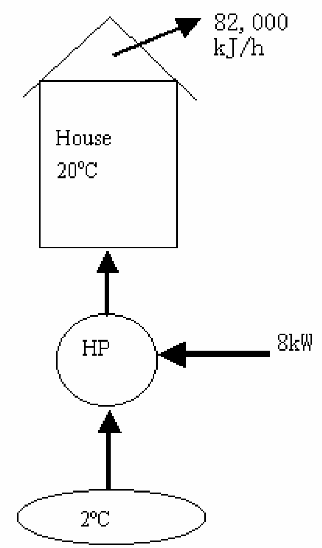


Solution

Thus the length of time the heat pump ran on that day is

$$\Delta t = \frac{W_{net,in}}{\dot{W}_{net,in}} = \frac{120736kJ}{8kJ/s} = 15092s = 4.19h$$

(b) The total heating cost on that day is

$$Cost = W \times price = (\dot{W}_{net,in} \times \Delta t)(price) = (8kW)(4.19h)(0.085\$/kWh) = \$2.85$$

(c) If resistance heating were used, the entire heating load on that day would have to be met by electrical energy. Therefore, the heating system would consume 1968000kJ of thermal energy supplied by electricity that would cost

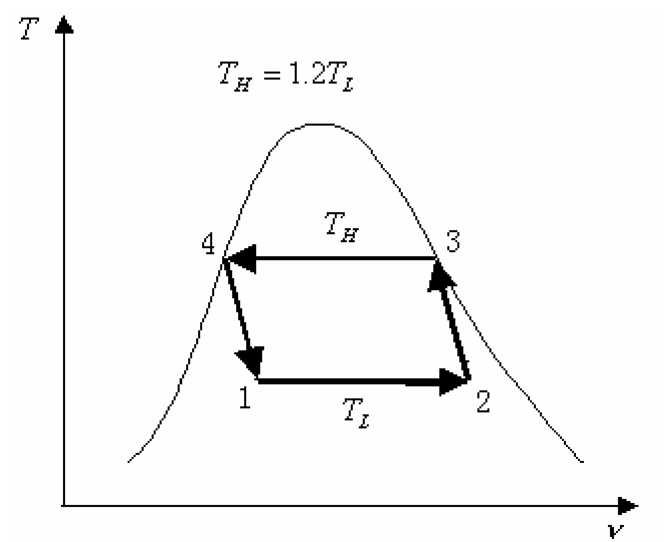
$$New - \cos t = Q_H \times price = (1.968 \times 10^6)(\frac{1kWh}{3600kJ})(0.085\$/kWh) = \$46.47$$

Question: what is the scenario for the energy-saving in heat-pump heating system?

Problem 2

Problem C2 (Problem 5-129)
Consider a Carnot refrigeration cycle executed in a closed system in the saturated liquid-vapor mixture region using 0.96kg of refrigerant-134a as the working fluid. It is known that the maximum absolute temperature is 1.2 times the minimum absolute temperature, and the net work input to the cycle is 22kJ. If the refrigerant changes from saturated vapor to saturated liquid during the heat rejection process, determine the minimum pressure in the cycle.

<u>**Solution**</u>



<u>**Assumptions:**</u> The refrigeration cycle is said to operate on the closed Carnot cycle, which is totally reversible.

The coefficient of performance of the cycle is

$$COP_R = \frac{1}{T_H/T_L - 1} = \frac{1}{1.2-1} = 5.0$$

Also,

$$COP_R = \frac{Q_L}{W_{in}} \rightarrow Q_L = COP_R \times W_{in} = (5)(22kJ) = 110kJ$$

Thus

$$Q_H = Q_L + W = 110 + 22 = 132(kJ)$$

Problem 2

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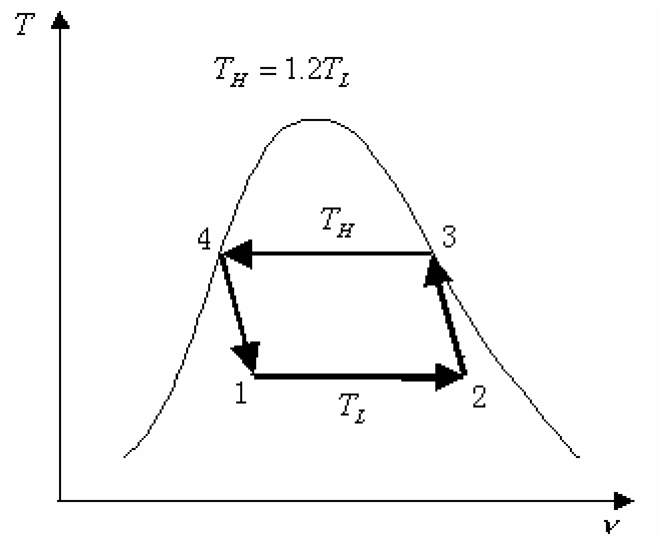
Solution



and $$Q_h = m(h_g - h_f)_{@T_H} = mh_{fg@T_H}$$

$$h_{fg@T_H} = \frac{Q_h}{m} = \frac{132kJ}{0.96kg} = 137.5kJ/kg$$

Since the enthalpy of vaporization h_{fg} at a given T or P represents the amount of heat transfer per unit mass as substance is converted from saturated liquid to saturated vapor at that T or P. Therefore, T_H is the temperature that corresponds to the h_{fg} value of 137.5kJ/kg, and is determined from the **Table A-11** to be

$$T_H \cong 61^o C = 334K$$

Problem 2

Problem C2 (Problem 5-129)
Consider a Carnot refrigeration cycle executed in a closed system in the saturated liquid-vapor mixture region using 0.96kg of refrigerant-134a as the working fluid. It is known that the maximum absolute temperature is 1.2 times the minimum absolute temperature, and the net work input to the cycle is 22kJ. If the refrigerant changes from saturated vapor to saturated liquid during the heat rejection process, determine the minimum pressure in the cycle.

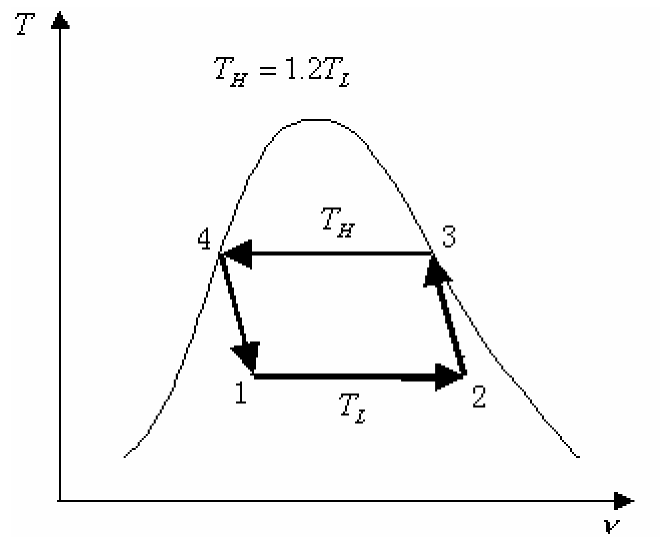
<u>**Solution**</u>

Then,

$$T_L = \frac{T_H}{1.2} = \frac{334K}{1.2} = 278.3K \cong 5.3^o C$$

Therefore,

$$P_{\min} = P_{sat @ 5.3^o C} = 0.354 MPa$$



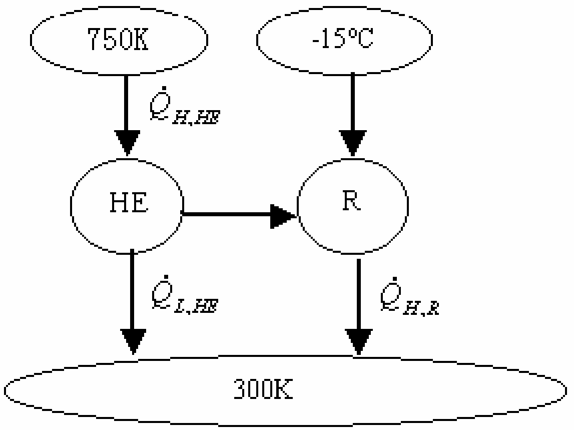
Question: could we do calculation as follows and then read off pressure from **Table A-12**?

$$Q_L = m(h_g - h_f)_{@T_L} = mh_{fg @ T_L}$$

$$h_{fg @ T_L} = \frac{Q_L}{m} = \frac{110kJ}{0.96kg} = ?\, kJ / kg$$

Problem 3

Problem C3 (Problem 5-134)
A Carnot heat engine receives heat at 750K and rejects the waste heat to the environment at 300K. the entire work output of the heat engine is used to drive a Carnot refrigerator that removes heat from the cooled space at –15ºC at a rate of 400kJ/min and rejects it to the same environment at 300K. Determine (a) the rate of heat supplied to the heat engine and (b) the total rate of heat rejection to environment.



Solution

(a) The coefficient of performance of the Carnot refrigerator is

$$COP_{R,C} = \frac{1}{T_H / T_L - 1} = \frac{1}{(300K)/(258K) - 1} = 6.14$$

Then power input to the refrigerator becomes

$$W_{net,in} = \frac{\dot{Q}_L}{COP_{R,C}} = \frac{400kJ/\min}{6.14} = 65.1kJ/\min$$

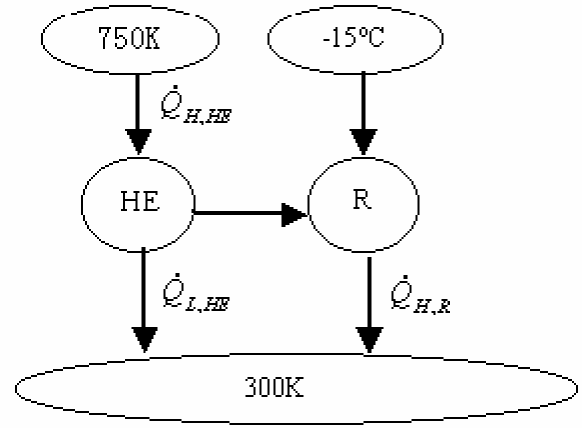
which is equal to the power output of the heat engine, $\dot{W}_{net,out}$

The thermal efficiency of the Carnot engine is determined from

$$\eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{300K}{750K} = 0.6$$

Problem 3

Solution



Then the rate of heat input to this engine is determined from the definition of the thermal efficiency to be

$$\dot{Q}_{H,HE} = \frac{\dot{W}_{net,out}}{\eta_{th,HE}} = \frac{65.1kJ/\min}{0.60} = 108.5kJ/\min$$

(b) The total rate of heat rejection to the ambient air is the sum of the heat rejected by the heat engine ($Q_{L,HE}$) and the heat discarded by the refrigerator ($\dot{Q}_{H,R}$),

$$\dot{Q}_{L,HE} = \dot{Q}_{H,HE} - \dot{W}_{net,out} = 108.5 - 65.1 = 43.4(kJ/\min)$$

$$\dot{Q}_{H,R} = \dot{Q}_{L,R} + \dot{W}_{net,in} = 400 + 65.1 = 465.1(kJ/\min)$$

$$\dot{Q}_{Ambient} = \dot{Q}_{L,HE} + \dot{Q}_{H,R} = 43.4 + 465.1 = 508.5(kJ/\min)$$

Questions: May we take the HE and Refrigerator as a combined system to calculate the total heat rejection, which is equal to the sum of $Q_{H,HE}$ and $Q_{L,R}$? Does the work interaction between HE and R affect the calculation in this case? Does it violate the first and second laws of Thermodynamics?

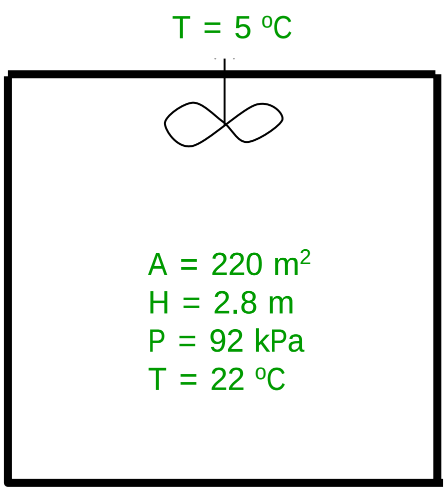
Problem 4

Problem C4 (Problem 5-155)
The kitchen, bath and other ventilation fans in a house should be used sparingly since these fans can discharge a houseful of warmed or cooled air in just one hour. Consider a 200m^2 house whose ceiling height is 2.8m. The house is heated by a 96 percent efficient gas heater and is maintained at 22^{o}C and 92kPa. If the unit cost of natural gas is \$0.60/therm (1therm=105500kJ), determine the cost of energy "vented out" by the fans in 1hr. Assume the average outdoor temperature during the heating season to be 5^{o}C.

Solution:

Assumptions:

(1) Steady operating conditions exist
(2) The house is maintained at 22^{o}C and 92kPa at all times
(3) The infiltrating air is heated to 22^{o}C before it is vented out
(4) Air is an ideal gas with constant specific heats at room temperature
(5) The volume occupied by the people, furniture, etc., is negligible



Properties:
The gas constant of air is $R = 0.287 kPa.m^3 / kg.K$ **(Table A-1)**

The specific heat of air at room temperature is $C_p = 1.0 kJ / kg.K$ **(Table A-2a)**

Problem 4

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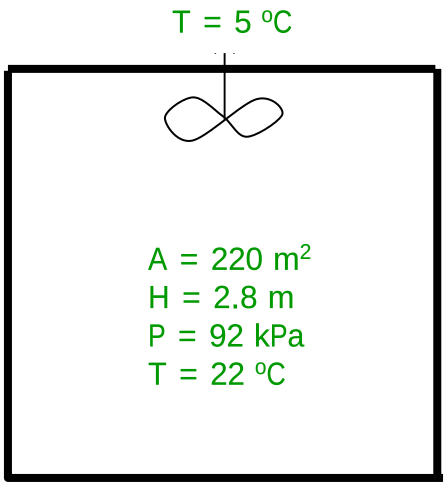

Solution:

The density of air at the indoor conditions of 92kPa and 22^{o}C is

$$\rho_0 = \frac{P_0}{RT_0} = \frac{92kPa}{(0.287kPa.m^3/kg.K)(22+273)} = 1.087kg/m^3$$

Noting that the interior volume of the house is $200 \times 2.8 = 560m^3$

the mass flow rate of air vented out becomes

$$\dot{m}_{air} = \rho \dot{V}_{air}/t = (1.087kg/m^3)(560m^3)/(1hr) = 608.7kg/h = 0.169kg/s$$

Noting that the indoor air vented out at 22^{o}C is replaced by infiltrating outdoor air at 5^{o}C, this corresponds to energy loss at a rate of

$$\dot{Q}_{loss,\,fan} = \dot{m}_{air}(h_{indoors} - h_{outdoors}) = \dot{m}_{air} C_P (T_{indoors} - T_{outdoors})$$

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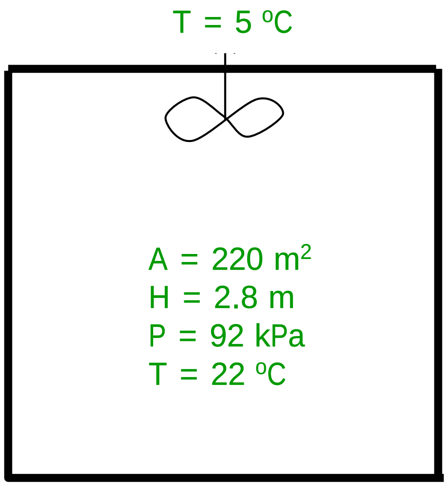


Solution:

$$= (0.169 kg/s)(1.0 kJ/kg.K)(22^o C - 5^o C) = 2.874 kJ/s = 2.874 kW$$

Then the amount and cost of the heat "vented out" per hour becomes

$$Fuel - Energy - Loss = \dot{Q}_{loss,\, fan} \Delta t / \eta_{furnace} = (2.874 kW)(1h)/0.96$$

$$= 3 kWh$$

$$Money - loss = (Fuel - Energy - Loss)(unit - \cos t - of \ - energy)$$

$$= (3 kWh/hr)(\$0.60/therm)(\frac{1 therm}{29.3 kWh}) = \$0.614/hr$$

Problem 5

Problem C5 (Problem 6-122)
An ordinary egg can be approximated as a 5.5 cm diameter sphere. The egg is initially at a uniform temperature of 8 °C and is dropped into boiling water at 97 °C. Taking the properties of the egg to be ρ = 1020 kg/m^3 and Cp = 3.32 kJ/(kg °C), determine how much heat is transferred to the egg by the time the average temperature of the egg rises to 70°C and the amount of entropy generation associated with this heat transfer process.

Solution:

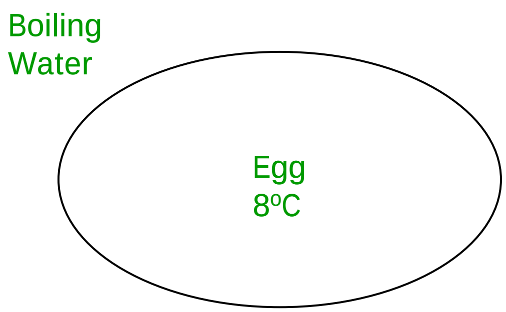
Assumptions

1. The egg is spherical in shape with a radius of 5.5cm.
2. The thermal properties of the egg are constant.
3. Energy absorption or release associated with any chemical and/or phase changes within the egg is negligible.
4. There are no changes in kinetic and potential energies.

Properties

The density and specific heat of the egg are given to be

$$\rho = 1020 kg/m^3 \quad \text{and} \quad c_p = 3.32 kJ/kg \cdot {}^o C$$



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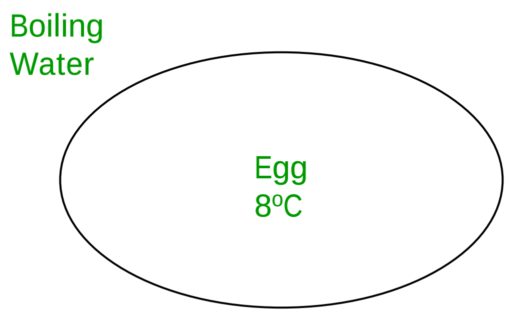
Analysis

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

Energy balance: $$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer By heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, Potential, etc. energies}}$$



$$Q_{in} = \Delta U_{egg} = m(u_2 - u_1) = mC_V(T_2 - T_1)$$

Then the mass of the egg and the amount of heat transfer become

$$m = \rho V = \rho \frac{\pi D^3}{6} = (1020 kg/m^3)\frac{\pi(0.055 m^3)}{6} = 0.0889 kg$$

$$Q_{in} = \Delta U_{egg} = m(u_2 - u_1) = mC_p(T_2 - T_1) = (0.0899 kg)(3.32 kJ/kg\cdot^o C)(70-8)^o C$$

Problem 5

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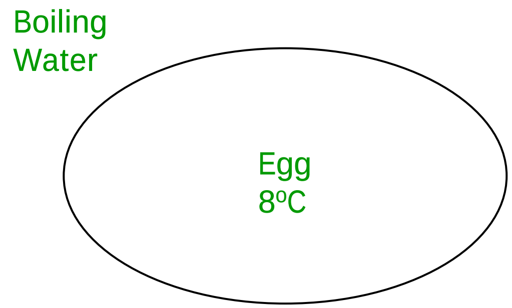
Solution:

We again take a single egg as the system. The entropy generated during this process can be determined by applying an entropy balance on an extended system that includes the egg and its immediate surroundings so that the boundary temperature of the extended system is at 97 °C at all times:

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



$$\frac{Q_{in}}{T_b} + S_{gen} = \Delta S_{system} \rightarrow S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system}$$

where

$$\Delta S_{system} = m(s_2 - s_1) = mC_{av} \ln\frac{T_2}{T_1} = (0.0889kg)(3.32kJ/kg \cdot K)\ln\frac{70+273}{8+273} = 0.0588kJ/K$$

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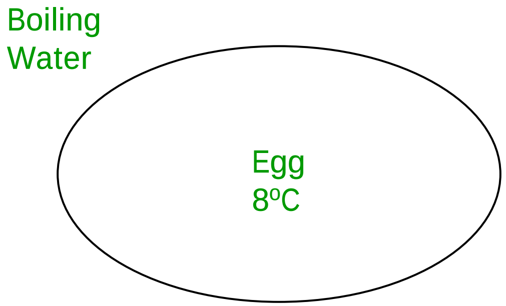
Solution:

Substituting,

$$S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system} = -\frac{18.3kJ}{370K} + 0.0588kJ/K = 0.00961kJ/K \quad \text{(per egg)}$$



Problem 6

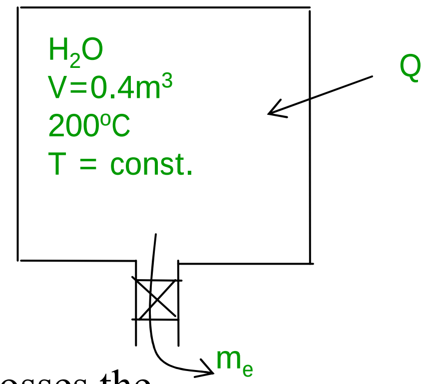
Problem C6 (Problem 6-133)

A 0.4m^3 rigid tank is filled with saturated liquid water at 200 ^oC. A valve at the bottom of the tank is now opened, and one-half of the total mass is withdrawn from the tank in liquid form. Heat is transferred to water from a source at 250 ^oC 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.

Solution:

Assumptions

1. This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as 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).
5. No water evaporates during discharging.



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

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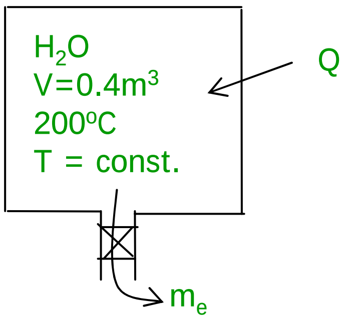
Solution:



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

Energy balance: $$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer By heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic, Potential, etc. energies}}$$

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

Properties

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

$$\left.\begin{array}{l} T_1 = 200^o C \\ sat.liquid \end{array}\right\} \Rightarrow \begin{cases} v_1 = v_{f@200^o C} = 0.001157 m^3/kg \\ u_2 = u_{f@200^o C} = 850.65 kJ/kg \\ s_1 = s_{f@200^o C} = 2.3309 kJ/kg \cdot K \end{cases}$$

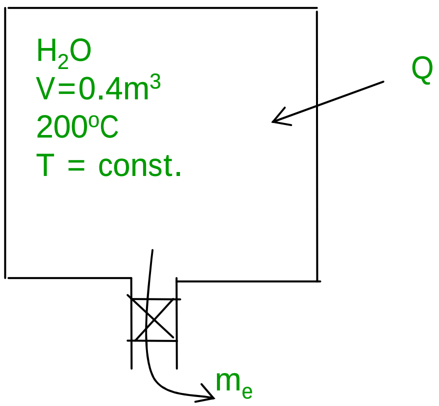
$$\left.\begin{array}{l} T_e = 200^o C \\ sat.liquid \end{array}\right\} \Rightarrow \begin{cases} h_e = h_{f@200^o C} = 852.45 kJ/kg \\ s_e = s_{f@200^o C} = 2.3309 kJ/kg \cdot K \end{cases}$$

Problem 6

Problem C6 (Problem 6-133)

A $0.4m^3$ rigid tank is filled with saturated liquid water at 200 ^oC. A valve at the bottom of the tank is now opened, and one-half of the total mass is withdrawn from the tank in liquid form. Heat is transferred to water from a source at 250 ^oC 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.

Solution:



The initial and the final masses in the tank are

$$m_1 = \frac{V}{v_1} = \frac{0.4m^3}{0.001157m^3/kg} = 345.72kg$$

$$m_2 = \frac{1}{2}m_1 = \frac{1}{2}(345.72kg) = 172.86kg = m_e$$

Now we determine the final internal energy and entropy,

$$v_2 = \frac{V}{m_2} = \frac{0.4m^3}{172.86kg} = 0.002314m^3/kg$$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.002314 - 0.001157}{0.12736 - 0.001157} = 0.00917$$

Problem 6

Problem C6 (Problem 6-133)

A 0.4m^3 rigid tank is filled with saturated liquid water at 200 ^oC. A valve at the bottom of the tank is now opened, and one-half of the total mass is withdrawn from the tank in liquid form. Heat is transferred to water from a source at 250 ^oC 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.

Solution:

$$\left.\begin{array}{l} T_2 = 200^o C \\ x_2 = 0.00917 \end{array}\right\} \Rightarrow \begin{cases} u_2 = u_f + x_2 u_{fg} = 850.65 + (0.00917)(1744.7) = 866.65 kJ/kg \\ s_2 = s_f + x_2 s_{fg} = 2.3309 + (0.00917)(1.1014) = 2.3685 kJ/kg \cdot K \end{cases}$$

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

$$\begin{aligned} Q_{in} &= m_e h_e + m_2 u_2 - m_1 u_1 \\ &= (172.86kg)(852.4kJ/kg) + (172.96kJ/kg)(866.65kJ/kg) - (345.72kg)(850.65kJ/kg) \\ &= 3077 kJ \end{aligned}$$

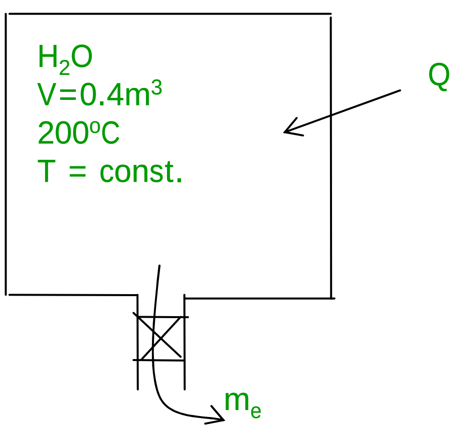
(b) The total entropy generation is determined by considering a combined system that includes the tank and the heat source. Noting that no heat crosses the boundaries of this combined system and no mass enters, the entropy balance for it can be expressed as

Problem 6

Problem C6 (Problem 6-133)

A 0.4m^3 rigid tank is filled with saturated liquid water at 200 ^oC. A valve at the bottom of the tank is now opened, and one-half of the total mass is withdrawn from the tank in liquid form. Heat is transferred to water from a source at 250 ^oC 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.

Solution:



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

$$-m_e s_e + S_{gen} = \Delta S_{\tan k} + \Delta S_{source}$$

Therefore, the total entropy generated during the process is

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

$$= (172.86kg)(2.3309kJ/kg\cdot K) + (172.86kg)(2.3685kJ/kg\cdot K)$$

$$-(345.72kg)(2.3309kJ/kg\cdot K) - \frac{3077kJ}{523K}$$

$$= 0.616kJ/K$$

Thank you for your attendance!