2-3-1 [IA] Heat is transferred from a TER at 1500 K to a TER at 300 K at a rate of 10 kW. Determine the rates at which entropy (a) leaves the TER at higher temperature and (b) enters the TER at lower temperature. (c) How do you explain the discontinuity in the result?

SOLUTION

The entropy balance equation is expressed as:

$$\underbrace{\frac{dS}{dt}}_{\substack{\text{Rate of increase}\\\text{of entropy for}\\\text{an open system.}}} = \underbrace{\sum_i \dot{m}_i s_i}_{\substack{\text{Entropy}\\\text{transported by}\\\text{mass flow in.}}} - \underbrace{\sum_e \dot{m}_e s_e}_{\substack{\text{Entropy}\\\text{transported by}\\\text{mass flow out.}}} + \underbrace{\frac{\dot{Q}}{T_B}}_{\substack{\text{Entropy}\\\text{transferred}\\\text{by heat.}}} + \underbrace{\dot{S}_{\text{gen}}}_{\substack{\text{Rate of}\\\text{generation of}\\\text{entropy inside}\\\text{the system}\\\text{boundary.}}}$$

For this analysis, we are only interested in the term that provides the rate of entropy transferred by heat.

(a) With a boundary chosen just inside of the 1500 K TER,

$$\frac{\dot{Q}_{\text{out}}}{T_B} = \frac{10}{1500}; \qquad \Rightarrow \frac{\dot{Q}_{\text{out}}}{T_B} = 0.00\overline{6}\ \frac{\text{kW}}{\text{K}}$$

(b) With a boundary chosen just inside of the 300 K TER,

$$\frac{\dot{Q}_{\text{in}}}{T_B} = \frac{10}{300}; \qquad \Rightarrow \frac{\dot{Q}_{\text{in}}}{T_B} = 0.0\overline{3}\ \frac{\text{kW}}{\text{K}}$$

(c) Entropy enters the 300 K TER at a higher rate than it leaves the 1500 K TER. This provides evidence that entropy generation is a result of temperature difference.

2-3-2 [IH] A wall separates a hot reservoir at 1000 K from a cold reservoir at 300 K. The temperature difference between the two reservoirs drive a heat transfer at the rate of 500 kW. If the wall maintains steady state, determine (a) $\dot{Q}$ (in kW), (b) $\dot{W}_{ext}$ (in kW), (c) d*S*/d*t* (in kW/K), and (d) $\dot{S}_{gen,univ.}$ (kW/K).

SOLUTION

(a) Treating the wall as the system, through which 500 kW of heat is transferred,

$$\dot{Q} = \dot{Q}_{in} - \dot{Q}_{out}; \qquad \Rightarrow \dot{Q} = 500 - 500; \qquad \Rightarrow \dot{Q} = 0 \text{ kW}$$

(b) There is not external (shaft, electrical, or boundary) work transfer.

$$\dot{W}_{ext} = 0 \text{ kW}$$

(c) Because the wall is at steady state

$$\frac{dS}{dt} = 0 \ \frac{\text{kW}}{\text{K}}$$

(d) An entropy balance on the system's universe produces:

$$\frac{dS}{dt} = \sum \cancel{\dot{m}_i s_i}^{0} - \sum \cancel{\dot{m}_e s_e}^{0} + \frac{\dot{Q}_{in}}{T_{hot}} - \frac{\dot{Q}_{out}}{T_{cold}} + \dot{S}_{gen,univ};$$

$$\Rightarrow \dot{S}_{gen,univ} = \frac{\dot{Q}_{out}}{T_{cold}} - \frac{\dot{Q}_{in}}{T_{hot}}; \qquad \Rightarrow \dot{S}_{gen,univ} = 500\left(\frac{1}{300} - \frac{1}{1000}\right); \qquad \Rightarrow \dot{S}_{gen,univ} = 1.167 \ \frac{\text{kW}}{\text{K}}$$

2-3-3 [IN] A resistance heater operates inside a tank consuming 0.5 kW of electricity. Due to heat transfer to the ambient atmosphere at 300 K, the tank is maintained at a steady state. The surface temperature of the tank remains constant at 400 K. Determine the rate at which entropy (a) leaves the tank and (b) enters the tank's universe. (c) How does the system maintain steady state with regard to entropy?

SOLUTION

(a) The energy equation is given as

$$\cancel{\frac{dE}{dt}}^{0,\text{ steady state}} = \cancel{\dot{J}_{\text{net}}}^{0} + \dot{Q} - \dot{W}_{\text{ext}};$$

$$\Rightarrow 0 = \left(-\dot{Q}_{\text{out}}\right) - \left(-\dot{W}_{\text{in}}\right);$$

$$\Rightarrow \dot{Q}_{\text{out}} = \dot{W}_{\text{in}} = 0.5 \text{ kW};$$

The entropy balance equation is expressed as

$$\underbrace{\frac{dS}{dt}}_{\substack{\text{Rate of increase}\\ \text{of entropy for}\\ \text{an open system.}}} = \underbrace{\sum_i \dot{m}_i s_i}_{\substack{\text{Entropy}\\ \text{transported by}\\ \text{mass flow in.}}} - \underbrace{\sum_e \dot{m}_e s_e}_{\substack{\text{Entropy}\\ \text{transported by}\\ \text{mass flow out.}}} + \underbrace{\frac{\dot{Q}}{T_B}}_{\substack{\text{Entropy}\\ \text{transferred}\\ \text{by heat.}}} + \underbrace{\dot{S}_{\text{gen}}}_{\substack{\text{Rate of}\\ \text{generation of}\\ \text{entropy inside}\\ \text{the system}\\ \text{boundary.}}}$$

For this analysis, we are only interested in the term that gives the rate of entropy transferred by heat. By creating a boundary just inside of the surface of the tank, the entropy leaving the tank is given by:

$$\frac{\dot{Q}}{T_B} = \frac{\dot{Q}_{\text{out}}}{T_B}; \quad \Rightarrow \frac{\dot{Q}}{T_B} = \frac{\dot{Q}_{\text{out}}}{T_{\text{tank}}}; \quad \Rightarrow \frac{\dot{Q}}{T_B} = \frac{0.5}{400}; \quad \Rightarrow \frac{\dot{Q}}{T_B} = 0.00125 \ \frac{\text{kW}}{\text{K}}$$

(b) By creating a boundary just outside of the surface of the tank

$$\frac{\dot{Q}}{T_B} = \frac{\dot{Q}_{\text{out}}}{T_{\text{surroundings}}}; \quad \Rightarrow \frac{\dot{Q}}{T_B} = \frac{0.5}{300}; \quad \Rightarrow \frac{\dot{Q}}{T_B} = 0.0016 \ \frac{\text{kW}}{\text{K}}$$

(c) System:

$$\cancel{\frac{dS}{dt}}^{0,\text{ steady state}} = \sum_i \cancel{\dot{m}_i}^{0} s_i - \sum_e \cancel{\dot{m}_e}^{0} s_e + \frac{\dot{Q}}{T_B} + \dot{S}_{\text{gen,univ}};$$

$$\Rightarrow \dot{S}_{\text{gen,univ}} = -\frac{\dot{Q}}{T_B}; \quad \Rightarrow \dot{S}_{\text{gen,univ}} = -\frac{\left(-\dot{Q}_{\text{out}}\right)}{T_B}; \quad \Rightarrow \dot{S}_{\text{gen,univ}} = \frac{0.5}{300}; \quad \Rightarrow \dot{S}_{\text{gen,univ}} = 0.0016 \ \frac{\text{kW}}{\text{K}}$$

The system maintains steady state by generating entropy.

2-3-4 [IE] Heat is conducted through a slab of thickness 2 cm. The temperature varies linearly from 500 K on the left face to 300 K on the right face. If the rate of heat transfer is 2 kW, determine the rate of entropy transfer dS/dt (magnitude only) at the (a) left and (b) right faces. (c) Plot how the rate of entropy transfer varies from the left to the right face.

SOLUTION

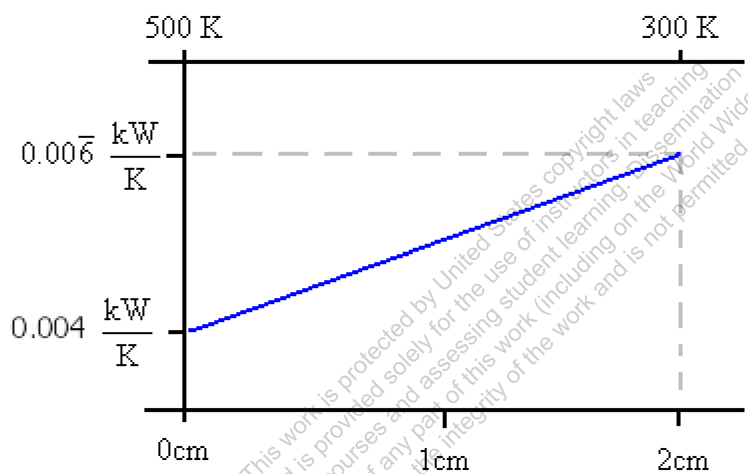
(a) On the left face,

$$\frac{\dot{Q}_{\text{left}}}{T_B} = \frac{2}{500}; \qquad \Rightarrow \frac{\dot{Q}_{\text{left}}}{T_B} = 0.004 \ \frac{\text{kW}}{\text{K}}$$

(b) On the right face,

$$\frac{\dot{Q}_{\text{right}}}{T_B} = \frac{2}{300}; \qquad \Rightarrow \frac{\dot{Q}_{\text{left}}}{T_B} = 0.00667 \ \frac{\text{kW}}{\text{K}}$$

(c)



2-3-5 [II] A 30 kg aluminum block cools down from its initial temperature of 500 K to the atmospheric temperature of 300 K. Determine the total amount of entropy transfer from the system's universe. Assume the specific internal energy of aluminum (in kJ/kg) is related to its absolute temperature (K) through *u* = *0.9T*.

SOLUTION

With no mass flow involved in this system:

$$\frac{dE}{dt} = \cancel{\dot{J}_{\text{net}}}^{0} + \dot{Q} - \cancel{\dot{W}_{\text{ext}}}^{0}; \quad \Rightarrow \frac{dU}{dt} = \left(-\dot{Q}_{\text{out}}\right);$$

$$\Rightarrow \frac{d\left(mu\right)}{dt} = -\dot{Q}_{\text{out}}; \quad \Rightarrow \frac{d\left(mu\right)}{dt} = -\dot{Q}_{\text{out}};$$

$$\Rightarrow m\frac{du}{dt} = -\dot{Q}_{\text{out}}; \quad \Rightarrow \left(0.9\right)m\frac{dT}{dt} = -\dot{Q}_{\text{out}}; \quad \left[\text{kW}\right]$$

$$\Rightarrow \left(0.9\right)mdT = -\dot{Q}_{\text{out}}dt; \quad \left[\text{kJ}\right]$$

$$\Rightarrow Q_{\text{out}} = -\left(0.9\right)m\Delta T; \quad \Rightarrow Q_{\text{out}} = -\left(0.9\right)\left(30\right)\left(300-500\right); \quad \Rightarrow Q_{\text{out}} = 5400 \text{ kJ};$$

The boundary for the system's universe passes through the surroundings. Therefore, the entropy transferred into the surroundings is:

$$\frac{Q_{\text{out}}}{T_B} = \frac{Q_{\text{out}}}{T_0}; \quad \Rightarrow \frac{Q_{\text{out}}}{T_B} = \frac{5400}{300}; \quad \Rightarrow \frac{Q_{\text{out}}}{T_B} = 18\ \frac{\text{kJ}}{\text{K}}$$

2-3-6 [IL] Water is heated in a boiler from a source at 1800 K. If the heat transfer rate is 20 kW, (a) determine the rate of entropy transfer into the boiler's universe. (b) Discuss the consequences of reducing the source temperature with respect to the boiler size and entropy transfer.

SOLUTION

(a) By choosing a boundary just outside of the boiler's surface, the rate of entropy transfer from the reservoir is given as:

$$\frac{\dot{Q}_{\text{in}}}{T_B} = \frac{20}{1800}; \qquad \Rightarrow \frac{\dot{Q}_{\text{in}}}{T_B} = 0.011\ \frac{\text{kW}}{\text{K}}$$

(b) As the reservoir temperature is decreased, the entropy transfer decreases. However, to maintain the same amount of heat transfer, the area of contact between the system and the reservoir must be increased resulting in the increase of system size.

2-3-7 [IG] An insulated tank contains 50 kg of water at 30°C, which is stirred by a paddle wheel at 300 rpm while transmitting a torque of 0.2 kNm. Determine (a) the rate of change of temperature (d*T*/d*t*) (b) the rate of change of total entropy (d*S*/d*t*) and (c) the rate of generation of entropy (S_{gen}) within the tank. Assume $s = 4.2\ln T$ and $u = 4.2T$, where *T* is in Kelvin.

SOLUTION

(a) The energy equation is given as:

$$\frac{d\cancel{E}^{U}}{dt} = \sum \cancel{\dot{m}_i j_i}^{0} - \sum \cancel{\dot{m}_e j_e}^{0} + \cancel{\dot{Q}}^{0} - \dot{W}_{ext};$$

$$\Rightarrow \frac{dU}{dt} = -\dot{W}_{\text{ext}}; \quad \Rightarrow \frac{dU}{dt} = -\left(-\dot{W}_{\text{sh,in}}\right);$$

$$\Rightarrow \frac{dU}{dt} = \dot{W}_{\text{sh,in}}; \quad \Rightarrow \frac{dU}{dt} = 2\pi\frac{300}{60}0.2; \quad \Rightarrow \frac{dU}{dt} = 6.28\ \text{kW};$$

$$\Rightarrow \frac{dU}{dt} = \frac{d(mu)}{dt}; \quad \Rightarrow \frac{dU}{dt} = m\frac{du}{dt}; \quad \Rightarrow \frac{dU}{dt} = m\frac{d(4.2T)}{dt};$$

$$\Rightarrow \frac{dU}{dt} = 4.2m\frac{dT}{dt}; \quad \Rightarrow \frac{dU}{dt} = 6.28\ \text{kW};$$

$$\Rightarrow \frac{dT}{dt} = \frac{6.28}{4.2(50)}; \quad \Rightarrow \frac{dT}{dt} = 0.03\ \frac{\text{K}}{\text{s}}$$

(b) The entropy equation is given as:

$$\frac{dS}{dt} = \sum \cancel{\dot{m}_i s_i}^{0} - \sum \cancel{\dot{m}_e s_e}^{0} + \frac{\cancel{\dot{Q}}^{0}}{T_B} + \dot{S}_{gen};$$

$$\Rightarrow \frac{dS}{dt} = \dot{S}_{gen}; \quad \Rightarrow \text{Answers b and c will be the same}$$

$$\frac{dS}{dt} = \frac{d(ms)}{dt}; \quad \Rightarrow \frac{dS}{dt} = m\frac{ds}{dt}; \quad \Rightarrow \frac{dS}{dt} = 4.2m\frac{d(\ln T)}{dt}; \quad \Rightarrow \frac{dS}{dt} = \frac{4.2m}{T}\frac{dT}{dt};$$

$$\Rightarrow \dot{S}_{gen} = \frac{dS}{dt}; \quad \Rightarrow \dot{S}_{gen} = \frac{4.2m}{T}\frac{dT}{dt}; \quad \Rightarrow \dot{S}_{gen} = \frac{4.2(50)}{(273+30)}\frac{dT}{dt}; \quad \Rightarrow \dot{S}_{gen} = \frac{4.2(50)}{303}(0.03);$$

$$\Rightarrow \dot{S}_{gen} = 0.0208\ \frac{\text{kW}}{\text{K}}$$

(c) $\dot{S}_{gen} = 0.0208\ \frac{\text{kW}}{\text{K}}$

2-3-8 [IZ] A rigid insulated tank contains 1 kg of air at 300 K and 100 kPa. A 1 kW internal heater is turned on. Determine the rate of (a) entropy transfer into the tank (b) the rate of change of total entropy of the system and (c) the rate of generation of entropy within the tank. Assume $s = \ln T$ and $u = T$, where T is in Kelvin.

SOLUTION

(a) Entropy transfer into the system is given as:

$$\frac{\cancel{\dot{Q}}^{0}}{T_B} = 0 \ \frac{\text{kW}}{\text{K}}$$

(b) The energy equation produces:

$$\frac{d\cancel{E}^{U}}{dt} = \sum \cancel{\dot{m}_i j_i}^{0} - \sum \cancel{\dot{m}_e j_e}^{0} + \cancel{\dot{Q}}^{0} - \dot{W}_{ext};$$

$$\Rightarrow \frac{dU}{dt} = -\dot{W}_{\text{ext}}; \qquad \Rightarrow \frac{dU}{dt} = -\left(-\dot{W}_{\text{el,in}}\right); \qquad \Rightarrow \frac{dU}{dt} = 1\ \text{kW};$$

$$\Rightarrow \frac{dU}{dt} = \frac{d(mu)}{dt}; \qquad \Rightarrow \frac{dU}{dt} = m\frac{du}{dt}; \qquad \Rightarrow \frac{dU}{dt} = m\frac{dT}{dt} = 1\ \text{kW};$$

$$\Rightarrow \frac{dT}{dt} = \frac{1}{m}; \qquad \Rightarrow \frac{dT}{dt} = \frac{1}{1}; \qquad \Rightarrow \frac{dT}{dt} = 1\ \frac{\text{K}}{\text{s}};$$

Therefore,

$$\frac{dS}{dt} = \frac{d(ms)}{dt}; \qquad \Rightarrow \frac{dS}{dt} = m\frac{ds}{dt}; \qquad \Rightarrow \frac{dS}{dt} = m\frac{d(\ln T)}{dt}; \qquad \Rightarrow \frac{dS}{dt} = \frac{m}{T}\frac{dT}{dt}; \qquad \Rightarrow \frac{dS}{dt} = \frac{1}{300}(1);$$

$$\Rightarrow \frac{dS}{dt} = 0.0033\ \frac{\text{kW}}{\text{K}}$$

(c) The entropy equation can be simplified as:

$$\frac{dS}{dt} = \sum \cancel{\dot{m}_i s_i}^{0} - \sum \cancel{\dot{m}_e s_e}^{0} + \frac{\cancel{\dot{Q}}^{0}}{T_B} + \dot{S}_{gen,univ};$$

$$\Rightarrow \dot{S}_{gen,univ} = \frac{dS}{dt}; \qquad \Rightarrow \dot{S}_{gen,univ} = 0.0033\ \frac{\text{kW}}{\text{K}}$$

2-3-9 [IK] A rigid tank contains 10 kg of air at 500 K and 100 kPa while the surroundings is at 300 K. A 2 kW internal heater keeps the gas hot by compensating the heat losses. At steady state, determine the rate of (a) heat transfer, (b) the rate of entropy generation (S_{gen}) inside the tank, and (c) the rate of entropy generation ($S_{gen,univ}$) in the system's universe.

SOLUTION

(a) $$\cancelto{0,\text{ steady state}}{\frac{dE}{dt}} = \cancelto{0}{\dot{J}_{net}} + \dot{Q} - \dot{W}_{ext} = \left(-\dot{Q}_{loss}\right) - \left(-\dot{W}_{el,in}\right);$$

$$\Rightarrow \dot{Q}_{loss} = \dot{W}_{el,in} = 2 \text{ kW};$$

$$\Rightarrow \dot{Q} = -2 \text{ kW}$$ (Negative sign indicates heat is being lost)

(b) Drawing the system boundary just inside the tank

$$\cancelto{0,\text{ steady state}}{\frac{dS}{dt}} = \sum_i \cancelto{0}{\dot{m}_i} s_i - \sum_e \cancelto{0}{\dot{m}_e} s_e + \frac{\dot{Q}}{T_B} + \dot{S}_{gen};$$

$$\Rightarrow \dot{S}_{gen} = -\frac{\dot{Q}}{T_B}; \quad \Rightarrow \dot{S}_{gen} = -\frac{\left(-\dot{Q}_{loss}\right)}{T_B}; \quad \Rightarrow \dot{S}_{gen} = \frac{\dot{Q}_{loss}}{T_B}; \quad \Rightarrow \dot{S}_{gen} = \frac{2}{500};$$

$$\Rightarrow \dot{S}_{gen} = 0.004 \ \frac{\text{kW}}{\text{K}}$$

(c) Drawing the boundary just outside the tank

$$\dot{S}_{gen,univ} = -\frac{\dot{Q}}{T_B}; \quad \Rightarrow \dot{S}_{gen,univ} = -\frac{\left(-\dot{Q}_{loss}\right)}{T_B}; \quad \Rightarrow \dot{S}_{gen,univ} = \frac{\dot{Q}_{loss}}{T_B}; \quad \Rightarrow \dot{S}_{gen,univ} = \frac{2}{300};$$

$$\Rightarrow \dot{S}_{gen,univ} = 0.0067 \ \frac{\text{kW}}{\text{K}}$$

2-3-10 [IP] A 10 m^3 insulated rigid tank contains 30 kg of wet steam with a quality of 0.9. An internal electric heater is turned on, which consumes electric power at a rate of 10 kW. After the heater is on for one minute, determine (a) the change in temperature, (b) the change in pressure and (c) the change in entropy of steam.

TEST Solution:

The energy equation produces:

$$\frac{d\cancel{E}^{U}}{dt} = \sum \cancel{\dot{m}_i j_i}^{0} - \sum \cancel{\dot{m}_e j_e}^{0} + \cancel{\dot{Q}}^{0} - \dot{W}_{ext};$$

$$\Rightarrow \frac{dU}{dt} = -\dot{W}_{\text{ext}}; \qquad \Rightarrow \frac{dU}{dt} = -\left(-\dot{W}_{\text{el,in}}\right); \qquad \Rightarrow \frac{dU}{dt} = 10 \text{ kW};$$

$$\Rightarrow \frac{dU}{dt} = \frac{d(mu)}{dt}; \qquad \Rightarrow \frac{dU}{dt} = m\frac{du}{dt}; \qquad \Rightarrow \frac{dU}{dt} = 1 \text{ kW};$$

$$\Rightarrow du = \frac{dt}{m}; \left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$\Rightarrow u_2 - u_1 = \frac{60}{m}; \left[\frac{\text{kJ}}{\text{kg}}\right]$$

Launch the PC system-state TESTcalc. Evaluate the initial state, State-1, from the given properties. For the final state, State-2, use m2=m1, Vol2=Vol1, and u2=u1+10*60/m1. Obtain the answers in the I/O panel by evaluating expressions:

(a) =T2-T1 = 0.451°C

(b) =p2-p1 = 6.11 kPa

(c) =m1*(s2-s1) = 1.02 $\frac{\text{kJ}}{\text{K}}$

2-3-11 [BEC] One kg of air is trapped in a rigid chamber of volume 0.2 m^3 at 300 K. Because of electric work transfer, the temperature of air increases at a rate of 1^{o}C/s. Using the *IG system state daemon*, calculate: (a) the rate of change of stored energy, dE/dt, (b) the rate of external work transfer (include sign), (c) the rate of change of total entropy of the system, dS/dt, (d) the rate of entropy generation inside the system. (Hint: Evaluate two states separated by 1 s).

TEST Solution:

The energy equation produces:

$$\frac{d\cancel{E}^{U}}{dt} = \sum \cancel{\dot{m}_i j_i}^{0} - \sum \cancel{\dot{m}_e j_e}^{0} + \cancel{\dot{Q}}^{0} - \dot{W}_{ext};$$

$$\Rightarrow \frac{dE}{dt} = \frac{dU}{dt}; \qquad \Rightarrow \frac{dE}{dt} = -\dot{W}_{\text{ext}};$$

$$\Rightarrow \frac{dE}{dt} = -\left(-\dot{W}_{\text{el,in}}\right); \qquad \Rightarrow \frac{dE}{dt} = \dot{W}_{\text{el,in}}; \quad [\text{kW}]$$

Launch the IG system-state TESTcalc. Evaluate the initial state, State-1, from the given properties. Let State-2 represent the state after 1 s. The new state now has T2 = T1+1. Also, for the closed system m2=m1 and Vol2=Vol1. In the I/O panel evaluate part a and part c:

(a) $\frac{\text{dE}}{\text{dt}}$ = m1*(e2-e1)/1 = 0.717 kW

(b) From the energy equation:

$$\dot{W}_{\text{ext}} = -\frac{dE}{dt}; \qquad \Rightarrow \dot{W}_{\text{ext}} = -0.717 \text{ kW}$$

(c) $\frac{\text{dS}}{\text{dt}}$ = m1*(s2-s1)/1 = 0.00239 $\frac{\text{kW}}{\text{K}}$

(d) The entropy equation produces:

$$\frac{dS}{dt} = \sum_i \cancel{\dot{m}_i}^{0} s_i - \sum_e \cancel{\dot{m}_e}^{0} s_e + \frac{\cancel{\dot{Q}}^{0}}{T_{\text{B}}} + \dot{S}_{\text{gen}};$$

$$\Rightarrow \dot{S}_{\text{gen}} = \frac{dS}{dt}; \qquad \Rightarrow \dot{S}_{\text{gen}} = 0.00239 \frac{\text{kW}}{\text{K}}$$

2-3-12 [IU] A rigid cylindrical tank stores 100 kg of a substance at 500 kPa and 500 K while the outside temperature is 300 K. A paddle wheel stirs the system transferring shaft work at a rate of 0.5 kW. At the same time an internal electrical resistance heater transfers electricity at the rate of 1 kW. (a) Do an energy analysis to determine the rate of heat transfer in kW for the tank. (b) Determine the absolute value of the rate at which entropy leaves the internal system (at a uniform temperature of 500 K) in kW/K. (c) Determine the rate of entropy generation for the system's universe.

SOLUTION

(a) $$\cancel{\frac{dE}{dt}}^{0} = \cancel{\dot{J}_{\text{net}}}^{0} + \dot{Q} - \dot{W}_{\text{ext}}; \quad \Rightarrow \dot{Q} = \dot{W}_{\text{ext}}; \quad \Rightarrow \dot{Q} = -(1+0.5);$$

$$\Rightarrow \dot{Q} = -1.5\text{kW}$$

(b) Taking the system just inside the tank

$$\frac{\dot{Q}_{\text{loss}}}{T_{\text{B}}} = \frac{1.5}{500}; \quad \Rightarrow \frac{\dot{Q}_{\text{loss}}}{T_{\text{B}}} = 0.003\ \frac{\text{kW}}{\text{K}}$$

(c) Application of the entropy equation over the system's universe produces:

$$\cancel{\frac{dS}{dt}}^{0,\text{ steady state}} = \sum_i \cancel{\dot{m}_i}^{0} s_i - \sum_e \cancel{\dot{m}_e}^{0} s_e + \frac{\dot{Q}}{T_{\text{B}}} + \dot{S}_{\text{gen,univ}};$$

$$\Rightarrow \dot{S}_{\text{gen,univ}} = -\frac{\dot{Q}}{T_{\text{B}}}; \quad \Rightarrow \dot{S}_{\text{gen,univ}} = -\frac{\left(-\dot{Q}_{\text{loss}}\right)}{T_{\text{B}}}; \quad \Rightarrow \dot{S}_{\text{gen,univ}} = \frac{\dot{Q}_{\text{loss}}}{T_{\text{B}}}; \quad \Rightarrow \dot{S}_{\text{gen,univ}} = \frac{1.5}{300};$$

$$\Rightarrow \dot{S}_{\text{gen,univ}} = 0.005\ \frac{\text{kW}}{\text{K}}$$

2-3-13 [IX] A 1 cm diameter insulated pipe carries a steady flow of water at a velocity of 30 m/s. The temperature increases from 300 K at the inlet to 301 K at the exit due to friction. If the specific entropy of water is related to its absolute temperature through $s = 4.2\ln T$, determine the rate of generation of entropy within the pipe. Assume water density to be 1000 kg/m^3.

SOLUTION

At steady state $\dot{m}_i = \dot{m}_e = \dot{m}$;

$$\dot{m} = \rho A V; \qquad \Rightarrow \dot{m} = 1000\left[\pi \frac{(0.01)^2}{4}\right](30); \qquad \Rightarrow \dot{m} = 2.36\ \frac{\text{kg}}{\text{s}};$$

The entropy equation is given as

$$\cancel{\frac{dS}{dt}}^{0} = \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \frac{\cancel{\dot{Q}}^{0}}{T_B} + \dot{S}_{gen};$$

$$\Rightarrow \dot{S}_{gen} = \dot{m}\left(s_e - s_i\right);$$

$$\Rightarrow \dot{S}_{gen} = \dot{m}(4.2)\left(\ln T_e - \ln T_i\right);$$

$$\Rightarrow \dot{S}_{gen} = \dot{m}(4.2)\left(\ln \frac{T_e}{T_i}\right);$$

$$\Rightarrow \dot{S}_{gen} = (2.36)(4.2)\left(\ln \frac{301}{300}\right);$$

$$\Rightarrow \dot{S}_{gen} = 0.033\ \frac{\text{kW}}{\text{K}}$$

2-3-14 [IC] Liquid water (density 997 kg/m^3) flows steadily through a pipe with a volume flow rate of 30,000 L/min. Due to viscous friction, the pressure drops from 500 kPa at the inlet to 150 kPa at the exit. If the specific internal energy and specific entropy remain constant along the flow, determine (a) the rate of heat transfer and (b) the rate of entropy generation in and around the pipe. Assume the temperature of the surroundings to be 300 K.

SOLUTION

(a) At steady state $\dot{m}_i = \dot{m}_e = \dot{m}$;

$$\dot{m} = \rho A V; \qquad \Rightarrow \dot{m} = \rho \dot{\cancel{V}}; \qquad \Rightarrow \dot{m} = \left(997 \frac{\text{kg}}{\text{m}^3}\right)\left(30{,}000 \frac{\text{L}}{\text{min}}\right)\left(\frac{1}{1000}\frac{\text{m}^3}{\text{L}}\right)\left(\frac{1}{60}\frac{\text{min}}{\text{s}}\right);$$

$$\Rightarrow \dot{m} = 448.5 \ \frac{\text{kg}}{\text{s}};$$

The energy balance equation is given as:

$$\frac{\cancel{dE}^{\,0}}{\cancel{dt}} = \sum \dot{m}_i j_i - \sum \dot{m}_e j_e + \dot{Q} - \cancel{\dot{W}_{ext}}^{\,0};$$

$$\Rightarrow \dot{Q} = \dot{m}\left(j_e - j_i\right); \qquad \Rightarrow \dot{Q} = \dot{m}\left(\Delta j\right);$$

$$\Rightarrow \dot{Q} = \dot{m}\left(\Delta h + \cancel{\Delta ke}^{\,0} + \cancel{\Delta pe}^{\,0}\right); \qquad \Rightarrow \dot{Q} = \dot{m}\left(+\cancel{\Delta u}^{\,0} + \Delta p v\right);$$

$$\Rightarrow \dot{Q} = \dot{m}\left(p_e v - p_i v\right);$$

$$\Rightarrow \dot{Q} = \frac{\dot{m}}{\rho}\left(p_e - p_i\right); \qquad \Rightarrow \dot{Q} = \frac{498.5}{997}\left(150 - 500\right); \qquad \Rightarrow \dot{Q} = -175 \text{ kW}$$

(b) The entropy equation is given as:

$$\frac{\cancel{dS}^{\,0}}{\cancel{dt}} = \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \frac{\dot{Q}}{T_B} + \dot{S}_{\text{gen,univ}};$$

$$\Rightarrow \dot{S}_{\text{gen,univ}} = \dot{m}\left(s_e - s_i\right) - \frac{\dot{Q}}{T_B};$$

$$\Rightarrow \dot{S}_{\text{gen,univ}} = \dot{m}\Delta \cancel{s}^{\,0} - \frac{\dot{Q}}{T_B};$$

$$\Rightarrow \dot{S}_{\text{gen,univ}} = -\frac{\dot{Q}}{T_B}; \qquad \Rightarrow \dot{S}_{\text{gen,univ}} = -\frac{-175}{300}; \qquad \Rightarrow \dot{S}_{\text{gen,univ}} = 0.583 \ \frac{\text{kW}}{\text{K}}$$

2-3-15 [IV] An electric water heater works by passing electricity through an electrical resistance placed inside the flow of liquid water as shown in the accompanying animation. The specific internal energy and entropy of water are correlated to its absolute temperature through $u = 4.2T$ and $s = 4.2\ln T$ (T in K) respectively. Water enters the heater at 300 K with a flow rate of 5 kg/s. At the exit the temperature is 370 K. Assuming steady state operation, negligible changes in ke and pe, and negligible heat transfer, determine (a) electrical power consumption rate and (b) the rate of entropy generation within the heater. What-if Scenario: What would the answers be if the exit temperature were reduced by 20°C?

SOLUTION

(a) The energy balance equation is given as:

$$\frac{d\cancel{E}^{0}}{\cancel{dt}} = \sum \dot{m}_i j_i - \sum \dot{m}_e j_e + \cancel{\dot{Q}}^{0} - \dot{W}_{ext};$$

$$\Rightarrow \dot{W}_{\text{ext}} = -\dot{m}\left(j_i - j_e\right); \quad \Rightarrow \dot{W}_{\text{ext}} = -\dot{m}\Delta j; \quad \Rightarrow \dot{W}_{\text{ext}} = -\dot{m}\left(\Delta h + \cancel{\Delta ke}^{0} + \cancel{\Delta pe}^{0}\right);$$

$$\Rightarrow \dot{W}_{\text{ext}} = -\dot{m}\left(\Delta u + \cancel{\Delta pv}^{0}\right); \quad \Rightarrow \dot{W}_{\text{ext}} = -\dot{m}\left(u_e - u_i\right);$$

$$\Rightarrow \dot{W}_{\text{ext}} = -\dot{m}\left(u_e - u_i\right); \quad \Rightarrow \dot{W}_{\text{ext}} = -\dot{m}(4.2)\left(T_e - T_i\right); \quad \Rightarrow \dot{W}_{\text{ext}} = -(5)(4.2)(370 - 300);$$

$$\Rightarrow \dot{W}_{\text{ext}} = -1470 \text{ kW}$$

(b) The entropy balance equation is given as:

$$\frac{d\cancel{S}^{0}}{\cancel{dt}} = \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \frac{\cancel{\dot{Q}}^{0}}{T_B} + \dot{S}_{\text{gen}};$$

$$\Rightarrow \dot{S}_{\text{gen}} = \dot{m}\left(s_e - s_i\right); \quad \Rightarrow \dot{S}_{\text{gen}} = \dot{m}(4.2)\left(\ln T_e - \ln T_i\right);$$

$$\Rightarrow \dot{S}_{\text{gen}} = \dot{m}(4.2)\left(\ln \frac{T_e}{T_i}\right); \quad \Rightarrow \dot{S}_{\text{gen}} = (5)(4.2)\ln\left(\frac{370}{300}\right); \quad \Rightarrow \dot{S}_{\text{gen}} = 4.04 \ \frac{\text{kW}}{\text{K}}$$

(c.1) $\dot{W}_{\text{ext}} = -\dot{m}(4.2)\left(T_e - T_i\right); \quad \Rightarrow \dot{W}_{\text{ext}} = -(5)(4.2)\left((370 - 20) - 300\right);$

$$\Rightarrow \dot{W}_{\text{ext}} = -1050 \text{ kW}$$

(c.2) $\dot{S}_{\text{gen}} = \dot{m}(4.2)\left(\ln \frac{T_e}{T_i}\right); \quad \Rightarrow \dot{S}_{\text{gen}} = (5)(4.2)\ln\left(\frac{(370 - 20)}{300}\right);$

$$\Rightarrow \dot{S}_{\text{gen}} = 3.237 \ \frac{\text{kW}}{\text{K}}$$

2-3-16 [IQ] An open system with only one inlet and one exit operates at steady state. Mass enters the system at a flow rate of 5 kg/s with the following properties: h = 3484 kJ/kg, s = 8.0871 kJ/kg-K and V = 20 m/s. At the exit the properties are as follows: h = 2611 kJ/kg, s = 8.146 kJ/kg-K and V = 25 m/s. The device produces 4313 kW of shaft work while rejecting some heat to the atmosphere at 25^{o}C. (a) Do a mass analysis to determine the mass flow rate at the exit. (b) Do an energy analysis to determine the rate of heat transfer (include sign). (c) Do an entropy analysis to evaluate the rate of entropy generation in the system's universe.

SOLUTION

(a) Mass analysis:

$$\frac{\cancel{dm}^{\,0}}{\cancel{dt}} = \sum \dot{m}_i - \sum \dot{m}_e;$$

$$\Rightarrow \dot{m}_e = \dot{m}_i = \dot{m} = 5\ \frac{\text{kg}}{\text{s}}$$

(b) Energy analysis:

$$\frac{\cancel{dE}^{\,0}}{\cancel{dt}} = \sum \dot{m}_i j_i - \sum \dot{m}_e j_e + \dot{Q} - \dot{W}_{\text{ext}};$$

$$\Rightarrow \dot{Q} = -\dot{m}\left(j_i - j_e\right) + \dot{W}_{\text{ext}}; \qquad \Rightarrow \dot{Q} = \dot{m}\Delta j + \dot{W}_{\text{ext}};$$

$$\Rightarrow \dot{Q} = \dot{m}\left(\Delta h + \Delta \text{ke} + \cancel{\Delta \text{pe}}^{\,0}\right) + \dot{W}_{\text{ext}};$$

$$\Rightarrow \dot{Q} = \dot{m}\left[\left(h_e + \frac{(V_e)^2}{2000}\right) - \left(h_i + \frac{(V_i)^2}{2000}\right)\right] + \dot{W}_{\text{ext}};$$

$$\Rightarrow \dot{Q} = (5)\left[\left(2611 + \frac{(25)^2}{2000}\right) - \left(3484 + \frac{(20)^2}{2000}\right)\right] + 4313;$$

$$\Rightarrow \dot{Q} = -51.4\ \text{kW}$$

(c) Entropy analysis:

$$\frac{\cancel{dS}^{\,0}}{\cancel{dt}} = \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \frac{\dot{Q}}{T_B} + \dot{S}_{\text{gen,univ}};$$

$$\Rightarrow \dot{S}_{\text{gen,univ}} = \dot{m}\left(s_e - s_i\right) + \frac{\dot{Q}}{T_B};$$

$$\Rightarrow \dot{S}_{\text{gen,univ}} = \dot{m}(8.146 - 8.0871) - \frac{51.4}{(273+25)}; \qquad \Rightarrow \dot{S}_{\text{gen,univ}} = 0.122\ \frac{\text{kW}}{\text{K}}$$

2-3-17 [IT] Steam flows steadily through a work-producing, adiabatic, single-flow device with a flow rate of 7 kg/s. At the inlet h = 3589 kJ/kg, s = 7.945 kJ/kg-K, and at the exit h = 2610 kJ/kg, s = 8.042 kJ/kg-K. If changes in ke and pe are negligible, determine (a) the work produced by the device, and (b) the rate of entropy generation within the device. What-if Scenario: What would the answer in part (b) be if the device lost 5 kW of heat from its surface at 200°C?

SOLUTION

(a) At steady state:

$$\dot{m}_i = \dot{m}_e = \dot{m};$$

The energy balance equation is given as:

$$\frac{\cancel{dE}^{\,0}}{\cancel{dt}} = \sum \dot{m}_i j_i - \sum \dot{m}_e j_e + \cancel{\dot{Q}}^{\,0} - \dot{W}_{\text{ext}};$$

$$\Rightarrow \dot{W}_{\text{ext}} = -\dot{m}\Delta j; \qquad \Rightarrow \dot{W}_{\text{ext}} = -\dot{m}\left(\Delta h + \cancel{\Delta ke}^{\,0} + \cancel{\Delta pe}^{\,0}\right); \qquad \Rightarrow \dot{W}_{\text{ext}} = -\dot{m}\Delta h;$$

$$\Rightarrow \dot{W}_{ext} = -\dot{m}\left(h_e - h_i\right); \qquad \Rightarrow \dot{W}_{\text{ext}} = -7\left(2610 - 3589\right); \qquad \Rightarrow \dot{W}_{\text{ext}} = 6853 \text{ kW}$$

(b) The entropy balance equation is given as

$$\frac{\cancel{dS}^{\,0}}{\cancel{dt}} = \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \frac{\cancel{\dot{Q}}^{\,0}}{T_B} + \dot{S}_{\text{gen}};$$

$$\Rightarrow \dot{S}_{\text{gen}} = \dot{m}\left(s_e - s_i\right); \qquad \Rightarrow \dot{S}_{\text{gen}} = (7)(8.042 - 7.945); \qquad \Rightarrow \dot{S}_{\text{gen}} = 0.679 \ \frac{\text{kW}}{\text{K}}$$

(c) In the presence of heat transfer, the entropy balance equation would become:

$$\Rightarrow \dot{S}_{\text{gen}} = \dot{m}\left(s_e - s_i\right) - \frac{\dot{Q}}{T_B}; \qquad \Rightarrow\Rightarrow \dot{S}_{\text{gen}} = (7)(8.042 - 7.945) - \frac{(-5)}{(273+200)};$$

$$\Rightarrow \dot{S}_{gen} = 0.69 \ \frac{\text{kW}}{\text{K}}$$

2-3-18 [IY] The following information are supplied at the inlet and exit of an adiabatic nozzle operating at steady state: Inlet: V = 30 m/s, h = 976.2 kJ/kg, s = 6.149 kJ/kg-K; Exit: h = 825.5 kJ/kg. Determine (a) the exit velocity and (b) the minimum specific entropy (s) possible at the exit.

SOLUTION

(a) At steady state:

$$\dot{m}_i = \dot{m}_e = \dot{m};$$

The energy balance equation is given as:

$$\frac{d\cancel{E}^{0}}{\cancel{d}t} = \sum \dot{m}_i j_i - \sum \dot{m}_e j_e + \cancel{\dot{Q}}^{0} - \cancel{\dot{W}_{ext}}^{0};$$

$$\Rightarrow \dot{m}j_i = \dot{m}j_e; \qquad \Rightarrow j_i = j_e;$$

Neglecting any change in potential energy:

$$\Rightarrow h_i + ke_i = h_e + ke_e; \qquad \Rightarrow h_i + \frac{(V_i)^2}{2000} = h_e + \frac{(V_e)^2}{2000};$$

$$\Rightarrow \mathrm{V}_e = \sqrt{\left(h_i + \frac{(V_i)^2}{2000} - h_e\right)(2000)}; \qquad \Rightarrow \mathrm{V} = \sqrt{\left(976.2 + \frac{(30)^2}{2000} - 825.5\right)(2000)};$$

$$\Rightarrow \mathrm{V} = 550 \ \frac{\mathrm{m}}{\mathrm{s}}$$

(b) The entropy balance equation is given as:

$$\frac{d\cancel{S}^{0}}{\cancel{d}t} = \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \frac{\cancel{\dot{Q}}^{0}}{T_B} + \dot{S}_{\text{gen}};$$

$$\Rightarrow \dot{S}_{\text{gen}} = \dot{m}(s_i - s_e);$$

$$\Rightarrow s_e = \frac{\dot{S}_{\text{gen}}}{\dot{m}} + s_i;$$

Since $\dot{S}_{\text{gen}} \geq 0$ (thermodynamic friction cannot be negative), the minimum value of the exit entropy is given as.

$$\Rightarrow s_{e,\min} = \frac{0}{\dot{m}} + 6.149; \qquad \Rightarrow s_{e,\min} = 6.149 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

2-3-19 [IF] A refrigerant flows steadily through an insulated tube, its entropy increases from 0.2718 kJ/kg-K at the inlet to 0.3075 kJ/kg-K at the exit. If the mass flow rate of the refrigerant is 0.2 kg/s and the pipe is insulated, determine (a) the rate of entropy generation within the pipe. (b) What-if Scenario: What would the rate of entropy generation be if the mass flow rate doubled?

SOLUTION

(a) At steady state:

$\dot{m}_i = \dot{m}_e = \dot{m};$

The entropy balance equation is given as:

$$\cancel{\frac{dS}{dt}}^{0} = \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \frac{\cancel{\dot{Q}}^{0}}{T_B} + \dot{S}_{\text{gen}};$$

$$\Rightarrow \dot{S}_{\text{gen}} = \dot{m}(s_e - s_i); \qquad \Rightarrow \dot{S}_{\text{gen}} = (0.2)(0.3075 - 0.2718); \qquad \Rightarrow \dot{S}_{\text{gen}} = 0.00714 \ \frac{\text{kW}}{\text{K}}$$

(b) By doubling the magnitude of the mass flow rate, the inlet and exit conditions do not change.

$$\Rightarrow \dot{S}_{\text{gen}} = (2\dot{m})(s_e - s_i); \qquad \Rightarrow \dot{S}_{\text{gen}} = (2)(0.2)(0.3075 - 0.2718); \qquad \Rightarrow \dot{S}_{\text{gen}} = 0.01428 \ \frac{\text{kW}}{\text{K}}$$