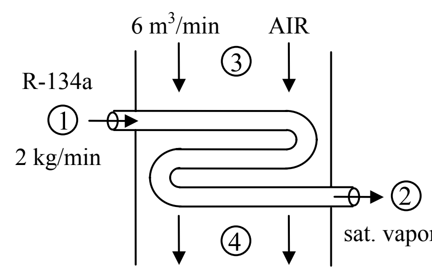
7-198 Refrigerant-134a is vaporized by air in the evaporator of an air-conditioner. For specified flow rates, the exit temperature of air and the rate of entropy generation are to be determined for the cases of an insulated and uninsulated evaporator.

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. **4** 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). The properties of R-134a at the inlet and the exit states are (Tables A-11 through A-13)

$$\left.\begin{array}{l} P_1 = 120\text{ kPa} \\ x_1 = 0.3 \end{array}\right\} \begin{array}{l} h_1 = h_f + x_1 h_{fg} = 22.49 + 0.3 \times 214.48 = 86.83\text{ kJ/kg} \\ s_1 = s_f + x_1 s_{fg} = 0.09275 + 0.3(0.85503) = 0.3493\text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} T_2 = 120\text{ kPa} \\ \text{sat. vapor} \end{array}\right\} \begin{array}{l} h_2 = h_{g\,@120\text{ kPa}} = 236.97\text{ kJ/kg} \\ s_2 = h_{g\,@120\text{ kPa}} = 0.9478\text{ kJ/kg}\cdot\text{K} \end{array}$$



Analysis (*a*) The mass flow rate of air is

$$\dot{m}_{\text{air}} = \frac{P_3\dot{V}_3}{RT_3} = \frac{(100\text{ kPa})(6\text{ m}^3/\text{min})}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})} = 6.97\text{ kg/min}$$

We take the entire heat exchanger 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 (*for each fluid stream*):

$$\dot{m}_{\text{in}} - \dot{m}_{\text{out}} = \Delta\dot{m}_{\text{system}}^{\;\nearrow 0\text{ (steady)}} = 0 \;\; \to \dot{m}_{\text{in}} = \dot{m}_{\text{out}} \to \dot{m}_1 = \dot{m}_2 = \dot{m}_{\text{air}} \;\text{ and }\; \dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

Energy balance (for the entire heat exchanger):

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

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

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} = \dot{W} = \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

Combining the two, $\dot{m}_R(h_2 - h_1) = \dot{m}_{\text{air}}(h_3 - h_4) = \dot{m}_{\text{air}} c_p (T_3 - T_4)$

Solving for T_4, $T_4 = T_3 - \dfrac{\dot{m}_R(h_2 - h_1)}{\dot{m}_{air} c_p}$

Substituting, $T_4 = 27°\text{C} - \dfrac{(2\text{ kg/min})(236.97 - 86.83)\text{ kJ/kg}}{(6.97\text{ kg/min})(1.005\text{ kJ/kg}\cdot\text{K})} = \mathbf{-15.9°C} = 257.1\text{ K}$

Noting that the condenser is well-insulated and thus heat transfer is negligible, the entropy balance for this steady-flow system can be expressed as

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

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

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

or,

$$\dot{S}_{gen} = \dot{m}_R(s_2 - s_1) + \dot{m}_{air}(s_4 - s_3)$$

where

$$s_4 - s_3 = c_p \ln\frac{T_4}{T_3} - R\ln\frac{P_4^{\nearrow 0}}{P_3} = c_p \ln\frac{T_4}{T_3} = (1.005\text{ kJ/kg}\cdot\text{K})\ln\frac{257.1\text{ K}}{300\text{ K}} = -0.1551\text{ kJ/kg}\cdot\text{K}$$

Substituting,

$$\begin{aligned}\dot{S}_{gen} &= (2\text{ kg/min})(0.9478 - 0.3493\text{ kJ/kg}\cdot\text{K}) + (6.97\text{ kg/min})(-0.1551\text{ kJ/kg}\cdot\text{K}) \\ &= 0.116\text{ kJ/min}\cdot\text{K} \\ &= \mathbf{0.00193\ \ kW/K}\end{aligned}$$

(*b*) When there is a heat gain from the surroundings at a rate of 30 kJ/min, the steady-flow energy equation reduces to

$$\dot{Q}_{in} = \dot{m}_R(h_2 - h_1) + \dot{m}_{air}c_p(T_4 - T_3)$$

Solving for T_4, $$T_4 = T_3 + \frac{\dot{Q}_{in} - \dot{m}_R(h_2 - h_1)}{\dot{m}_{air}c_p}$$

Substituting, $$T_4 = 27°\text{C} + \frac{(30\text{ kJ/min}) - (2\text{ kg/min})(236.97 - 86.83)\text{ kJ/kg}}{(6.97\text{ kg/min})(1.005\text{ kJ/kg}\cdot\text{K})} = \mathbf{-11.6°C} = 261.4\text{ K}$$

The entropy generation in this case is determined by applying the entropy balance on an *extended system* that includes the evaporator and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surrounding air at all times. The entropy balance for the extended system can be expressed as

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

$$\frac{Q_{in}}{T_{b,out}} + \dot{m}_1 s_1 + \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_4 s_4 + \dot{S}_{gen} = 0$$

$$\frac{Q_{in}}{T_{surr}} + \dot{m}_R s_1 + \dot{m}_{air} s_3 - \dot{m}_R s_2 - \dot{m}_{air} s_4 + \dot{S}_{gen} = 0$$

or $$\dot{S}_{gen} = \dot{m}_R(s_2 - s_1) + \dot{m}_{air}(s_4 - s_3) - \frac{\dot{Q}_{in}}{T_0}$$

where $$s_4 - s_3 = c_p \ln\frac{T_4}{T_3} - R\ln\frac{P_4^{\nearrow 0}}{P_3} = (1.005\text{ kJ/kg}\cdot\text{K})\ln\frac{261.4\text{ K}}{300\text{ K}} = -0.1384\text{ kJ/kg}\cdot\text{K}$$

Substituting,

$$\begin{aligned}\dot{S}_{gen} &= (2\text{ kg/min})(0.9478 - 0.3493)\text{ kJ/kg}\cdot\text{K} + (6.97\text{ kg/min})(-0.1384\text{ kJ/kg}\cdot\text{K}) - \frac{30\text{ kJ/min}}{305\text{ K}} \\ &= 0.1340\text{ kJ/min}\cdot\text{K} \\ &= \mathbf{0.00223\ \ kW/K}\end{aligned}$$

Discussion Note that the rate of entropy generation in the second case is greater because of the irreversibility associated with heat transfer between the evaporator and the surrounding air.

7-199 A room is to be heated by hot water contained in a tank placed in the room. The minimum initial temperature of the water needed to meet the heating requirements of this room for a 24-h period and the entropy generated are to be determined.

Assumptions **1** Water is an incompressible substance with constant specific heats. **2** Air is an ideal gas with constant specific heats. **3** The energy stored in the container itself is negligible relative to the energy stored in water. **4** The room is maintained at 20°C at all times. **5** The hot water is to meet the heating requirements of this room for a 24-h period.

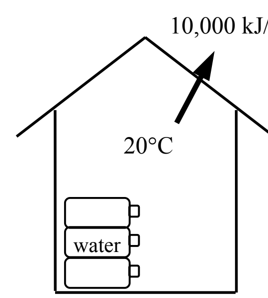
Properties The specific heat of water at room temperature is $c = 4.18$ kJ/kg·°C (Table A-3).

Analysis Heat loss from the room during a 24-h period is

$$Q_{loss} = (10{,}000\text{ kJ/h})(24\text{ h}) = 240{,}000\text{ kJ}$$

Taking the contents of the room, including the water, as our system, the energy balance can be written as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}} \rightarrow -Q_{out} = \Delta U = (\Delta U)_{water} + (\Delta U)_{air}^{\nearrow 0}$$



or

$$-Q_{out} = [mc(T_2 - T_1)]_{water}$$

Substituting,

$$-240{,}000\text{ kJ} = (1500\text{ kg})(4.18\text{ kJ/kg·°C})(20 - T_1)$$

It gives

$$T_1 = \mathbf{58.3°C}$$

where T_1 is the temperature of the water when it is first brought into the room.

(*b*) We take the house as the system, which is a closed system. The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the house and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. The entropy balance for the extended system can be expressed as

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

$$-\frac{Q_{out}}{T_{b,out}} + S_{gen} = \Delta S_{water} + \Delta S_{air}^{\nearrow 0} = \Delta S_{water}$$

since the state of air in the house (and thus its entropy) remains unchanged. Then the entropy generated during the 24 h period becomes

$$S_{gen} = \Delta S_{water} + \frac{Q_{out}}{T_{b,out}} = \left(mc\ln\frac{T_2}{T_1}\right)_{water} + \frac{Q_{out}}{T_{surr}}$$

$$= (1500\text{ kg})(4.18\text{ kJ/kg}\cdot\text{K})\ln\frac{293\text{ K}}{331.3\text{ K}} + \frac{240{,}000\text{ kJ}}{278\text{ K}}$$

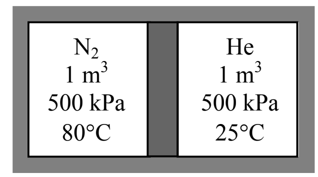
$$= -770.3 + 863.3 = \mathbf{93.0\ kJ/K}$$

7-200 An insulated cylinder is divided into two parts. One side of the cylinder contains N_2 gas and the other side contains He gas at different states. The final equilibrium temperature in the cylinder and the entropy generated are to be determined for the cases of the piston being fixed and moving freely.

Assumptions **1** Both N_2 and He are ideal gases with constant specific heats. **2** The energy stored in the container itself is negligible. **3** The cylinder is well-insulated and thus heat transfer is negligible.

Properties The gas constants and the constant volume specific heats are R = 0.2968 kPa.m^3/kg.K, c_v = 0.743 kJ/kg·°C and c_p =1.039 kJ/kg·°C for N_2, and R = 2.0769 kPa.m^3/kg.K, c_v = 3.1156 kJ/kg·°C, and c_p = 5.1926 kJ/kg·°C for He (Tables A-1 and A-2)

Analysis The mass of each gas in the cylinder is



$$m_{N_2} = \left(\frac{P_1 V_1}{RT_1}\right)_{N_2} = \frac{(500 \text{ kPa})(1 \text{ m}^3)}{(0.2968 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(353 \text{ K})} = 4.77 \text{ kg}$$

$$m_{He} = \left(\frac{P_1 V_1}{RT_1}\right)_{He} = \frac{(500 \text{ kPa})(1 \text{ m}^3)}{(2.0769 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298 \text{ K})} = 0.808 \text{ kg}$$

Taking the entire contents of the cylinder as our system, the 1st law relation can be written as

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

$$0 = \Delta U = (\Delta U)_{N_2} + (\Delta U)_{He} \longrightarrow 0 = [mc_v(T_2 - T_1)]_{N_2} + [mc_v(T_2 - T_1)]_{He}$$

Substituting,

$$(4.77 \text{ kg})(0.743 \text{ kJ/kg}\cdot^\circ\text{C})(T_f - 80)^\circ\text{C} + (0.808 \text{ kg})(3.1156 \text{ kJ/kg}\cdot^\circ\text{C})(T_f - 25)^\circ\text{C} = 0$$

It gives T_f = **57.2°C**

where T_f is the final equilibrium temperature in the cylinder.

The answer would be the **same** if the piston were not free to move since it would effect only pressure, and not the specific heats.

(*b*) We take the entire cylinder as our system, which is a closed system. Noting that the cylinder is well-insulated and thus there is no heat transfer, the entropy balance for this closed system can be expressed as

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

$$0 + S_{gen} = \Delta S_{N_2} + \Delta S_{He}$$

But first we determine the final pressure in the cylinder:

$$N_{total} = N_{N_2} + N_{He} = \left(\frac{m}{M}\right)_{N_2} + \left(\frac{m}{M}\right)_{He} = \frac{4.77 \text{ kg}}{28 \text{ kg/kmol}} + \frac{0.808 \text{ kg}}{4 \text{ kg/kmol}} = 0.372 \text{ kmol}$$

$$P_2 = \frac{N_{total} R_u T}{V_{total}} = \frac{(0.372 \text{ kmol})(8.314 \text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(330.2 \text{ K})}{2 \text{ m}^3} = 510.6 \text{ kPa}$$

Then,

$$\Delta S_{N_2} = m\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}\right)_{N_2}$$

$$= (4.77 \text{ kg})\left[(1.039 \text{ kJ/kg}\cdot\text{K})\ln\frac{330.2 \text{ K}}{353 \text{ K}} - (0.2968 \text{ kJ/kg}\cdot\text{K})\ln\frac{510.6 \text{ kPa}}{500 \text{ kPa}}\right]$$

$$= -0.361 \text{ kJ/K}$$

$$\Delta S_{\mathrm{He}} = m\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}\right)_{\mathrm{He}}$$

$$= (0.808\ \mathrm{kg})\left[(5.1926\ \mathrm{kJ/kg\cdot K})\ln\frac{330.2\ \mathrm{K}}{298\ \mathrm{K}} - (2.0769\ \mathrm{kJ/kg\cdot K})\ln\frac{510.6\ \mathrm{kPa}}{500\ \mathrm{kPa}}\right]$$

$$= 0.395\ \mathrm{kJ/K}$$

$$S_{\mathrm{gen}} = \Delta S_{\mathrm{N_2}} + \Delta S_{\mathrm{He}} = -0.361 + 0.395 = \mathbf{0.034\ kJ/K}$$

If the piston were not free to move, we would still have T_2 = 330.2 K but the volume of each gas would remain constant in this case:

$$\Delta S_{\mathrm{N_2}} = m\left(c_v \ln\frac{T_2}{T_1} - R\ln\frac{V_2}{V_1}^{\nearrow 0}\right)_{\mathrm{N_2}} = (4.77\ \mathrm{kg})(0.743\ \mathrm{kJ/kg\cdot K})\ln\frac{330.2\ \mathrm{K}}{353\ \mathrm{K}} = -0.237\ \mathrm{kJ/K}$$

$$\Delta S_{\mathrm{He}} = m\left(c_v \ln\frac{T_2}{T_1} - R\ln\frac{V_2}{V_1}^{\nearrow 0}\right)_{\mathrm{He}} = (0.808\ \mathrm{kg})(3.1156\ \mathrm{kJ/kg\cdot K})\ln\frac{330.2\ \mathrm{K}}{298\ \mathrm{K}} = 0.258\ \mathrm{kJ/K}$$

$$S_{\mathrm{gen}} = \Delta S_{\mathrm{N_2}} + \Delta S_{\mathrm{He}} = -0.237 + 0.258 = \mathbf{0.021\ \ kJ/K}$$

7-201 EES Problem 7-200 is reconsidered. The results for constant specific heats to those obtained using variable specific heats are to be compared using built-in EES or other functions.

Analysis The problem is solved using EES, and the results are given below.

```
"Knowns:"
R_u=8.314 [kJ/kmol-K]
V_N2[1]=1 [m^3]
Cv_N2=0.743 [kJ/kg-K]  "From Table A-2(a) at 27C"
R_N2=0.2968 [kJ/kg-K]  "From Table A-2(a)"
T_N2[1]=80 [C]
P_N2[1]=500 [kPa]
Cp_N2=R_N2+Cv_N2
V_He[1]=1 [m^3]
Cv_He=3.1156 [kJ/kg-K] "From Table A-2(a) at 27C"
T_He[1]=25 [C]
P_He[1]=500 [kPa]
R_He=2.0769 [kJ/kg-K]  "From Table A-2(a)"
Cp_He=R_He+Cv_He

"Solution:"

"mass calculations:"
P_N2[1]*V_N2[1]=m_N2*R_N2*(T_N2[1]+273)
P_He[1]*V_He[1]=m_He*R_He*(T_He[1]+273)

"The entire cylinder is considered to be a closed system, allowing the piston to move."
"Conservation of Energy for the closed system:"
"E_in - E_out = DELTAE,  we neglect DELTA KE and DELTA PE for the cylinder."
E_in - E_out = DELTAE
E_in =0 [kJ]
E_out = 0 [kJ]

"At the final equilibrium state, N2 and He will have a common temperature."
DELTAE= m_N2*Cv_N2*(T_2-T_N2[1])+m_He*Cv_He*(T_2-T_He[1])

"Total volume of gases:"
V_total=V_N2[1]+V_He[1]
MM_He = 4 [kg/kmol]
MM_N2 = 28 [kg/kmol]

N_total = m_He/MM_He+m_N2/MM_N2
"Final pressure at equilibrium:"
"Allowing the piston to move, the pressure on both sides is the same, P_2 is:"
P_2*V_total=N_total*R_u*(T_2+273)

S_gen_PistonMoving = DELTAS_He_PM+DELTAS_N2_PM
DELTAS_He_PM=m_He*(Cp_He*ln((T_2+273)/(T_He[1]+273))-R_He*ln(P_2/P_He[1]))
DELTAS_N2_PM=m_N2*(Cp_N2*ln((T_2+273)/(T_N2[1]+273))-R_N2*ln(P_2/P_N2[1]))

"The final temperature of the system when the piston does not move will be the same as when it
does move.  The volume of the gases remain constant and the entropy changes are given by:"

S_gen_PistNotMoving = DELTAS_He_PNM+DELTAS_N2_PNM
DELTAS_He_PNM=m_He*(Cv_He*ln((T_2+273)/(T_He[1]+273)))
DELTAS_N2_PNM=m_N2*(Cv_N2*ln((T_2+273)/(T_N2[1]+273)))
```

```
"The following uses the EES functions for the nitrogen.  Since helium is monatomic, we use the
constant specific heat approach to find its property changes."
E_in - E_out = DELTAE_VP
DELTAE_VP= m_N2*(INTENERGY(N2,T=T_2_VP)-
INTENERGY(N2,T=T_N2[1]))+m_He*Cv_He*(T_2_VP-T_He[1])

"Final Pressure for moving piston:"
P_2_VP*V_total=N_total*R_u*(T_2_VP+273)
S_gen_PistMoving_VP = DELTAS_He_PM_VP+DELTAS_N2_PM_VP
DELTAS_N2_PM_VP=m_N2*(ENTROPY(N2,T=T_2_VP,P=P_2_VP)-
ENTROPY(N2,T=T_N2[1],P=P_N2[1]))
DELTAS_He_PM_VP=m_He*(Cp_He*ln((T_2+273)/(T_He[1]+273))-R_He*ln(P_2/P_He[1]))

"Fianl N2 Pressure for piston not moving."
P_2_N2_VP*V_N2[1]=m_N2*R_N2*(T_2_VP+273)

S_gen_PistNotMoving_VP = DELTAS_He_PNM_VP+DELTAS_N2_PNM_VP
DELTAS_N2_PNM_VP = m_N2*(ENTROPY(N2,T=T_2_VP,P=P_2_N2_VP)-
ENTROPY(N2,T=T_N2[1],P=P_N2[1]))
DELTAS_He_PNM_VP=m_He*(Cv_He*ln((T_2_VP+273)/(T_He[1]+273)))
```

SOLUTION

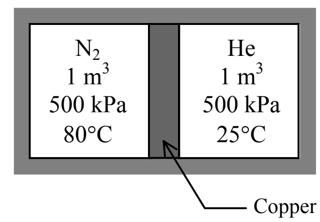
Cp_He=5.193 [kJ/kg-K]	P_2=511.1 [kPa]
Cp_N2=1.04 [kJ/kg-K]	P_2_N2_VP=467.7
Cv_He=3.116 [kJ/kg-K]	P_2_VP=511.2
Cv_N2=0.743 [kJ/kg-K]	P_He[1]=500 [kPa]
DELTAE=0 [kJ]	P_N2[1]=500 [kPa]
DELTAE_VP=0 [kJ]	R_He=2.077 [kJ/kg-K]
DELTAS_He_PM=0.3931 [kJ/K]	R_N2=0.2968 [kJ/kg-K]
DELTAS_He_PM_VP=0.3931 [kJ/K]	R_u=8.314 [kJ/kmol-K]
DELTAS_He_PNM=0.258 [kJ/K]	S_gen_PistMoving_VP=0.02993 [kJ/K]
DELTAS_He_PNM_VP=0.2583 [kJ/K]	S_gen_PistNotMoving=0.02089 [kJ/K]
DELTAS_N2_PM=-0.363 [kJ/K]	S_gen_PistNotMoving_VP=0.02106 [kJ/K]
DELTAS_N2_PM_VP=-0.3631 [kJ/K]	S_gen_PistonMoving=0.03004 [kJ/K]
DELTAS_N2_PNM=-0.2371 [kJ/K]	T_2=57.17 [C]
DELTAS_N2_PNM_VP=-0.2372 [kJ/K]	T_2_VP=57.2 [C]
E_in=0 [kJ]	T_He[1]=25 [C]
E_out=0 [kJ]	T_N2[1]=80 [C]
MM_He=4 [kg/kmol]	V_He[1]=1 [m^3]
MM_N2=28 [kg/kmol]	V_N2[1]=1 [m^3]
m_He=0.8079 [kg]	V_total=2 [m^3]
m_N2=4.772 [kg]	
N_total=0.3724 [kmol]	

7-202 An insulated cylinder is divided into two parts. One side of the cylinder contains N_2 gas and the other side contains He gas at different states. The final equilibrium temperature in the cylinder and the entropy generated are to be determined for the cases of the piston being fixed and moving freely.

Assumptions **1** Both N_2 and He are ideal gases with constant specific heats. **2** The energy stored in the container itself, except the piston, is negligible. **3** The cylinder is well-insulated and thus heat transfer is negligible. **4** Initially, the piston is at the average temperature of the two gases.

Properties The gas constants and the constant volume specific heats are R = 0.2968 kPa.m^3/kg.K, c_v = 0.743 kJ/kg·°C and c_p =1.039 kJ/kg·°C for N_2, and R = 2.0769 kPa.m^3/kg.K, c_v = 3.1156 kJ/kg·°C, and c_p = 5.1926 kJ/kg·°C for He (Tables A-1 and A-2). The specific heat of the copper at room temperature is c = 0.386 kJ/kg·°C (Table A-3).

Analysis The mass of each gas in the cylinder is



$$m_{N_2} = \left(\frac{P_1 V_1}{RT_1}\right)_{N_2} = \frac{(500\text{ kPa})(1\text{ m}^3)}{(0.2968\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(353\text{ K})} = 4.77\text{ kg}$$

$$m_{He} = \left(\frac{P_1 V_1}{RT_1}\right)_{He} = \frac{(500\text{ kPa})(1\text{m}^3)}{(2.0769\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(298\text{ K})} = 0.808\text{ kg}$$

Taking the entire contents of the cylinder as our system, the 1st law relation can be written as

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

$$0 = \Delta U = (\Delta U)_{N_2} + (\Delta U)_{He} + (\Delta U)_{Cu}$$

$$0 = [mc_v(T_2 - T_1)]_{N_2} + [mc_v(T_2 - T_1)]_{He} + [mc(T_2 - T_1)]_{Cu}$$

where

$$T_{1,\,Cu} = (80 + 25) / 2 = 52.5°\text{C}$$

Substituting,

$$(4.77\text{ kg})(0.743\text{ kJ/kg}\cdot°\text{C})(T_f - 80)°\text{C} + (0.808\text{ kg})(3.1156\text{ kJ/kg}\cdot°\text{C})(T_f - 25)°\text{C}$$
$$+ (5.0\text{ kg})(0.386\text{ kJ/kg}\cdot°\text{C})(T_f - 52.5)°\text{C} = 0$$

It gives

$$T_f = \mathbf{56.0°C}$$

where T_f is the final equilibrium temperature in the cylinder.

The answer would be the **same** if the piston were not free to move since it would effect only pressure, and not the specific heats.

(b) We take the entire cylinder as our system, which is a closed system. Noting that the cylinder is well-insulated and thus there is no heat transfer, the entropy balance for this closed system can be expressed as

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

$$0 + S_{gen} = \Delta S_{N_2} + \Delta S_{He} + \Delta S_{piston}$$

But first we determine the final pressure in the cylinder:

$$N_{total} = N_{N_2} + N_{He} = \left(\frac{m}{M}\right)_{N_2} + \left(\frac{m}{M}\right)_{He} = \frac{4.77\text{ kg}}{28\text{ kg/kmol}} + \frac{0.808\text{ kg}}{4\text{ kg/kmol}} = 0.372\text{ kmol}$$

$$P_2 = \frac{N_{total} R_u T}{V_{total}} = \frac{(0.372\text{ kmol})(8.314\text{ kPa}\cdot\text{m}^3/\text{kmol}\cdot\text{K})(329\text{ K})}{2\text{ m}^3} = 508.8\text{ kPa}$$

Then,

$$\Delta S_{N_2} = m\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}\right)_{N_2}$$
$$= (4.77\text{ kg})\left[(1.039\text{ kJ/kg}\cdot\text{K})\ln\frac{329\text{ K}}{353\text{ K}} - (0.2968\text{ kJ/kg}\cdot\text{K})\ln\frac{508.8\text{ kPa}}{500\text{ kPa}}\right]$$
$$= -0.374\text{ kJ/K}$$

$$\Delta S_{He} = m\left(c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}\right)_{He}$$
$$= (0.808\text{ kg})\left[(5.1926\text{ kJ/kg}\cdot\text{K})\ln\frac{329\text{ K}}{298\text{ K}} - (2.0769\text{ kJ/kg}\cdot\text{K})\ln\frac{508.8\text{ kPa}}{500\text{ kPa}}\right]$$
$$= 0.386\text{ kJ/K}$$

$$\Delta S_{piston} = \left(mc\ln\frac{T_2}{T_1}\right)_{piston} = (5\text{ kg})(0.386\text{ kJ/kg}\cdot\text{K})\ln\frac{329\text{ K}}{325.5\text{ K}} = 0.021\text{ kJ/K}$$

$$S_{gen} = \Delta S_{N_2} + \Delta S_{He} + \Delta S_{piston} = -0.374 + 0.386 + 0.021 = \mathbf{0.033\text{ kJ/K}}$$

If the piston were not free to move, we would still have T_2 = 329 K but the volume of each gas would remain constant in this case:

$$\Delta S_{N_2} = m\left(c_v \ln\frac{T_2}{T_1} - R\ln\frac{V_2}{V_1}^{\nearrow 0}\right)_{N_2} = (4.77\text{ kg})(0.743\text{ kJ/kg}\cdot\text{K})\ln\frac{329\text{ K}}{353\text{ K}} = -0.250\text{ kJ/K}$$

$$\Delta S_{He} = m\left(c_v \ln\frac{T_2}{T_1} - R\ln\frac{V_2}{V_1}^{\nearrow 0}\right)_{He} = (0.808\text{ kg})(3.1156\text{ kJ/kg}\cdot\text{K})\ln\frac{329\text{ K}}{298\text{ K}} = 0.249\text{ kJ/K}$$

$$S_{gen} = \Delta S_{N_2} + \Delta S_{He} + \Delta S_{piston} = -0.250 + 0.249 + 0.021 = \mathbf{0.020\text{ kJ/K}}$$

7-203 An insulated rigid tank equipped with an electric heater initially contains pressurized air. A valve is opened, and air is allowed to escape at constant temperature until the pressure inside drops to a specified value. The amount of electrical work done during this process and the total entropy change are to be determined.

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 exit temperature (and enthalpy) of air remains constant. **2** Kinetic and potential energies are negligible. **3** The tank is insulated and thus heat transfer is negligible. **4** Air is an ideal gas with variable specific heats.

Properties The gas constant is R = 0.287 kPa.m^3/kg.K (Table A-1). The properties of air are (Table A-17)

$$T_e = 330 \text{ K} \longrightarrow h_e = 330.34 \text{ kJ/kg}$$
$$T_1 = 330 \text{ K} \longrightarrow u_1 = 235.61 \text{ kJ/kg}$$
$$T_2 = 330 \text{ K} \longrightarrow u_2 = 235.61 \text{ kJ/kg}$$

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

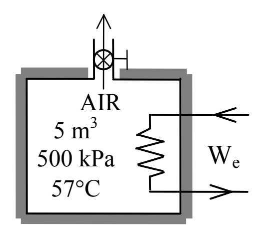
Energy balance: $$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}}$$

$$W_{\text{e,in}} - m_e h_e = m_2 u_2 - m_1 u_1 \quad (\text{since } Q \cong \text{ke} \cong \text{pe} \cong 0)$$

The initial and the final masses of air in the tank are

$$m_1 = \frac{P_1 \boldsymbol{V}}{RT_1} = \frac{(500 \text{ kPa})(5 \text{ m}^3)}{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(330 \text{ K})} = 26.40 \text{ kg}$$

$$m_2 = \frac{P_2 \boldsymbol{V}}{RT_2} = \frac{(200 \text{ kPa})(5 \text{ m}^3)}{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(330 \text{ K})} = 10.56 \text{ kg}$$



Then from the mass and energy balances,

$$m_e = m_1 - m_2 = 26.40 - 10.56 = 15.84 \text{ kg}$$

$$\begin{aligned} W_{\text{e,in}} &= m_e h_e + m_2 u_2 - m_1 u_1 \\ &= (15.84 \text{ kg})(330.34 \text{ kJ/kg}) + (10.56 \text{ kg})(235.61 \text{ kJ/kg}) - (26.40 \text{ kg})(235.61 \text{ kJ/kg}) = \mathbf{1501 \text{ kJ}} \end{aligned}$$

(b) The total entropy change, or the total entropy generation within the tank boundaries is determined from an entropy balance on the tank expressed as

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

$$-m_e s_e + S_{\text{gen}} = \Delta S_{\text{tank}}$$

or,

$$\begin{aligned} S_{\text{gen}} &= m_e s_e + \Delta S_{\text{tank}} = m_e s_e + (m_2 s_2 - m_1 s_1) \\ &= (m_1 - m_2)s_e + (m_2 s_2 - m_1 s_1) = m_2(s_2 - s_e) - m_1(s_1 - s_e) \end{aligned}$$

Assuming a constant average pressure of (500 + 200)/2 = 350 kPa for the exit stream, the entropy changes are determined to be

$$s_2 - s_e = c_p \ln\frac{T_2}{T_e}^{\nearrow 0} - R\ln\frac{P_2}{P_e} = -R\ln\frac{P_2}{P_e} = -(0.287 \text{ kJ/kg}\cdot\text{K})\ln\frac{200 \text{ kPa}}{350 \text{ kPa}} = 0.1606 \text{ kJ/kg}\cdot\text{K}$$

$$s_1 - s_e = c_p \ln\frac{T_1}{T_e}^{\nearrow 0} - R\ln\frac{P_2}{P_e} = -R\ln\frac{P_1}{P_e} = -(0.287 \text{ kJ/kg}\cdot\text{K})\ln\frac{500 \text{ kPa}}{350 \text{ kPa}} = -0.1024 \text{ kJ/kg}\cdot\text{K}$$

Therefore, the total entropy generated within the tank during this process is

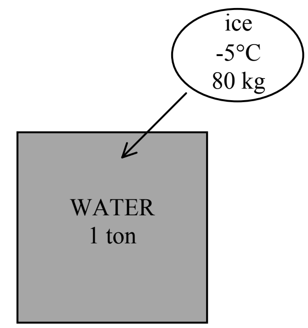
$$S_{\text{gen}} = (10.56 \text{ kg})(0.1606 \text{ kJ/kg}\cdot\text{K}) - (26.40 \text{ kg})(-0.1024 \text{ kJ/kg}\cdot\text{K}) = \mathbf{4.40 \text{ kJ/K}}$$

7-204 A 1- ton (1000 kg) of water is to be cooled in a tank by pouring ice into it. The final equilibrium temperature in the tank and the entropy generation are to be determined.

Assumptions **1** Thermal properties of the ice and water are constant. **2** Heat transfer to the water tank is negligible. **3** There is no stirring by hand or a mechanical device (it will add energy).

Properties The specific heat of water at room temperature is c = 4.18 kJ/kg·°C, and the specific heat of ice at about 0°C is c = 2.11 kJ/kg·°C (Table A-3). The melting temperature and the heat of fusion of ice at 1 atm are 0°C and 333.7 kJ/kg..

Analysis (*a*) We take the ice and the water as the system, and disregard any heat transfer between the system and the surroundings. Then the energy balance for this process can be written as



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

$$0 = \Delta U$$

$$0 = \Delta U_{\text{ice}} + \Delta U_{\text{water}}$$

$$[mc(0°\text{C} - T_1)_{\text{solid}} + mh_{if} + mc(T_2 - 0°\text{C})_{\text{liquid}}]_{\text{ice}} + [mc(T_2 - T_1)]_{\text{water}} = 0$$

Substituting,

$$(80\text{ kg})\{(2.11\text{ kJ/kg}\cdot°\text{C})[0-(-5)]°\text{C} + 333.7\text{ kJ/kg} + (4.18\text{ kJ/kg}\cdot°\text{C})(T_2 - 0)°\text{C}\}$$
$$+ (1000\text{ kg})(4.18\text{ kJ/kg}\cdot°\text{C})(T_2 - 20)°\text{C} = 0$$

It gives T_2 = **12.42°C**

which is the final equilibrium temperature in the tank.

(*b*) We take the ice and the water as our system, which is a closed system. Considering that the tank is well-insulated and thus there is no heat transfer, the entropy balance for this closed system can be expressed as

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

$$0 + S_{\text{gen}} = \Delta S_{\text{ice}} + \Delta S_{\text{water}}$$

where

$$\Delta S_{\text{water}} = \left(mc\ln\frac{T_2}{T_1}\right)_{\text{water}} = (1000\text{ kg})(4.18\text{ kJ/kg}\cdot\text{K})\ln\frac{285.42\text{ K}}{293\text{ K}} = -109.6\text{ kJ/K}$$

$$\Delta S_{\text{ice}} = \left(\Delta S_{\text{solid}} + \Delta S_{\text{melting}} + \Delta S_{\text{liquid}}\right)_{\text{ice}}$$

$$= \left(\left(mc\ln\frac{T_{\text{melting}}}{T_1}\right)_{\text{solid}} + \frac{mh_{if}}{T_{\text{melting}}} + \left(mc\ln\frac{T_2}{T_1}\right)_{\text{liquid}}\right)_{\text{ice}}$$

$$= (80\text{ kg})\left((2.11\text{ kJ/kg}\cdot\text{K})\ln\frac{273\text{ K}}{268\text{ K}} + \frac{333.7\text{ kJ/kg}}{273\text{ K}} + (4.18\text{ kJ/kg}\cdot\text{K})\ln\frac{285.42\text{ K}}{273\text{ K}}\right)$$

$$= 115.8\text{ kJ/K}$$

Then,

$$S_{\text{gen}} = \Delta S_{\text{water}} + \Delta S_{\text{ice}} = -109.6 + 115.8 = \mathbf{6.2\ kJ/K}$$

7-205 An insulated cylinder initially contains a saturated liquid-vapor mixture of water at a specified temperature. The entire vapor in the cylinder is to be condensed isothermally by adding ice inside the cylinder. The amount of ice added and the entropy generation are to be determined.

Assumptions **1** Thermal properties of the ice are constant. **2** The cylinder is well-insulated and thus heat transfer is negligible. **3** There is no stirring by hand or a mechanical device (it will add energy).

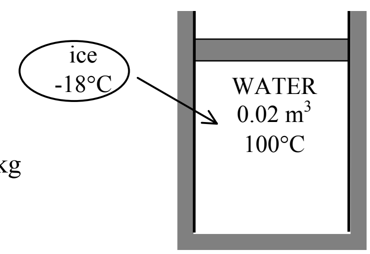
Properties The specific heat of ice at about 0°C is c = 2.11 kJ/kg·°C (Table A-3). The melting temperature and the heat of fusion of ice at 1 atm are 0°C and 333.7 kJ/kg.

Analysis (*a*) We take the contents of the cylinder (ice and saturated water) as our system, which is a closed system. Noting that the temperature and thus the pressure remains constant during this phase change process and thus $W_b + \Delta U = \Delta H$, the energy balance for this system can be written as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc. energies}}} \longrightarrow W_{b,in} = \Delta U \;\rightarrow\; \Delta H = 0 \longrightarrow \Delta H_{\text{ice}} + \Delta H_{\text{water}} = 0$$

or $$[mc(0°\text{C} - T_1)_{\text{solid}} + mh_{if} + mc(T_2 - 0°\text{C})_{\text{liquid}}]_{\text{ice}} + [m(h_2 - h_1)]_{\text{water}} = 0$$

The properties of water at 100°C are (Table A-4)



$$v_f = 0.001043, \quad v_g = 1.6720 \text{ m}^3/\text{kg}$$
$$h_f = 419.17, \quad h_{fg} = 2256.4 \text{ kJ.kg}$$
$$s_f = 1.3072 \quad s_{fg} = 6.0490 \text{ kJ/kg.K}$$

$$v_1 = v_f + x_1 v_{fg} = 0.001043 + (0.1)(1.6720 - 0.001043) = 0.16814 \text{ m}^3/\text{kg}$$
$$h_1 = h_f + x_1 h_{fg} = 419.17 + (0.1)(2256.4) = 644.81 \text{ kJ/kg}$$
$$s_1 = s_f + x_1 s_{fg} = 1.3072 + (0.1)(6.0470) = 1.9119 \text{ kJ/kg}\cdot\text{K}$$
$$h_2 = h_{f@100^\circ\text{C}} = 419.17 \text{ kJ/kg}$$
$$s_2 = s_{f@100^\circ\text{C}} = 1.3072 \text{ kJ/kg}\cdot\text{K}$$
$$m_{\text{steam}} = \frac{V_1}{v_1} = \frac{0.02 \text{ m}^3}{0.16814 \text{ m}^3/\text{kg}} = 0.119 \text{ kg}$$

Noting that $T_{1,\text{ ice}}$ = -18°C and T_2 = 100°C and substituting gives

$$m\{(2.11 \text{ kJ/kg.K})[0-(-18)] + 333.7 \text{ kJ/kg} + (4.18 \text{ kJ/kg·°C})(100-0)°\text{C}\} + (0.119 \text{ kg})(419.17 - 644.81) \text{ kJ/kg} = 0$$

m = 0.034 kg = **34.0 g ice**

(*b*) We take the ice and the steam as our system, which is a closed system. Considering that the tank is well-insulated and thus there is no heat transfer, the entropy balance for this closed system can be expressed as

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

$$0 + S_{\text{gen}} = \Delta S_{\text{ice}} + \Delta S_{\text{steam}}$$

$$\Delta S_{\text{steam}} = m(s_2 - s_1) = (0.119 \text{ kg})(1.3072 - 1.9119)\text{kJ/kg}\cdot\text{K} = -0.0719 \text{ kJ/K}$$

$$\Delta S_{\text{ice}} = (\Delta S_{\text{solid}} + \Delta S_{\text{melting}} + \Delta S_{\text{liquid}})_{\text{ice}} = \left(\left(mc\ln\frac{T_{\text{melting}}}{T_1}\right)_{\text{solid}} + \frac{mh_{if}}{T_{\text{melting}}} + \left(mc\ln\frac{T_2}{T_1}\right)_{\text{liquid}}\right)_{\text{ice}}$$

$$= (0.034 \text{ kg})\left((2.11 \text{ kJ/kg}\cdot\text{K})\ln\frac{273.15 \text{ K}}{255.15 \text{ K}} + \frac{333.7 \text{ kJ/kg}}{273.15 \text{ K}} + (4.18 \text{ kJ/kg}\cdot\text{K})\ln\frac{373.15 \text{ K}}{273.15 \text{ K}}\right) = 0.0907 \text{ kJ/K}$$

Then, $$S_{\text{gen}} = \Delta S_{\text{steam}} + \Delta S_{\text{ice}} = -0.0719 + 0.0907 = \mathbf{0.0188 \text{ kJ/K}}$$

7-206 An evacuated bottle is surrounded by atmospheric air. A valve is opened, and air is allowed to fill the bottle. The amount of heat transfer through the wall of the bottle when thermal and mechanical equilibrium is established and the amount of entropy generated are to be determined.

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 at the inlet remains constant. **2** Air is an ideal gas. **3** Kinetic and potential energies are negligible. **4** There are no work interactions involved. **5** The direction of heat transfer is to the air in the bottle (will be verified).

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

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

Mass balance: $m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \rightarrow m_i = m_2 \quad (\text{since } m_{\text{out}} = m_{\text{initial}} = 0)$

Energy balance:

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

$$Q_{\text{in}} + m_i h_i = m_2 u_2 \quad (\text{since } W \cong E_{\text{out}} = E_{\text{initial}} = \text{ke} \cong \text{pe} \cong 0)$$

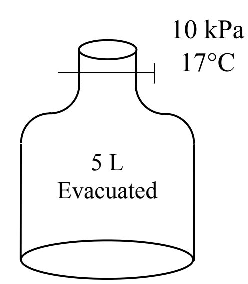
Combining the two balances:

$$Q_{\text{in}} = m_2(u_2 - h_i)$$

where

$$m_2 = \frac{P_2 V}{RT_2} = \frac{(100\text{ kPa})(0.005\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(290\text{ K})} = 0.0060\text{ kg}$$

$$T_i = T_2 = 290\text{ K} \xrightarrow{\text{Table A-17}} \begin{array}{l} h_i = 290.16\text{ kJ/kg} \\ u_2 = 206.91\text{ kJ/kg} \end{array}$$



Substituting,

$$Q_{\text{in}} = (0.0060\text{ kg})(206.91 - 290.16)\text{ kJ/kg} = -0.5\text{ kJ} \quad \rightarrow \quad Q_{\text{out}} = \mathbf{0.5\text{ kJ}}$$

Note that the negative sign for heat transfer indicates that the assumed direction is wrong. Therefore, we reverse the direction.

The entropy generated during this process is determined by applying the entropy balance on an *extended system* that includes the bottle and its immediate surroundings so that the boundary temperature of the extended system is the temperature of the surroundings at all times. The entropy balance for it can be expressed as

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

$$m_i s_i - \frac{Q_{\text{out}}}{T_{\text{b,in}}} + S_{\text{gen}} = \Delta S_{\text{tank}} = m_2 s_2 - m_1 s_1^{\nearrow 0} = m_2 s_2$$

Therefore, the total entropy generated during this process is

$$S_{\text{gen}} = -m_i s_i + m_2 s_2 + \frac{Q_{\text{out}}}{T_{\text{b,out}}} = m_2(s_2 - s_i)^{\nearrow 0} + \frac{Q_{\text{out}}}{T_{\text{b,out}}} = \frac{Q_{\text{out}}}{T_{\text{surr}}} = \frac{0.5\text{ kJ}}{290\text{ K}} = \mathbf{0.0017\text{ kJ/K}}$$

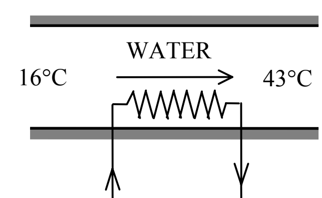
7-207 Water is heated from 16°C to 43°C by an electric resistance heater placed in the water pipe as it flows through a showerhead steadily at a rate of 10 L/min. The electric power input to the heater and the rate of entropy generation are to be determined. The reduction in power input and entropy generation as a result of installing a 50% efficient regenerator are also to be determined.

Assumptions **1** This is a steady-flow process since there is no change with time at any point within the system and thus $\Delta m_{\rm CV} = 0$ and $\Delta E_{\rm CV} = 0$. **2** Water is an incompressible substance with constant specific heats. **3** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **4** Heat losses from the pipe are negligible.

Properties The density of water is given to be ρ = 1 kg/L. The specific heat of water at room temperature is $c = 4.18$ kJ/kg·°C (Table A-3).

Analysis (*a*) We take the pipe as the system. This is a *control volume* since mass crosses the system boundary during the process. We observe that there is only one inlet and one exit and thus $\dot m_1 = \dot m_2 = \dot m$. Then the energy balance for this steady-flow system can be expressed in the rate form as

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



$$\dot W_{\rm e,in} + \dot m h_1 = \dot m h_2 \quad (\text{since } \Delta\text{ke} \cong \Delta\text{pe} \cong 0)$$

$$\dot W_{\rm e,in} = \dot m (h_2 - h_1) = \dot m c (T_2 - T_1)$$

where $\qquad \dot m = \rho \dot{\boldsymbol{V}} = (1 \text{ kg/L})(10 \text{ L/min}) = 10 \text{ kg/min}$

Substituting, $\qquad \dot W_{\rm e,in} = (10/60 \text{ kg/s})(4.18 \text{ kJ/kg}\cdot\text{°C})(43-16)\text{°C} = \mathbf{18.8\ kW}$

The rate of entropy generation in the heating section during this process is determined by applying the entropy balance on the heating section. Noting that this is a steady-flow process and heat transfer from the heating section is negligible,

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

$$\dot m s_1 - \dot m s_2 + \dot S_{\rm gen} = 0 \longrightarrow \dot S_{\rm gen} = \dot m (s_2 - s_1)$$

Noting that water is an incompressible substance and substituting,

$$\dot S_{\rm gen} = \dot m c \ln\frac{T_2}{T_1} = (10/60 \text{ kg/s})(4.18 \text{ kJ/kg}\cdot\text{K})\ln\frac{316 \text{ K}}{289 \text{ K}} = \mathbf{0.0622\ kJ/K}$$

(*b*) The energy recovered by the heat exchanger is

$$\dot Q_{\rm saved} = \varepsilon \dot Q_{\max} = \varepsilon \dot m C (T_{\max} - T_{\min}) = 0.5(10/60 \text{ kg/s})(4.18 \text{ kJ/kg}\cdot\text{°C})(39-16)\text{°C} = 8.0 \text{ kJ/s} = 8.0 \text{ kW}$$

Therefore, 8.0 kW less energy is needed in this case, and the required electric power in this case reduces to

$$\dot W_{\rm in,new} = \dot W_{\rm in,old} - \dot Q_{\rm saved} = 18.8 - 8.0 = \mathbf{10.8\ kW}$$

Taking the cold water stream in the heat exchanger as our control volume (a steady-flow system), the temperature at which the cold water leaves the heat exchanger and enters the electric resistance heating section is determined from

$$\dot Q = \dot m c (T_{\rm c,out} - T_{\rm c,in})$$

Substituting, $\qquad 8 \text{ kJ/s} = (10/60 \text{ kg/s})(4.18 \text{ kJ/kg}\cdot{}^\circ\text{C})(T_{\rm c,out} - 16^\circ\text{C})$

It yields $\qquad T_{\rm c,out} = 27.5^\circ\text{C} = 300.5\text{K}$

The rate of entropy generation in the heating section in this case is determined similarly to be

$$\dot S_{\rm gen} = \dot m c \ln\frac{T_2}{T_1} = (10/60 \text{ kg/s})(4.18 \text{ kJ/kg}\cdot\text{K})\ln\frac{316 \text{ K}}{300.5 \text{ K}} = \mathbf{0.0350\ kJ/K}$$

Thus the reduction in the rate of entropy generation within the heating section is

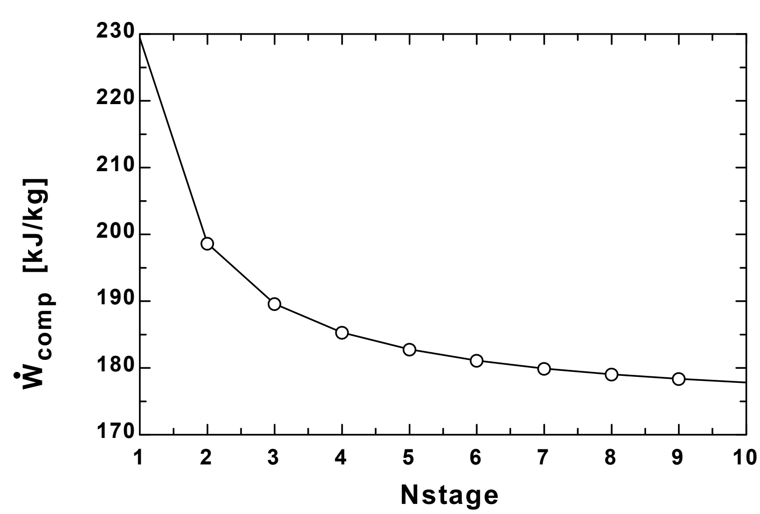
$$\dot S_{\rm reduction} = 0.0622 - 0.0350 = \mathbf{0.0272\ kW/K}$$

7-208 EES Using EES (or other) software, the work input to a multistage compressor is to be determined for a given set of inlet and exit pressures for any number of stages. The pressure ratio across each stage is assumed to be identical and the compression process to be polytropic. The compressor work is to be tabulated and plotted against the number of stages for P_1 = 100 kPa, T_1 = 17°C, P_2 = 800 kPa, and n = 1.35 for air.

Analysis The problem is solved using EES, and the results are tabulated and plotted below.

```
GAS$ = 'Air'
Nstage = 2  "number of stages of compression with intercooling, each having same pressure
ratio."
n=1.35
MM=MOLARMASS(GAS$)
R_u = 8.314 [kJ/kmol-K]
R=R_u/MM
k=1.4
P1=100 [kPa]
T1=17 [C]
P2=800 [kPa]
R_p = (P2/P1)^(1/Nstage)
W_dot_comp= Nstage*n*R*(T1+273)/(n-1)*((R_p)^((n-1)/n) - 1)
```

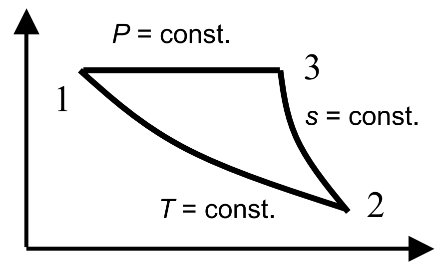
Nstage	W_{comp} [kJ/kg]
1	229.4
2	198.7
3	189.6
4	185.3
5	182.8
6	181.1
7	179.9
8	179
9	178.4
10	177.8



7-209 A piston-cylinder device contains air that undergoes a reversible thermodynamic cycle composed of three processes. The work and heat transfer for each process are to be determined.

Assumptions **1** All processes are reversible. **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 kPa.m^3/kg.K (Table A-1).



Analysis Using variable specific heats, the properties can be determined using the air table as follows

$$T_1 = T_2 = 300\text{ K} \longrightarrow \begin{array}{l} u_1 = u_2 = 214.07\text{ kJ/kg} \\ s_1^0 = s_2^0 = 1.70203\text{ kJ/kg.K} \\ P_{r1} = P_{r2} = 1.3860 \end{array}$$

$$P_{r3} = \frac{P_3}{P_2} P_{r2} = \frac{400\text{ kPa}}{150\text{ kPa}}(1.3860) = 3.696 \longrightarrow \begin{array}{l} u_3 = 283.71\text{ kJ/kg} \\ T_3 = 396.6\text{ K} \end{array}$$

The mass of the air and the volumes at the various states are

$$m = \frac{P_1 V_1}{RT_1} = \frac{(400\text{ kPa})(0.3\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})} = 1.394\text{ kg}$$

$$V_2 = \frac{mRT_2}{P_2} = \frac{(1.394\text{ kg})(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\text{ K})}{150\text{ kPa}} = 0.8\text{ m}^3$$

$$V_3 = \frac{mRT_3}{P_3} = \frac{(1.394\text{ kg})(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(396.6\text{ K})}{400\text{ kPa}} = 0.3967\text{ m}^3$$

Process 1-2: Isothermal expansion ($T_2 = T_1$)

$$\Delta S_{1-2} = -mR\ln\frac{P_2}{P_1} = (1.394\text{ kg})(0.287\text{ kJ/kg.K})\ln\frac{150\text{ kPa}}{400\text{ kPa}} = 0.3924\text{ kJ/kg.K}$$

$$Q_{\text{in},1-2} = T_1 \Delta S_{1-2} = (300\text{ K})(0.3924\text{ kJ/K}) = \mathbf{117.7\text{ kJ}}$$

$$W_{\text{out},1-2} = Q_{\text{in},1-2} = \mathbf{117.7\text{ kJ}}$$

Process 2-3: Isentropic (reversible-adiabatic) compression ($s_2 = s_1$)

$$W_{\text{in},2-3} = m(u_3 - u_2) = (1.394\text{ kg})(283.71 - 214.07)\text{ kJ/kg} = \mathbf{97.1\text{ kJ}}$$

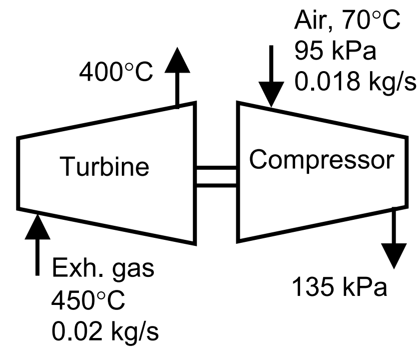
$$Q_{2\text{-}3} = \mathbf{0\text{ kJ}}$$

Process 3-1: Constant pressure compression process ($P_1 = P_3$)

$$W_{\text{in},3-1} = P_3(V_3 - V_1) = (400\text{ kg})(0.3924 - 0.3)\text{ kJ/kg} = \mathbf{37.0\text{ kJ}}$$

$$Q_{\text{out},3-1} = W_{\text{in},3-1} - m(u_1 - u_3) = 37.0\text{ kJ} - (1.394\text{ kg})(214.07 - 283.71)\text{ kJ/kg} = \mathbf{135.8\text{ kJ}}$$

7-210 The turbocharger of an internal combustion engine consisting of a turbine driven by hot exhaust gases and a compressor driven by the turbine is considered. The air temperature at the compressor exit and the isentropic efficiency of the compressor are to be determined.



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

Properties The specific heat of exhaust gases at the average temperature of 425ºC is c_p = 1.075 kJ/kg.K and properties of air at an anticipated average temperature of 100ºC are c_p = 1.011 kJ/kg.K and k =1.397 (Table A-2).

Analysis (*a*) The turbine power output is determined from

$$\begin{aligned}\dot{W}_\mathrm{T} &= \dot{m}_\mathrm{exh} c_p (T_1 - T_2) \\ &= (0.02\ \mathrm{kg/s})(1.075\ \mathrm{kJ/kg.°C})(450 - 400)\mathrm{°C} = 1.075\ \mathrm{kW}\end{aligned}$$

For a mechanical efficiency of 95% between the turbine and the compressor,

$$\dot{W}_\mathrm{C} = \eta_m \dot{W}_\mathrm{T} = (0.95)(1.075\ \mathrm{kW}) = 1.021\ \mathrm{kW}$$

Then, the air temperature at the compressor exit becomes

$$\begin{aligned}\dot{W}_\mathrm{C} &= \dot{m}_\mathrm{air} c_p (T_2 - T_1) \\ 1.021\ \mathrm{kW} &= (0.018\ \mathrm{kg/s})(1.011\ \mathrm{kJ/kg.°C})(T_2 - 70)\mathrm{°C} \\ T_2 &= \mathbf{126.1°C}\end{aligned}$$

(*b*) The air temperature at the compressor exit for the case of isentropic process is

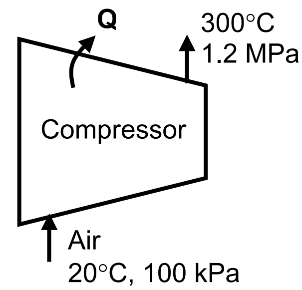
$$T_{2s} = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = (70 + 273\ \mathrm{K})\left(\frac{135\ \mathrm{kPa}}{95\ \mathrm{kPa}}\right)^{(1.397-1)/1.397} = 379\ \mathrm{K} = 106°\mathrm{C}$$

The isentropic efficiency of the compressor is determined to be

$$\eta_\mathrm{C} = \frac{T_{2s} - T_1}{T_2 - T_1} = \frac{106 - 70}{126.1 - 70} = \mathbf{0.642}$$

7-211 Air is compressed in a compressor that is intentionally cooled. The work input, the isothermal efficiency, and the entropy generation are to be determined.

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



Properties The gas constant of air is R = 0.287 kJ/kg.K and the specific heat of air at an average temperature of (20+300)/2 = 160ºC = 433 K is c_p = 1.018 kJ/kg.K (Table A-2).

Analysis (*a*) The power input is determined from an energy balance on the control volume

$$\begin{aligned}\dot{W}_\mathrm{C} &= \dot{m}c_p(T_2 - T_1) + \dot{Q}_\mathrm{out} \\ &= (0.4\ \mathrm{kg/s})(1.018\ \mathrm{kJ/kg.°C})(300-20)\mathrm{°C} + 15\ \mathrm{kW} \\ &= \mathbf{129.0\ kW}\end{aligned}$$

(*b*) The power input for a reversible-isothermal process is given by

$$\dot{W}_{T=\mathrm{const.}} = \dot{m}RT_1 \ln\frac{P_2}{P_1} = (0.4\ \mathrm{kg/s})(0.287\ \mathrm{kJ/kg.K})(20+273\ \mathrm{K})\ln\left(\frac{1200\ \mathrm{kPa}}{100\ \mathrm{kPa}}\right) = 83.6\ \mathrm{kW}$$

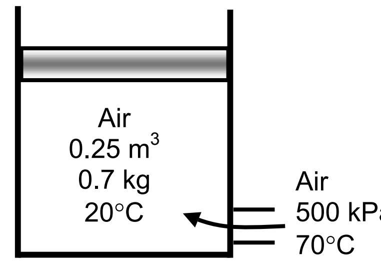
Then, the isothermal efficiency of the compressor becomes

$$\eta_T = \frac{\dot{W}_{T=\mathrm{const.}}}{\dot{W}_\mathrm{C}} = \frac{83.6\ \mathrm{kW}}{129.0\ \mathrm{kW}} = \mathbf{0.648}$$

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

$$\begin{aligned}\dot{S}_\mathrm{gen} &= \Delta\dot{S}_\mathrm{air} + \Delta\dot{S}_\mathrm{surr} = c_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1} + \frac{\dot{Q}_\mathrm{out}}{T_\mathrm{surr}} \\ &= (1.018\ \mathrm{kJ/kg.K})\ln\frac{300+273\ \mathrm{K}}{20+273\ \mathrm{K}} - (0.287\ \mathrm{kJ/kg.K})\ln\frac{1200\ \mathrm{kPa}}{100\ \mathrm{kPa}} + \frac{15\ \mathrm{kW}}{(20+273)\ \mathrm{K}} \\ &= \mathbf{0.0390\ kW/K}\end{aligned}$$

7-212 Air is allowed to enter an insulated piston-cylinder device until the volume of the air increases by 50%. The final temperature in the cylinder, the amount of mass that has entered, the work done, and the entropy generation are to be determined.



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

Properties The gas constant of air is R = 0.287 kJ/kg.K and the specific heats of air at room temperature are c_p = 1.005 kJ/kg.K, c_v = 0.718 kJ/kg.K (Table A-2).

Analysis The initial pressure in the cylinder is

$$P_1 = \frac{m_1 R T_1}{\mathbf{V}_1} = \frac{(0.7\text{ kg})(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(20+273\text{ K})}{0.25\text{ m}^3} = 235.5\text{ kPa}$$

$$m_2 = \frac{P_2 \mathbf{V}_2}{RT_2} = \frac{(235.5\text{ kPa})(1.5\times 0.25\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})T_2} = \frac{307.71}{T_2}$$

A mass balance on the system gives the expression for the mass entering the cylinder

$$m_i = m_2 - m_1 = \frac{307.71}{T_2} - 0.7$$

(c) Noting that the pressure remains constant, the boundary work is determined to be

$$W_{\text{b,out}} = P_1(\mathbf{V}_2 - \mathbf{V}_1) = (235.5\text{ kPa})(1.5\times 0.25\text{ - }0.5)\text{m}^3 = \mathbf{29.43\text{ kJ}}$$

(a) An energy balance on the system may be used to determine the final temperature

$$m_i h_i - W_{\text{b,out}} = m_2 u_2 - m_1 u_1$$

$$m_i c_p T_i - W_{\text{b,out}} = m_2 c_v T_2 - m_1 c_v T_1$$

$$\left(\frac{307.71}{T_2} - 0.7\right)(1.005)(70+273) - 29.43 = \left(\frac{307.71}{T_2}\right)(0.718)T_2 - (0.7)(0.718)(20+273)$$

There is only one unknown, which is the final temperature. By a trial-error approach or using EES, we find

T_2 = **308.0 K**

(b) The final mass and the amount of mass that has entered are

$$m_2 = \frac{307.71}{308.0} = 0.999\text{ kg}$$

$$m_i = m_2 - m_1 = 0.999 - 0.7 = \mathbf{0.299\text{ kg}}$$

(d) The rate of entropy generation is determined from

$$S_{\text{gen}} = m_2 s_2 - m_1 s_1 - m_i s_i = m_2 s_2 - m_1 s_1 - (m_2 - m_1)s_i = m_2(s_2 - s_i) - m_1(s_1 - s_i)$$

$$= m_2\left(c_p \ln\frac{T_2}{T_i} - R\ln\frac{P_2}{P_i}\right) - m_1\left(c_p \ln\frac{T_1}{T_i} - R\ln\frac{P_1}{P_i}\right)$$

$$= (0.999\text{ kg})\left[(1.005\text{ kJ/kg.K})\ln\left(\frac{308\text{ K}}{343\text{ K}}\right) - (0.287\text{ kJ/kg.K})\ln\left(\frac{235.5\text{ kPa}}{500\text{ kPa}}\right)\right]$$

$$-(0.7\text{ kg})\left[(1.005\text{ kJ/kg.K})\ln\left(\frac{293\text{ K}}{343\text{ K}}\right) - (0.287\text{ kJ/kg.K})\ln\left(\frac{235.5\text{ kPa}}{500\text{ kPa}}\right)\right]$$

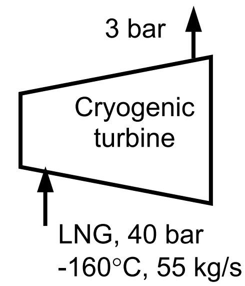
$$= \mathbf{0.0673\text{ kJ/K}}$$

7-213 A cryogenic turbine in a natural gas liquefaction plant produces 350 kW of power. The efficiency of the turbine is to be determined.

Assumptions **1** The turbine operates steadily. **2** The properties of methane is used for natural gas.

Properties The density of natural gas is given to be 423.8 kg/m^3.

Analysis The maximum possible power that can be obtained from this turbine for the given inlet and exit pressures can be determined from



$$\dot{W}_{\max} = \frac{\dot{m}}{\rho}(P_{\text{in}} - P_{\text{out}}) = \frac{(55\text{ kg/s})}{423.8\text{ kg/m}^3}(4000 - 300)\text{kPa} = 480.2\text{ kW}$$

Given the actual power, the efficiency of this cryogenic turbine becomes

$$\eta = \frac{\dot{W}}{\dot{W}_{\max}} = \frac{350\text{ kW}}{480.2\text{ kW}} = \mathbf{0.729} = \mathbf{72.9\%}$$

This efficiency is also known as hydraulic efficiency since the cryogenic turbine handles natural gas in liquid state as the hydraulic turbine handles liquid water.

Fundamentals of Engineering (FE) Exam Problems

7-214 Steam is condensed at a constant temperature of 30°C as it flows through the condenser of a power plant by rejecting heat at a rate of 55 MW. The rate of entropy change of steam as it flows through the condenser is

(a) –1.83 MW/K (b) –0.18 MW/K (c) 0 MW/K (d) 0.56 MW/K (e) 1.22 MW/K

Answer (b) –0.18 MW/K

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
T1=30 "C"
Q_out=55 "MW"
S_change=-Q_out/(T1+273)  "MW/K"

"Some Wrong Solutions with Common Mistakes:"
W1_S_change=0 "Assuming no change"
W2_S_change=Q_out/T1 "Using temperature in C"
W3_S_change=Q_out/(T1+273) "Wrong sign"
W4_S_change=-s_fg "Taking entropy of vaporization"
s_fg=(ENTROPY(Steam_IAPWS,T=T1,x=1)-ENTROPY(Steam_IAPWS,T=T1,x=0))
```

7-215 Steam is compressed from 6 MPa and 300°C to 10 MPa isentropically. The final temperature of the steam is

(a) 290°C (b) 300°C (c) 311°C (d) 371°C (e) 422°C

Answer (d) 371°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
P1=6000 "kPa"
T1=300 "C"
P2=10000 "kPa"
s2=s1
s1=ENTROPY(Steam_IAPWS,T=T1,P=P1)
T2=TEMPERATURE(Steam_IAPWS,s=s2,P=P2)

"Some Wrong Solutions with Common Mistakes:"
W1_T2=T1 "Assuming temperature remains constant"
W2_T2=TEMPERATURE(Steam_IAPWS,x=0,P=P2) "Saturation temperature at P2"
W3_T2=TEMPERATURE(Steam_IAPWS,x=0,P=P2) "Saturation temperature at P1"
```

7-216 An apple with an average mass of 0.15 kg and average specific heat of 3.65 kJ/kg.°C is cooled from 20°C to 5°C. The entropy change of the apple is
(a) –0.0288 kJ/K (b) –0.192 kJ/K (c) -0.526 kJ/K (d) 0 kJ/K (e) 0.657 kJ/K

Answer (a) –0.0288 kJ/K

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
C=3.65 "kJ/kg.K"
m=0.15 "kg"
T1=20 "C"
T2=5 "C"
S_change=m*C*ln((T2+273)/(T1+273))

"Some Wrong Solutions with Common Mistakes:"
W1_S_change=C*ln((T2+273)/(T1+273)) "Not using mass"
W2_S_change=m*C*ln(T2/T1) "Using C"
W3_S_change=m*C*(T2-T1) "Using Wrong relation"
```

7-217 A piston-cylinder device contains 5 kg of saturated water vapor at 3 MPa. Now heat is rejected from the cylinder at constant pressure until the water vapor completely condenses so that the cylinder contains saturated liquid at 3 MPa at the end of the process. The entropy change of the system during this process is
(a) 0 kJ/K (b) -3.5 kJ/K (c) -12.5 kJ/K (d) -17.7 kJ/K (e) -19.5 kJ/K

Answer (d) -17.7 kJ/K

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
P1=3000 "kPa"
m=5 "kg"
s_fg=(ENTROPY(Steam_IAPWS,P=P1,x=1)-ENTROPY(Steam_IAPWS,P=P1,x=0))
S_change=-m*s_fg "kJ/K"
```

7-218 Helium gas is compressed from 1 atm and 25°C to a pressure of 10 atm adiabatically. The lowest temperature of helium after compression is
(a) 25°C (b) 63°C (c) 250°C (d) 384°C (e) 476°C

Answer (e) 476°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
k=1.667
P1=101.325 "kPa"
T1=25 "C"
P2=10*101.325 "kPa"
```

```
"s2=s1"
"The exit temperature will be lowest for isentropic compression,"
T2=(T1+273)*(P2/P1)^((k-1)/k) "K"
T2_C= T2-273 "C"

"Some Wrong Solutions with Common Mistakes:"
W1_T2=T1 "Assuming temperature remains constant"
W2_T2=T1*(P2/P1)^((k-1)/k) "Using C instead of K"
W3_T2=(T1+273)*(P2/P1)-273 "Assuming T is proportional to P"
W4_T2=T1*(P2/P1) "Assuming T is proportional to P, using C"
```

7-219 Steam expands in an adiabatic turbine from 8 MPa and 500°C to 0.1 MPa at a rate of 3 kg/s. If steam leaves the turbine as saturated vapor, the power output of the turbine is

(a) 2174 kW (b) 698 kW (c) 2881 kW (d) 1674 kW (e) 3240 kW

Answer (a) 2174 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
P1=8000 "kPa"
T1=500 "C"
P2=100 "kPa"
x2=1
m=3 "kg/s"
h1=ENTHALPY(Steam_IAPWS,T=T1,P=P1)
h2=ENTHALPY(Steam_IAPWS,x=x2,P=P2)
W_out=m*(h1-h2)

"Some Wrong Solutions with Common Mistakes:"
s1=ENTROPY(Steam_IAPWS,T=T1,P=P1)
h2s=ENTHALPY(Steam_IAPWS, s=s1,P=P2)
W1_Wout=m*(h1-h2s)  "Assuming isentropic expansion"
```

7-220 Argon gas expands in an adiabatic turbine from 3 MPa and 750°C to 0.2 MPa at a rate of 5 kg/s. The maximum power output of the turbine is

(a) 1.06 MW (b) 1.29 MW (c) 1.43 MW (d) 1.76 MW (e) 2.08 MW

Answer (d) 1.76 MW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Cp=0.5203
k=1.667
P1=3000 "kPa"
T1=750 "C"
m=5 "kg/s"
P2=200 "kPa"
```

```
"s2=s1"
T2=(T1+750)*(P2/P1)^((k-1)/k)
W_max=m*Cp*(T1-T2)

"Some Wrong Solutions with Common Mistakes:"
Cv=0.2081"kJ/kg.K"
W1_Wmax=m*Cv*(T1-T2) "Using Cv"
T22=T1*(P2/P1)^((k-1)/k) "Using C instead of K"
W2_Wmax=m*Cp*(T1-T22)
W3_Wmax=Cp*(T1-T2) "Not using mass flow rate"
T24=T1*(P2/P1) "Assuming T is proportional to P, using C"
W4_Wmax=m*Cp*(T1-T24)
```

7-221 A unit mass of a substance undergoes an irreversible process from state 1 to state 2 while gaining heat from the surroundings at temperature T in the amount of q. If the entropy of the substance is s_1 at state 1, and s_2 at state 2, the entropy change of the substance Δs during this process is

(a) $\Delta s < s_2 - s_1$ (b) $\Delta s > s_2 - s_1$ (c) $\Delta s = s_2 - s_1$ (d) $\Delta s = s_2 - s_1 + q/T$
(e) $\Delta s > s_2 - s_1 + q/T$

Answer (c) $\Delta s = s_2 - s_1$

7-222 A unit mass of an ideal gas at temperature T undergoes a reversible isothermal process from pressure P_1 to pressure P_2 while loosing heat to the surroundings at temperature T in the amount of q. If the gas constant of the gas is R, the entropy change of the gas Δs during this process is

(a) $\Delta s = R\ln(P_2/P_1)$ (b) $\Delta s = R\ln(P_2/P_1) - q/T$ (c) $\Delta s = R\ln(P_1/P_2)$ (d) $\Delta s = R\ln(P_1/P_2) - q/T$
(e) $\Delta s = 0$

Answer (c) $\Delta s = R\ln(P_1/P_2)$

7-223 Air is compressed from room conditions to a specified pressure in a reversible manner by two compressors: one isothermal and the other adiabatic. If the entropy change of air is Δs_{isot} during the reversible isothermal compression, and Δs_{adia} during the reversible adiabatic compression, the correct statement regarding entropy change of air per unit mass is

(a) $\Delta s_{isot} = \Delta s_{adia} = 0$ (b) $\Delta s_{isot} = \Delta s_{adia} > 0$ (c) $\Delta s_{adia} > 0$ (d) $\Delta s_{isot} < 0$ (e) $\Delta s_{isot} = 0$

Answer (d) $\Delta s_{isot} < 0$

7-224 Helium gas is compressed from 15°C and 5.4 m^3/kg to 0.775 m^3/kg in a reversible adiabatic manner. The temperature of helium after compression is

(a) 105°C (b) 55°C (c) 1734°C (d) 1051°C (e) 778°C

Answer (e) 778°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
k=1.667
v1=5.4 "m^3/kg"
T1=15 "C"
v2=0.775 "m^3/kg"
"s2=s1"
"The exit temperature is determined from isentropic compression relation,"
T2=(T1+273)*(v1/v2)^(k-1) "K"
T2_C= T2-273 "C"

"Some Wrong Solutions with Common Mistakes:"
W1_T2=T1 "Assuming temperature remains constant"
W2_T2=T1*(v1/v2)^(k-1) "Using C instead of K"
W3_T2=(T1+273)*(v1/v2)-273 "Assuming T is proportional to v"
W4_T2=T1*(v1/v2) "Assuming T is proportional to v, using C"
```

7-225 Heat is lost through a plane wall steadily at a rate of 600 W. If the inner and outer surface temperatures of the wall are 20°C and 5°C, respectively, the rate of entropy generation within the wall is
(a) 0.11 W/K (b) 4.21 W/K (c) 2.10 W/K (d) 42.1 W/K (e) 90.0 W/K

Answer (a) 0.11 W/K

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Q=600 "W"
T1=20+273 "K"
T2=5+273 "K"
"Entropy balance S_in - S_out + S_gen= DS_system for the wall for steady operation gives"
Q/T1-Q/T2+S_gen=0   "W/K"

"Some Wrong Solutions with Common Mistakes:"
Q/(T1+273)-Q/(T2+273)+W1_Sgen=0  "Using C instead of K"
W2_Sgen=Q/((T1+T2)/2)   "Using avegage temperature in K"
W3_Sgen=Q/((T1+T2)/2-273)   "Using avegage temperature in C"
W4_Sgen=Q/(T1-T2+273)  "Using temperature difference in K"
```

7-226 Air is compressed steadily and adiabatically from 17°C and 90 kPa to 200°C and 400 kPa. Assuming constant specific heats for air at room temperature, the isentropic efficiency of the compressor is
(a) 0.76 (b) 0.94 (c) 0.86 (d) 0.84 (e) 1.00

Answer (d) 0.84

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Cp=1.005 "kJ/kg.K"
k=1.4
P1=90 "kPa"
T1=17 "C"
```

```
P2=400 "kPa"
T2=200 "C"
T2s=(T1+273)*(P2/P1)^((k-1)/k)-273
Eta_comp=(Cp*(T2s-T1))/(Cp*(T2-T1))

"Some Wrong Solutions with Common Mistakes:"
T2sW1=T1*(P2/P1)^((k-1)/k) "Using C instead of K in finding T2s"
W1_Eta_comp=(Cp*(T2sW1-T1))/(Cp*(T2-T1))
W2_Eta_comp=T2s/T2 "Using wrong definition for isentropic efficiency, and using C"
W3_Eta_comp=(T2s+273)/(T2+273) "Using wrong definition for isentropic efficiency, with K"
```

7-227 Argon gas expands in an adiabatic turbine steadily from 500°C and 800 kPa to 80 kPa at a rate of 2.5 kg/s. For an isentropic efficiency of 80%, the power produced by the turbine is

(a) 194 kW (b) 291 kW (c) 484 kW (d) 363 kW (e) 605 kW

Answer (c) 484 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Cp=0.5203 "kJ/kg-K"
k=1.667
m=2.5 "kg/s"
T1=500 "C"
P1=800 "kPa"
P2=80 "kPa"
T2s=(T1+273)*(P2/P1)^((k-1)/k)-273
Eta_turb=0.8
Eta_turb=(Cp*(T2-T1))/(Cp*(T2s-T1))
W_out=m*Cp*(T1-T2)

"Some Wrong Solutions with Common Mistakes:"
T2sW1=T1*(P2/P1)^((k-1)/k) "Using C instead of K to find T2s"
Eta_turb=(Cp*(T2W1-T1))/(Cp*(T2sW1-T1))
W1_Wout=m*Cp*(T1-T2W1)
Eta_turb=(Cp*(T2s-T1))/(Cp*(T2W2-T1))  "Using wrong definition for isentropic efficiency, and
using C"
W2_Wout=m*Cp*(T1-T2W2)
W3_Wout=Cp*(T1-T2) "Not using mass flow rate"
Cv=0.3122 "kJ/kg.K"
W4_Wout=m*Cv*(T1-T2) "Using Cv instead of Cp"
```

7-228 Water enters a pump steadily at 100 kPa at a rate of 35 L/s and leaves at 800 kPa. The flow velocities at the inlet and the exit are the same, but the pump exit where the discharge pressure is measured is 6.1 m above the inlet section. The minimum power input to the pump is

(a) 34 kW (b) 22 kW (c) 27 kW (d) 52 kW (e) 44 kW

Answer (c) 27 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
V=0.035 "m^3/s"
g=9.81 "m/s^2"
h=6.1 "m"
P1=100 "kPa"
T1=20 "C"
P2=800 "kPa"
"Pump power input is minimum when compression is reversible and thus w=v(P2-P1)+Dpe"
v1=VOLUME(Steam_IAPWS,T=T1,P=P1)
m=V/v1
W_min=m*v1*(P2-P1)+m*g*h/1000 "kPa.m^3/s=kW"
"(The effect of 6.1 m elevation difference turns out to be small)"

"Some Wrong Solutions with Common Mistakes:"
W1_Win=m*v1*(P2-P1) "Disregarding potential energy"
W2_Win=m*v1*(P2-P1)-m*g*h/1000  "Subtracting potential energy instead of adding"
W3_Win=m*v1*(P2-P1)+m*g*h "Not using the conversion factor 1000 in PE term"
W4_Win=m*v1*(P2+P1)+m*g*h/1000 "Adding pressures instead of subtracting"
```

7-229 Air at 15°C is compressed steadily and isothermally from 100 kPa to 700 kPa at a rate of 0.12 kg/s. The minimum power input to the compressor is
(a) 1.0 kW (b) 11.2 kW (c) 25.8 kW (d) 19.3 kW (e) 161 kW

Answer (d) 19.3 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Cp=1.005 "kJ/kg.K"
R=0.287 "kJ/kg.K"
Cv=0.718 "kJ/kg.K"
k=1.4
P1=100 "kPa"
T=15 "C"
m=0.12 "kg/s"
P2=700 "kPa"
Win=m*R*(T+273)*ln(P2/P1)

"Some Wrong Solutions with Common Mistakes:"
W1_Win=m*R*T*ln(P2/P1)  "Using C instead of K"
W2_Win=m*T*(P2-P1) "Using wrong relation"
W3_Win=R*(T+273)*ln(P2/P1)  "Not using mass flow rate"
```

7-230 Air is to be compressed steadily and isentropically from 1 atm to 25 atm by a two-stage compressor. To minimize the total compression work, the intermediate pressure between the two stages must be
(a) 3 atm (b) 5 atm (c) 8 atm (d) 10 atm (e) 13 atm

Answer (b) 5 atm

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
P1=1 "atm"
P2=25 "atm"
P_mid=SQRT(P1*P2)

"Some Wrong Solutions with Common Mistakes:"
W1_P=(P1+P2)/2  "Using average pressure"
W2_P=P1*P2/2  "Half of product"
```

7-231 Helium gas enters an adiabatic nozzle steadily at 500°C and 600 kPa with a low velocity, and exits at a pressure of 90 kPa. The highest possible velocity of helium gas at the nozzle exit is

(a) 1475 m/s (b) 1662 m/s (c) 1839 m/s (d) 2066 m/s (e) 3040 m/s

Answer (d) 2066 m/s

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
k=1.667
Cp=5.1926 "kJ/kg.K"
Cv=3.1156 "kJ/kg.K"
T1=500 "C"
P1=600 "kPa"
Vel1=0
P2=90 "kPa"
"s2=s1 for maximum exit velocity"
"The exit velocity will be highest for isentropic expansion,"
T2=(T1+273)*(P2/P1)^((k-1)/k)-273 "C"
"Energy balance for this case is h+ke=constant for the fluid stream (Q=W=pe=0)"
(0.5*Vel1^2)/1000+Cp*T1=(0.5*Vel2^2)/1000+Cp*T2

"Some Wrong Solutions with Common Mistakes:"
T2a=T1*(P2/P1)^((k-1)/k) "Using C for temperature"
(0.5*Vel1^2)/1000+Cp*T1=(0.5*W1_Vel2^2)/1000+Cp*T2a
T2b=T1*(P2/P1)^((k-1)/k) "Using Cv"
(0.5*Vel1^2)/1000+Cv*T1=(0.5*W2_Vel2^2)/1000+Cv*T2b
T2c=T1*(P2/P1)^k "Using wrong relation"
(0.5*Vel1^2)/1000+Cp*T1=(0.5*W3_Vel2^2)/1000+Cp*T2c
```

7-232 Combustion gases with a specific heat ratio of 1.3 enter an adiabatic nozzle steadily at 800°C and 800 kPa with a low velocity, and exit at a pressure of 85 kPa. The lowest possible temperature of combustion gases at the nozzle exit is

(a) 43°C (b) 237°C (c) 367°C (d) 477°C (e) 640°C

Answer (c) 367°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
k=1.3
T1=800 "C"
P1=800 "kPa"
P2=85 "kPa"
"Nozzle exit temperature will be lowest for isentropic operation"
T2=(T1+273)*(P2/P1)^((k-1)/k)-273

"Some Wrong Solutions with Common Mistakes:"
W1_T2=T1*(P2/P1)^((k-1)/k) "Using C for temperature"
W2_T2=(T1+273)*(P2/P1)^((k-1)/k) "Not converting the answer to C"
W3_T2=T1*(P2/P1)^k "Using wrong relation"
```

7-233 Steam enters an adiabatic turbine steadily at 400°C and 3 MPa, and leaves at 50 kPa. The highest possible percentage of mass of steam that condenses at the turbine exit and leaves the turbine as a liquid is

(a) 5% (b) 10% (c) 15% (d) 20% (e) 0%

Answer (b) 10%

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
P1=3000 "kPa"
T1=400 "C"
P2=50 "kPa"
s2=s1
s1=ENTROPY(Steam_IAPWS,T=T1,P=P1)
x2=QUALITY(Steam_IAPWS,s=s2,P=P2)
misture=1-x2
"Checking x2 using data from table"
x2_table=(6.9212-1.091)/6.5029
```

7-234 Liquid water enters an adiabatic piping system at 15°C at a rate of 8 kg/s. If the water temperature rises by 0.2°C during flow due to friction, the rate of entropy generation in the pipe is

(a) 23 W/K (b) 55 W/K (c) 68 W/K (d) 220 W/K (e) 443 W/K

Answer (a) 23 W/K

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Cp=4180 "J/kg.K"
m=8 "kg/s"
T1=15 "C"
T2=15.2 "C"
S_gen=m*Cp*ln((T2+273)/(T1+273)) "W/K"
```

```
"Some Wrong Solutions with Common Mistakes:"
W1_Sgen=m*Cp*ln(T2/T1) "Using deg. C"
W2_Sgen=Cp*ln(T2/T1) "Not using mass flow rate with deg. C"
W3_Sgen=Cp*ln((T2+273)/(T1+273)) "Not using mass flow rate with deg. C"
```

7-235 Liquid water is to be compressed by a pump whose isentropic efficiency is 75 percent from 0.2 MPa to 5 MPa at a rate of 0.15 m^3/min. The required power input to this pump is
(*a*) 4.8 kW (*b*) 6.4 kW (*c*) 9.0 kW (*d*) 16.0 kW (*e*) 12.0 kW

Answer (*d*) 16.0 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
V=0.15/60 "m^3/s"
rho=1000 "kg/m^3"
v1=1/rho
m=rho*V "kg/s"
P1=200 "kPa"
Eta_pump=0.75
P2=5000 "kPa"
"Reversible pump power input is w =mv(P2-P1) = V(P2-P1)"
W_rev=m*v1*(P2-P1) "kPa.m^3/s=kW"
W_pump=W_rev/Eta_pump

"Some Wrong Solutions with Common Mistakes:"
W1_Wpump=W_rev*Eta_pump "Multiplying by efficiency"
W2_Wpump=W_rev "Disregarding efficiency"
W3_Wpump=m*v1*(P2+P1)/Eta_pump "Adding pressures instead of subtracting"
```

7-236 Steam enters an adiabatic turbine at 8 MPa and 500°C at a rate of 18 kg/s, and exits at 0.2 MPa and 300°C. The rate of entropy generation in the turbine is
(*a*) 0 kW/K (*b*) 7.2 kW/K (*c*) 21 kW/K (*d*) 15 kW/K (*e*) 17 kW/K

Answer (*c*) 21 kW/K

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
P1=8000 "kPa"
T1=500 "C"
m=18 "kg/s"
P2=200 "kPa"
T2=300 "C"
s1=ENTROPY(Steam_IAPWS,T=T1,P=P1)
s2=ENTROPY(Steam_IAPWS,T=T2,P=P2)
S_gen=m*(s2-s1) "kW/K"
```

```
"Some Wrong Solutions with Common Mistakes:"
W1_Sgen=0 "Assuming isentropic expansion"
```

7-237 Helium gas is compressed steadily from 90 kPa and 25°C to 600 kPa at a rate of 2 kg/min by an adiabatic compressor. If the compressor consumes 70 kW of power while operating, the isentropic efficiency of this compressor is

(*a*) 56.7% (*b*) 83.7% (*c*) 75.4% (*d*) 92.1% (*e*) 100.0%

Answer (*b*) 83.7%

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen. (Similar problems and their solutions can be obtained easily by modifying numerical values).

```
Cp=5.1926 "kJ/kg-K"
Cv=3.1156 "kJ/kg.K"
k=1.667
m=2/60 "kg/s"
T1=25 "C"
P1=90 "kPa"
P2=600 "kPa"
W_comp=70 "kW"
T2s=(T1+273)*(P2/P1)^((k-1)/k)-273
W_s=m*Cp*(T2s-T1)
Eta_comp=W_s/W_comp

"Some Wrong Solutions with Common Mistakes:"
T2sA=T1*(P2/P1)^((k-1)/k) "Using C instead of K"
W1_Eta_comp=m*Cp*(T2sA-T1)/W_comp
W2_Eta_comp=m*Cv*(T2s-T1)/W_comp "Using Cv instead of Cp"
```

7-238 … 7-241 Design and Essay Problems
