6-2-1 [ONJ] A house is electrically heated with a resistance heater that draws 15 kW of electric power. It maintains the house at a temperature of 20°C while the outside is 5°C. Assuming steady state, determine (a) the reversible power and (b) the rate of irreversibility.

SOLUTION

At steady state, the energy equation simplifies as:

$$\cancel{\frac{dE}{dt}}^{0} = \dot{Q} - \dot{W}_{\text{ext}} = \left(-\dot{Q}_{\text{loss}}\right) - \left(-\dot{W}_{\text{el,in}}\right);$$

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

(a) The exergy equation simplifies as:

$$\frac{d\Phi}{dt} = \sum_k \dot{Q}_k \left(1 - \frac{T_0}{T_k}\right) - \dot{W}_u - \dot{I};$$

$$\Rightarrow \cancel{\frac{d\Phi}{dt}}^{0} = \left(-\dot{Q}_{\text{loss}}\right)\left(1 - \frac{T_0}{T_0}\right) - \left(-\dot{W}_{\text{el,in}}\right) - \dot{I};$$

$$\Rightarrow \dot{I} = \dot{W}_{\text{el,in}} = 15 \text{ kW}$$

(b) $\dot{W}_{\text{rev}} = \dot{W}_u + \dot{I} = \left(-\dot{W}_{\text{el,in}}\right) + \dot{I} = -15 + 15 = 0 \text{ kW}$

xx6-2-2 [OEO] Heat is conducted steadily through a 5 m x 10 m x 10 cm brick wall of a house. On a certain day, the temperature inside is maintained at 25°C when the temperature outside is -5°C. The temperature of the inner and outer surface of the wall are measured to be 20°C and 0°C respectively. If the rate of heat transfer (Q) is 1 kW, determine the rate of exergy destruction (I) (a) in the wall and (b) in its universe.

SOLUTION

At steady state, the energy equation for the wall (a closed-steady system) simplifies as:

$$\cancel{\frac{dE}{dt}}^{0} = \dot{Q} - \cancel{\dot{W}_{\text{ext}}}^{0} = \dot{Q}_{\text{left}} - \dot{Q}_{\text{right}};$$

$$\Rightarrow \dot{Q}_{\text{left}} = \dot{Q}_{\text{right}} = \dot{Q}_{\text{loss}} = 1 \text{ kW};$$

(a) The exergy equation for the wall simplifies as:

$$\frac{d\Phi}{dt} = \sum_k \dot{Q}_k \left(1 - \frac{T_0}{T_k}\right) - \dot{W}_u - \dot{I};$$

$$\Rightarrow \cancel{\frac{d\Phi}{dt}}^{0} = \dot{Q}_{\text{left}} \left(1 - \frac{T_0}{T_{\text{left}}}\right) - \dot{Q}_{\text{right}} \left(1 - \frac{T_0}{T_{\text{right}}}\right) - \cancel{\dot{W}_u}^{0} - \dot{I};$$

$$\Rightarrow \dot{I} = T_0 \dot{Q}_{\text{loss}} \left(\frac{1}{T_{\text{right}}} - \frac{1}{T_{\text{left}}}\right) = (268)(1)\left(\frac{1}{273} - \frac{1}{293}\right) = 0.068 \text{ kW}$$

(b) The exergy equation for the wall's universe simplifies as:

$$\dot{I}_{\text{univ}} = T_0 \dot{Q}_{\text{loss}} \left(\frac{1}{T_{\text{right}}} - \frac{1}{T_{\text{left}}}\right) = (268)(1)\left(\frac{1}{268} - \frac{1}{298}\right) = 0.101 \text{ kW}$$

6-2-3 [OES] A refrigerator has a second-law efficiency of 45%, and heat is removed from it at a rate of 200 kJ/min. If the refrigerator is maintained at 2°C, while the surrounding air is at 27°C, determine (a) the power input to the refrigerator.

SOLUTION

At steady state, the exergy equation applied to the closed refrigeration cycle simplifies as:

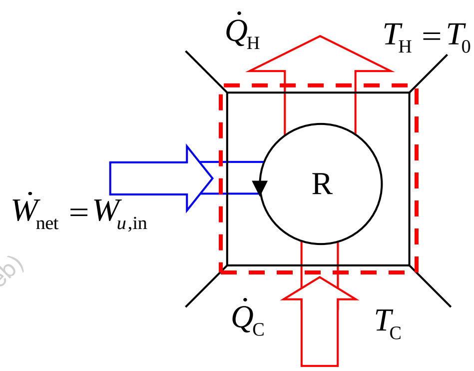
$$\frac{d\Phi}{dt} = \sum_k \dot{Q}_k\left(1-\frac{T_0}{T_k}\right) - \dot{W}_u - \dot{I} = \sum_k \dot{Q}_k\left(1-\frac{T_0}{T_k}\right) - \dot{W}_{\text{rev}};$$

$$\Rightarrow \cancelto{0}{\frac{d\Phi}{dt}} = \dot{Q}_C\left(1-\frac{T_0}{T_C}\right) - \dot{Q}_H\cancelto{0}{\left(1-\frac{T_0}{T_0}\right)} - \left(-\dot{W}_{\text{rev,in}}\right);$$

$$\Rightarrow \dot{W}_{\text{rev,in}} = -\dot{Q}_C\left(1-\frac{T_0}{T_C}\right);$$

$$\Rightarrow \dot{W}_{\text{rev,in}} = -\left(\frac{200}{60}\right)\left(1-\frac{300}{275}\right) - 1;$$

$$\Rightarrow \dot{W}_{\text{rev,in}} = 0.303 \text{ kW};$$



$$\eta_{II} = \frac{\text{Ideal exergy input}}{\text{Actual exergy input}} = \frac{\dot{W}_{\text{rev,in}}}{\dot{W}_{u,\text{in}}};$$

$$\Rightarrow \dot{W}_{u,\text{in}} = \frac{\dot{W}_{\text{rev,in}}}{\eta_{II}} = \frac{0.303}{0.45} = 0.673 \text{ kW}$$

TEST Solution:

Launch the closed-steady TESTcalc and select the Refrigerator button. Enter the known variables: T_H, T_C, Qdot_C, and eta_II. Click Calculate to obtain the desired answers.

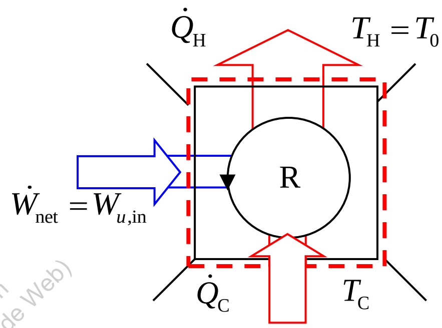
6-2-4 [OER] An air-conditioning system is required to transfer heat from a house at a rate of 800 kJ/min to maintain its temperature at 20°C while the outside temperature is 40°C. If the COP of the system is 3.7, determine (a) the power required for air conditioning the house and (b) the rate of exergy destruction (I) in the universe.

SOLUTION

Given:

$\dot{Q}_C = 13.33$ kW;

$\mathrm{COP_R} = 3.7$;



(a) The useful power input to the refrigerator

$$\dot{W}_{u,\mathrm{in}} = \frac{\dot{Q}_C}{\mathrm{COP_R}} = \frac{13.33}{3.7} = 3.6\,\mathrm{kW}$$

The reversible power input to the refrigerator

$$\dot{W}_\mathrm{rev} = \frac{\dot{Q}_C}{COP_\mathrm{R,Carnot}} = \frac{\dot{Q}_C}{\left(\dfrac{T_C}{T_H - T_C}\right)} = \frac{13.33}{14.6575} = 0.909\ \mathrm{kW}$$

(b) The exergy equation for the refrigerator's universe produces:

$$\frac{d\Phi}{dt} = \sum_k \dot{Q}_k\left(1 - \frac{T_0}{T_k}\right) - \dot{W}_u - \dot{I} = \sum_k \dot{Q}_k\left(1 - \frac{T_0}{T_k}\right) - \dot{W}_\mathrm{rev};$$

$$\Rightarrow \cancelto{0}{\frac{d\Phi}{dt}} = \dot{Q}_C\left(1 - \frac{T_0}{T_C}\right) - \dot{Q}_H\cancelto{0}{\left(1 - \frac{T_0}{T_0}\right)} - \left(-\dot{W}_{u,\mathrm{in}}\right) - \dot{I};$$

$$\Rightarrow \dot{I} = \dot{W}_{u,\mathrm{in}} - \dot{Q}_C\left(\frac{T_0}{T_C} - 1\right) = 3.6 - \left(\frac{800}{60}\right)\left(\frac{313}{293} - 1\right) - 1 = 2.69\ \mathrm{kW}$$

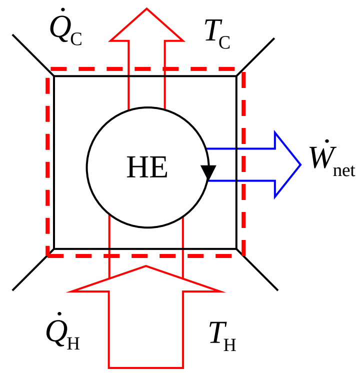
TEST Solution:

Launch the closed-steady TESTcalc and select the Refrigerator button. Enter the known variables: T_H, T_C, Qdot_C, and COP. Click Calculate to obtain the desired answers.

6-2-5 [OEB] A heat engine receives heat from a source at 2000 K at a rate of 500 kW and rejects the waste heat to the atmosphere at 300 K. The net output from the engine is 300 kW. Determine (a) the reversible power output, (b) the rate of exergy input into the engine, (c) the rate of exergy destruction (*I*) in the universe and (d) the exergetic (second-law) efficiency.

SOLUTION

Given: $\dot{Q} = 500\text{ kW};\ T_H = 2000\text{ K};\ T_C = 300\text{ K};$



(a) The exergy equation simplifies as:

$$\frac{d\Phi}{dt} = \sum_k \dot{Q}_k\left(1-\frac{T_0}{T_k}\right) - \dot{W}_u - \dot{I} = \sum_k \dot{Q}_k\left(1-\frac{T_0}{T_k}\right) - \dot{W}_{\text{rev}};$$

$$\Rightarrow \cancelto{0}{\frac{d\Phi}{dt}} = \dot{Q}_H\left(1-\frac{T_0}{T_H}\right) - \dot{Q}_C\left(1-\frac{T_0}{T_C}\right) - \dot{W}_{\text{rev}};$$

$$\Rightarrow \dot{W}_{\text{rev}} = \dot{Q}_H\left(1-\frac{T_0}{T_H}\right) - \dot{Q}_C\cancelto{0}{\left(1-\frac{T_0}{T_0}\right)};$$

$$\Rightarrow \dot{W}_{\text{rev}} = (500)\left(1-\frac{300}{2000}\right) = 425\text{ kW}$$

(b) The rate of exergy input:

$$\dot{Q}_H\left(1-\frac{T_0}{T_H}\right) = 425\text{ kW}$$

(c) $\dot{W}_{\text{rev}} = \dot{W}_u + \dot{I};$

$$\Rightarrow \dot{I} = \dot{W}_{\text{rev}} - \dot{W}_u = 425 - 300 = 125\text{ kW}$$

(d) The exergetic efficiency

$$\eta_{\text{II}} = \frac{\text{Actual exergy output}}{\text{Ideal exergy output}} = \frac{\dot{W}_{\text{net}}}{\dot{W}_{\text{rev}}} = \frac{300}{425} = 70.5\%$$

TEST Solution:

Launch the closed-steady TESTcalc and select the Heat Engine button. Enter the known variables: T_H, T_C, Qdot_H, and Wdot_net. Click Calculate to obtain the desired answers.

6-2-6 [OEA] A heat engine produces 40 kW of power while consuming 40 kW of heat from a source at 1200 K, 50 kW of heat from a source at 1500 K, and rejecting the waste heat to the atmosphere at 300 K. Determine (a) the reversible power and (b) the rate of exergy destruction (I) in the engine's universe.

SOLUTION

Given: $\dot{W}_{net} = 40\,\text{kW};\ \dot{Q}_H = 40\text{ kW};\ T_H = 1200\text{ K};\ T_C = 300\text{ K};$

The reversible power

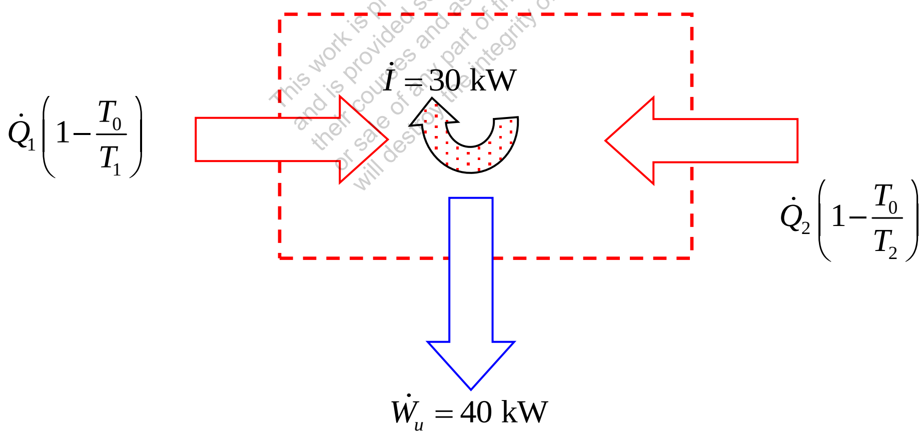
$$\frac{d\Phi}{dt} = \sum_k \dot{Q}_k\left(1-\frac{T_0}{T_k}\right) - \dot{W}_u - \dot{I} = \sum_k \dot{Q}_k\left(1-\frac{T_0}{T_k}\right) - \dot{W}_{\text{rev}}$$

$$\Rightarrow \cancel{\frac{d\Phi}{dt}}^{0} = \dot{Q}_{H1}\left(1-\frac{T_0}{T_{H1}}\right) + \dot{Q}_{H2}\left(1-\frac{T_0}{T_{H2}}\right) - \dot{Q}_C\cancel{\left(1-\frac{T_0}{T_0}\right)}^{0} - \dot{W}_{\text{rev}};$$

(a) $\dot{W}_{\text{rev}} = (40)\left(1-\dfrac{300}{1200}\right) + (50)\left(1-\dfrac{300}{1500}\right) = 70\text{ kW}$

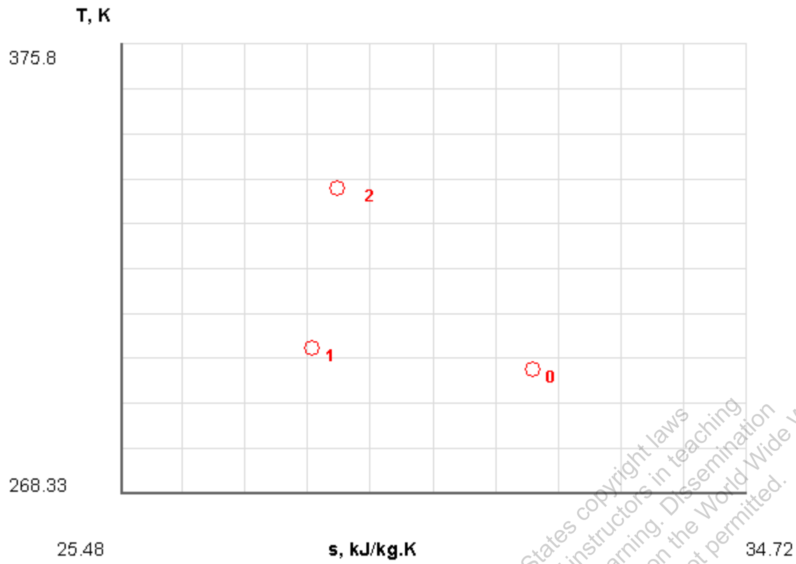
(b) Rate of exergy destruction,

$$\dot{I} = \dot{W}_{\text{rev}} - \dot{W}_u = \dot{W}_{\text{rev}} - \dot{W}_{\text{net}} = 70 - 40 = 30\text{ kW}$$



6-2-7 [OEE] An insulated rigid tank contains 1.5 kg of helium at 30°C and 500 kPa. A paddle wheel with a power rating of 0.1 kW is operated within the tank for 30 minutes. Determine (a) the minimum work in which this process could be accomplished and (b) the exergy destroyed (I) in the universe during the process. Assume the surroundings to be at 100 kPa and 25°C.

SOLUTION



From Table C-1 or the PG closed-process TESTcalc for helium, obtain:

$$R = 2.0785 \ \frac{\text{kJ}}{\text{kg.K}};$$

$$c_v = 3.2 \ \frac{\text{kJ}}{\text{kg.K}};$$

The energy equation for the closed process simplifies as:

$$\Delta E = \cancel{Q}^{0} - W_{\text{ext}};$$

$$\Rightarrow \Delta U = -\left(-W_{\text{el,in}}\right); \qquad \Rightarrow mc_v\left(T_2 - T_1\right) = W_{\text{el,in}} = \dot{W}_{\text{el,in}}\Delta t;$$

$$\Rightarrow (1.5)(3.2)(T_2 - 303) = (0.1)(30)(60); \qquad [\text{kJ}]$$

$$\Rightarrow T_2 = 341.46 \text{ K};$$

Using the IG equation of state,

$$pv = RT;$$

$$\Rightarrow v_1 = \frac{RT_1}{p_1} = \frac{(2.0785)(303)}{500} = 1.26 \ \frac{\text{m}^3}{\text{kg}};$$

Realizing that v remains constant,

$$p_2 = \frac{RT_2}{v_2} = \frac{RT_2}{v_1} = \frac{(2.0785)(341.5)}{1.26} = 563.5 \text{ kPa};$$

(a) The exergy equation for the closed process simplifies as:

$$\Delta\Phi = \sum_k Q_k\left(1-\frac{T_0}{T_k}\right) - W_u - I = \sum_k \cancel{Q_k}^{0}\left(1-\frac{T_0}{T_k}\right) - W_{\text{rev}};$$

$$\Rightarrow W_{\text{rev}} = \Phi_1 - \Phi_2 = m(\phi_1 - \phi_2);$$

$$\Rightarrow W_{\text{rev}} = m\left[(u_1-u_2) - T_0(s_1-s_2) + p_0\cancel{(v_1-v_2)}^{0} + \cancel{\Delta\text{ke}}^{0} + \cancel{\Delta\text{pe}}^{0}\right];$$

$$\Rightarrow W_{\text{rev}} = m\left[c_v(T_1-T_2) - T_0\left(c_v \ln\frac{T_1}{T_2} + R\ln\cancel{\frac{v_1}{v_2}}^{1}\right)\right] = mc_v\left[(T_1-T_2) - T_0\ln\frac{T_1}{T_2}\right];$$

$$\Rightarrow W_{\text{rev}} = (1.5)(3.2)\left[(303-341) - (298)\ln\frac{303}{341}\right] = -13.42 \text{ kJ}$$

(b) The exergy destroyed is given by

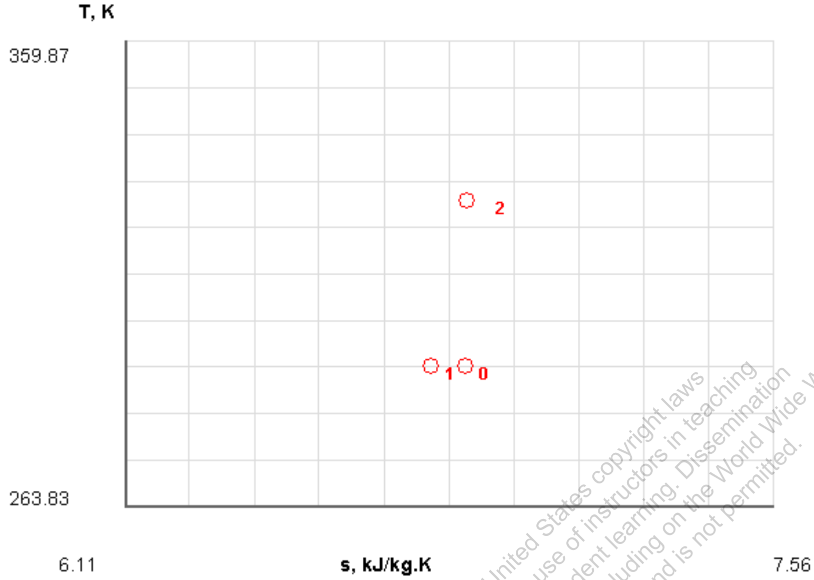
$$I = W_{\text{rev}} - W_u = (-13.42) - (-180) = 166.6 \text{ kJ}$$

TEST Solution:

Launch the PG closed-process TESTcalc and select Helium. Evaluate the dead, initial, and final states as completely as possible from the given information. In the process panel, analyze the process to determine e2, which is posted back to State-2. Click Super-Calculate to complete the calculations. The answers are displayed in the exergy panel. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-8 [OEH] An insulated rigid tank contains 1.0 kg of air at 130 kPa and 20°C. A paddle wheel inside the tank is rotated by an external power source until the temperature in the tank rises to 54°C. If the surrounding air is at 20°C, determine (a) the exergy destroyed (I) and (b) the reversible work (W_{rev}). Use the IG model for air. (c) What-if Scenario: What would the exergy destroyed be if the initial pressure were 180 kPa instead?

SOLUTION



Use the IG closed-process TESTcalc (Air*) or the manual approach to determine the dead state, State-0, the initial state, State-1, and the final state, State-2.

State-0 (given $p_0 = 100$ kPa and $T_0 = 20$°C):

$$u_0 = 208.8 \ \frac{\text{kJ}}{\text{kg}}; \quad v_0 = 0.8413 \ \frac{\text{m}^3}{\text{kg}};$$

State-1 (given $p_1 = 130$ kPa, $T_1 = 20^\circ$C and $m_1 = 1$ kg):

$$h_1 = 293.16 \ \frac{\text{kJ}}{\text{kg}}; \quad u_1 = 209.06 \ \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 6.794 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$v_1 = 0.647 \ \frac{\text{m}^3}{\text{kg}};$$

$$\phi_1 = (u_1 - u_0) - T_0(s_1 - s_0) + p_0(v_1 - v_0);$$

$$\Rightarrow \phi = 2.658 \ \frac{\text{kJ}}{\text{kg}};$$

State-2 (given $T_2 = 54^\circ$C , $\cancel{V_2} = \cancel{V_1}$, and $m_2 = m_1$):

$$p_2 = \frac{mRT_2}{\cancel{V}_2} = 145.05;$$

$$h_2 = 327.3\ \frac{\text{kJ}}{\text{kg}}; \quad u_2 = 233.45\ \frac{\text{kJ}}{\text{kg}}; \quad s_2 = 1.789\ \frac{\text{kJ}}{\text{kg K}};$$

$$\phi_2 = (u_2 - u_0) - T_0(s_2 - s_0) + p_0(v_2 - v_0);$$

$$\Rightarrow \phi_2 = 3.975\ \frac{\text{kJ}}{\text{kg}};$$

The energy equation for the closed process simplifies as:

$$\Delta E = \cancel{Q}^0 - W_{\text{ext}};$$

$$\Rightarrow \Delta U = -(-W_{\text{sh,in}});$$

$$\Rightarrow W_{\text{el,in}} = m(u_2 - u_1) = 24.42 \text{ kJ};$$

$$\Rightarrow W_u = -24.42 \text{ kJ};$$

(a) The exergy equation for the closed process simplifies as:

$$\Delta\Phi = \sum_k Q_k\left(1 - \frac{T_0}{T_k}\right) - W_u - I = \sum_k \cancel{Q_k}^0\left(1 - \frac{T_0}{T_k}\right) - W_{\text{rev}};$$

$$\Rightarrow W_{\text{rev}} = \Phi_1 - \Phi_2 = m(\phi_1 - \phi_2);$$

$$\Rightarrow W_{\text{rev}} = (1)(2.658 - 3.975) = -1.317 \text{ kJ}$$

(b) The exergy destroyed is given by

$$I = W_{\text{rev}} - W_u = (-1.317) - (-24.42) = 23.11 \text{ kJ}$$

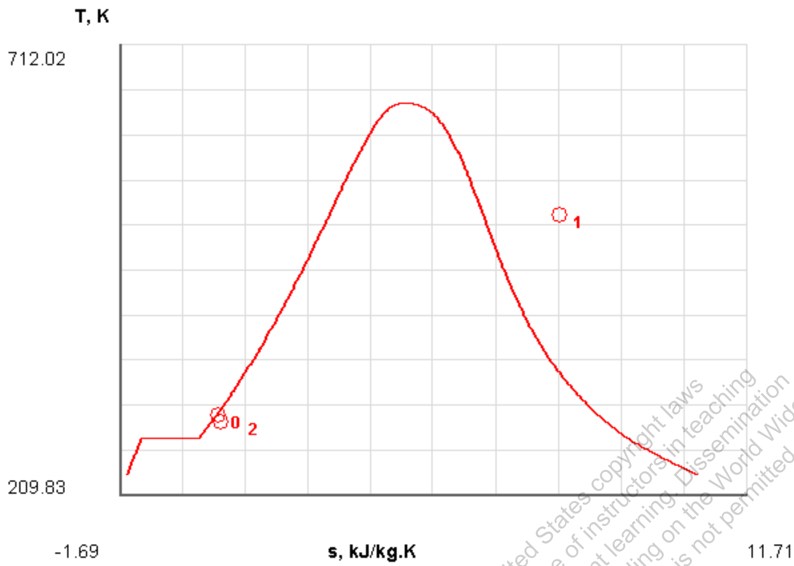
TEST Solution:

Launch the IG closed-process TESTcalc and select Air*. Evaluate the dead, initial, and final states from the given information. In the process panel, analyze the process (load the initial and final states, enter Q=0, W_O=0, and Calculate) to determine W_ext. In the exergy panel, click Calculate to obtain the desired answers. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

(c) Change p1 to 180 kPa and click Super-Calculate. The new answer for the irreversibilities (in the exergy panel) remains unchanged at 23.11 kJ.

6-2-9 [OEN] A steam radiator (used for space heating) has a volume of 20 L and is filled up with steam at 200 kPa and 250°C. The inlet and exit ports are then closed. As the radiator cools down to a room temperature of 20°C, determine (a) the heat transfer (Q) and (b) reversible work (W_{rev}). (c) What-if Scenario: What would the reversible work be if the steam pressure in the radiator were 400 kPa instead?

SOLUTION



Use the PC closed-process TESTcalc or the manual approach to determine the dead state, State-0, the beginning state, State-1, and the final state, State-2.

State-0 (given $p_0 = 100$ kPa and $T_0 = 25$°C):

$$u_0 = 112.6\ \frac{\text{kJ}}{\text{kg}};\qquad v_0 = 0.001\ \frac{\text{m}^3}{\text{kg}};$$

State-1 (given $p_1 = 200$ kPa, $T_1 = 250^\circ\text{C}$ and $\cancel{V}_1 = 20$ L):

$$v_1 = 1.198\ \frac{\text{m}^3}{\text{kg}};\qquad u_1 = 2731.20\ \frac{\text{kJ}}{\text{kg}};\qquad s_1 = 7.708\ \frac{\text{kJ}}{\text{kg K}};$$

$$m = \frac{\cancel{V}_1}{v_1} = \frac{0.02}{1.198} = 0.0167\ \text{kg};$$

$$\phi_1 = (u_1 - u_0) - T_0(s_1 - s_0) + p_0(v_1 - v_0) = 543.7\ \frac{\text{kJ}}{\text{kg}};$$

State-2 (given $T_2 = 20^\circ\text{C}$ and $v_2 = v_1$):

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = 0.020;$$

$$u_2 = u_f + x_2 u_{fg} = 132.022 \ \frac{\text{kJ}}{\text{kg}};$$

$$s_2 = s_f + x_2 s_{fg} = 0.470 \ \frac{\text{kJ}}{\text{kg K}};$$

$$\phi_2 = (u_2 - u_0) - T_0 (s_2 - s_0) + p_0 (v_2 - v_0) = 116.1 \ \frac{\text{kJ}}{\text{kg}};$$

(a) Using the energy balance equation we obtain

$$\Delta U = m(u_2 - u_1) = Q - \cancel{W_{\text{ext}}}^{0};$$

$$\Rightarrow Q = -43.41 \text{ kJ}$$

(b) Using the exergy balance we obtain

$$\Delta \Phi = \sum_k Q_k \left(1 - \frac{T_0}{T_k}\right) - W_u - I = \sum_k \cancel{Q_k}^{0} \left(1 - \frac{T_0}{T_k}\right) - W_{\text{rev}};$$

$$\Rightarrow W_{\text{rev}} = \Phi_1 - \Phi_2 = m(\phi_1 - \phi_2);$$

$$\Rightarrow W_{\text{rev}} = 7.14 \text{ kJ}$$

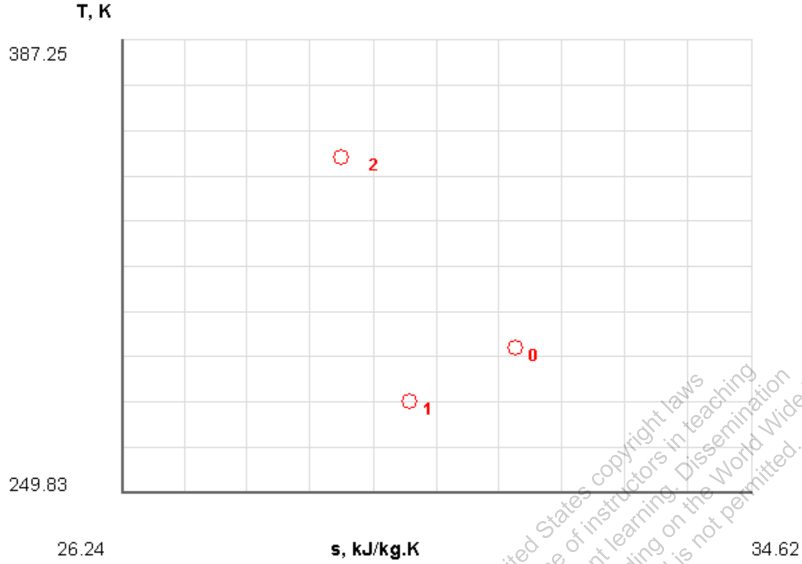
TEST Solution:

Launch the PC closed-process TESTcalc and select H2O. Evaluate the dead, initial, and final states from the given information. In the process panel, analyze the process (load the initial and final states, enter W_B, and W_O as 0, and Calculate) to determine Q. In the exergy panel, click Calculate to obtain the desired answers. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

(c) Change p1 to 400 kPa and click Super-Calculate. The new answer for W_rev (in the exergy panel) is displayed as 17.45 kJ.

6-2-10 [OEG] A piston cylinder device initially contains 10 ft^3 of helium gas at 25 psia and 40^{o}F. The gas is then compressed in a polytropic process ($pv^{1.3}$ = constant) to 70 psia. Determine (a) the minimum work with which this process could be accomplished and (b) second-law efficiency. Assume the surroundings to be at 14.7 psia and 70^{o}F.

SOLUTION



From Table C-1 or the PG closed-process TESTcalc obtain: $R = 2.0785\ \dfrac{\text{kJ}}{\text{kg.K}}$ and

$c_v = 3.2\ \dfrac{\text{kJ}}{\text{kg.K}}$ for helium.

State-0 (given $p_0 = 14.7$ psia , $T_0 = 70^\circ$F or $p_0 = 101$ kPa, $T_0 = 294$ K)

State-1 (given $p_1 = 25$ psia; $T_1 = 40^\circ$F; $\cancel{V}_1 = 10$ ft^3 or $p_1 = 172$ kPa; $T_1 = 278$ K; $\cancel{V}_1 = 0.283$ K):

$$m = \frac{p_1 \cancel{V}_1}{T_1 R} = \frac{(172)(0.283)}{(278)(2.078)} = 0.085 \text{ kg};$$

$$\phi_1 = (u_1 - u_0) - T_0(s_1 - s_0) + p_0(v_1 - v_0) = 89.6\ \frac{\text{kJ}}{\text{kg}};$$

State-2 (given $p_2 = 70$ psia or $p_2 = 483$ kPa and $m_2 = m_1$):

$$\cancel{V}_2 = \cancel{V}_1 \left(\frac{p_1}{p_2}\right)^{1/n} = 0.128 \text{ m}^3;$$

$$T_2 = \frac{p_2 \cancel{V}_2}{mR} = \frac{(483)(0.128)}{(0.085)(2.078)} = 352 \text{ K};$$

$$\phi_2 = (u_2 - u_0) - T_0(s_2 - s_0) + p_0(v_2 - v_0) = 402.6\ \frac{\text{kJ}}{\text{kg}};$$

The boundary and useful work done in this process can be calculated as:

$$W_B = \frac{p_2 \cancel{V}_2 - p_1 \cancel{V}_1}{1-n} = -43.6\ \text{kJ};$$

$$W_u = W_B - W_0 = W_B - p_0(\cancel{V}_2 - \cancel{V}_1) = -43.6 - (101)(0.128 - 0.283) = -27.9\ \text{kJ};$$

Using the exergy balance we obtain

$$\Delta\Phi = \sum_k Q_k \left(1 - \frac{T_0}{T_k}\right) - W_u - I = \sum_k Q_0 \cancelto{0}{\left(1 - \frac{T_0}{T_0}\right)} - W_{\text{rev}};$$

$$\Rightarrow W_{\text{rev}} = \Phi_1 - \Phi_2 = m(\phi_1 - \phi_2);$$

$$\Rightarrow W_{\text{rev}} = -26.45\ \text{kJ};$$

(a) The minimum work input, therefore, is: 26.45 kJ or 66098 $\text{ft}\cdot\text{lbf}$

(b) The second law efficiency is

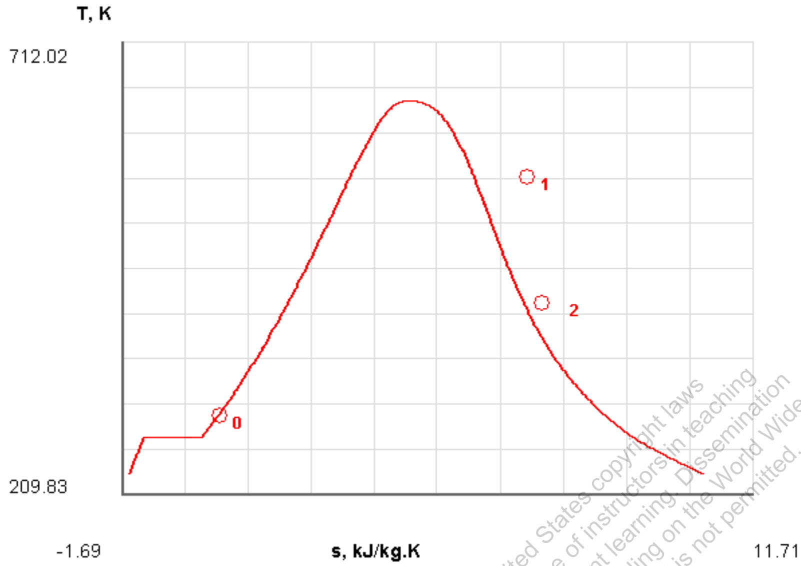
$$\eta_{II} = \frac{\text{Ideal exergy input}}{\text{Actual exergy input}} = \frac{\dot{W}_{\text{rev,in}}}{\dot{W}_{u,\text{in}}} = \frac{26.3}{27.9} = 94.6\%$$

TEST Solution:

Launch the PG closed-process TESTcalc and select Helium. Evaluate the dead, initial, and final states from the given information. In the process panel, analyze the process (load the initial and final states, enter W_O as 0, and Calculate) to determine W_B and Q. In the exergy panel, click Calculate to obtain the terms of the exergy balance equation. From the W_rev and W_u, the second law efficiency can be calculated. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-11 [OEI] A piston-cylinder device contains 0.1 kg of steam at 1.4 MPa and 290°C. Steam then expands to a final state of 220 kPa and 150°C, doing boundary work. Heat losses from the system to the surroundings are estimated to be 4 kJ during this process. Assume the surroundings to be at 25°C and 100 kPa, determine (a) the exergy change ($\Delta\Phi$) of steam and (b) the exergy destroyed (I) during the process.

SOLUTION



Use the PC closed-process TESTcalc or the manual approach to determine the dead state, State-0, the beginning state, State-1, and the final state, State-2.

State-0 (given $p_0 = 100$ kPa and $T_0 = 25$°C):

$$v_0 = 0.0010 \ \frac{\text{m}^3}{\text{kg}}; \quad u_0 = 104.87 \ \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 0.367 \ \frac{\text{kJ}}{\text{kg K}};$$

State-1 (given $p_1 = 1.4$ MPa, $T_1 = 290^\circ$C):

$$v_1 = 0.179 \ \frac{\text{m}^3}{\text{kg}}; \quad u_1 = 2767.7 \ \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 6.91 \ \frac{\text{kJ}}{\text{kg K}};$$

$$\phi_1 = (u_1 - u_0) - T_0(s_1 - s_0) + p_0(v_1 - v_0);$$

$$\Rightarrow \phi_1 = (2767.7 - 104.87) - 298(6.91 - 0.367) + 100(0.179 - 0.0010);$$

$$\Rightarrow \phi_1 = 730.8 \ \frac{\text{kJ}}{\text{kg}};$$

State-2 (given $p_2 = 220$ kPa, $T_2 = 150^\circ$C):

$$v_2 = 0.871 \ \frac{\text{m}^3}{\text{kg}}; \quad u_2 = 2575.6 \ \frac{\text{kJ}}{\text{kg}}; \quad s_2 = 7.23 \ \frac{\text{kJ}}{\text{kg K}};$$

$$\phi_2 = (u_2 - u_0) - T_0(s_2 - s_0) + p_0(v_2 - v_0);$$

$$\Rightarrow \phi_2 = (2575.6 - 104.87) - 298(7.23 - 0.367) + 100(0.871 - 0.0010);$$

$$\Rightarrow \phi_2 = 512.5 \ \frac{\text{kJ}}{\text{kg}};$$

(a) The exergy change

$$\Delta\Phi = m(\phi_2 - \phi_1) = -0.1(730.8 - 512.5);$$

$$\Rightarrow \Delta\Phi = -21.8 \text{ kJ}$$

(b) The entropy equation for the closed process is:

$$\Delta S = m(s_2 - s_1) = \frac{Q}{T_B} + S_{\text{gen.univ}} = \frac{Q}{T_0} + S_{\text{gen.univ}};$$

$$\Rightarrow I = T_0 S_{\text{gen.univ}} = T_0 \Delta S - Q;$$

$$\Rightarrow I = (298)(0.1)(0.32) - (-4);$$

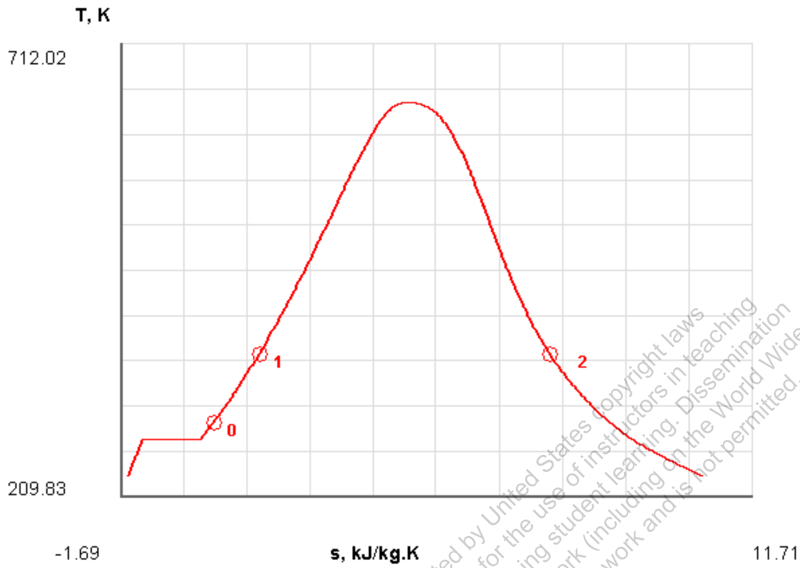
$$\Rightarrow I = 13.5 \text{ kJ}$$

TEST Solution:

Launch the PC closed-process TESTcalc and select H2O. Evaluate the dead, initial, and final states from the given information. In the process panel, analyze the process (load the initial and final states, enter W_O as 0, Q, and Calculate) to determine W_B. In the exergy panel, click Calculate to obtain the irreversibilities I along with other exergy related variables. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-12 [OEL] Water initially a saturated liquid at 95ºC is contained in a piston-cylinder assembly. The water undergoes a process to the corresponding saturated vapor state, during which the piston moves freely in the cylinder. The change in state is brought about adiabatically by the stirring action of paddle wheel. Determine on a unit of mass basis, the (a) change in stored exergy ($\Delta\Phi$), (b) the exergy transfer accompanying work, (c) the exergy transfer accompanying heat and (d) the exergy destruction (I). Let T_0 = 20ºC and p_0 = 1 bar.

SOLUTION



Use the PC closed-process TESTcalc or the manual approach to determine the dead state, State-0, the beginning state, State-1, and the final state, State-2.

State-0 (given $p_0 = 100$ kPa and $T_0 = 25$ºC):

$$v_0 = 0.0010\ \frac{\text{m}^3}{\text{kg}};\quad u_0 = 83.96\ \frac{\text{kJ}}{\text{kg}};\quad s_1 = 0.297\ \frac{\text{kJ}}{\text{kg K}};$$

State-1 (given $T_1 = 95^{\circ}\text{C}$ and $x_1 = 0$):

$$v_1 = 0.00104\ \frac{\text{m}^3}{\text{kg}};\quad u_1 = 397.87\ \frac{\text{kJ}}{\text{kg}};\quad s_1 = 1.25\ \frac{\text{kJ}}{\text{kg K}};$$

$$\phi_1 = (u_1 - u_0) - T_0(s_1 - s_0) + p_0(v_1 - v_0);$$

$$\Rightarrow \phi_1 = (397.87207 - 83.95766) - 293.15(1.25 - 0.2966) + 100(0.00104 - 0.0010);$$

$$\Rightarrow \phi_1 = 34.43\ \frac{\text{kJ}}{\text{kg}};$$

State-2 (given $x_2 = 1$ and $p_2 = p_1$):

$$v_2 = 1.98\ \frac{\text{m}^3}{\text{kg}}; \quad u_2 = 2500.52\ \frac{\text{kJ}}{\text{kg}}; \quad s_2 = 7.42\ \frac{\text{kJ}}{\text{kg K}};$$

$$\phi_2 = (u_2 - u_0) - T_0(s_2 - s_0) + p_0(v_2 - v_0);$$

$$\Rightarrow \phi_2 = (2500.5178 - 83.95766) - 293.15(7.41594 - 0.2966) + 100(1.98225 - 0.0010);$$

$$\Rightarrow \phi_2 = 527.65\ \frac{\text{kJ}}{\text{kg}};$$

(a) $\Delta\phi = \phi_2 - \phi_1 = 527.65 - 34.43 = 493.223\ \frac{\text{kJ}}{\text{kg}}$

The energy equation for the closed process simplifies as:

$$\Delta E = \cancel{Q}^0 - W_{\text{ext}};$$

$$\Rightarrow w_{\text{ext}} = -\Delta e = -(e_2 - e_1) = -(u_2 - u_1) = -(2500.52 - 397.87);$$

$$\Rightarrow w_{ext} = (w_B) + (-w_{\text{sh,in}}) = -2102.65\ \frac{\text{kJ}}{\text{kg}};$$

The work done on the atmosphere by the freely moving piston is calculated as:

$$w_0 = p_0(v_2 - v_1) = 100(1.98225 - 0.00104) = 198.12\ \frac{\text{kJ}}{\text{kg}};$$

(b) The useful work (exergy transferred by work) is:

$$w_u = w_{\text{ext}} - w_0 = (-2102.65) - 198.12 = -2300.77\ \frac{\text{kJ}}{\text{kg}}$$

(c) The exergy transferred by heat is 0 as the system is adiabatic.

$$w_u = w_{\text{ext}} - w_0 = (-2102.65) - 198.12 = -2300.77\ \frac{\text{kJ}}{\text{kg}}$$

(d) The exergy destruction per unit mass:

$$\Delta\Phi = \cancel{Q}^0\left(1 - \frac{T_o}{T_k}\right) - W_u - I;$$

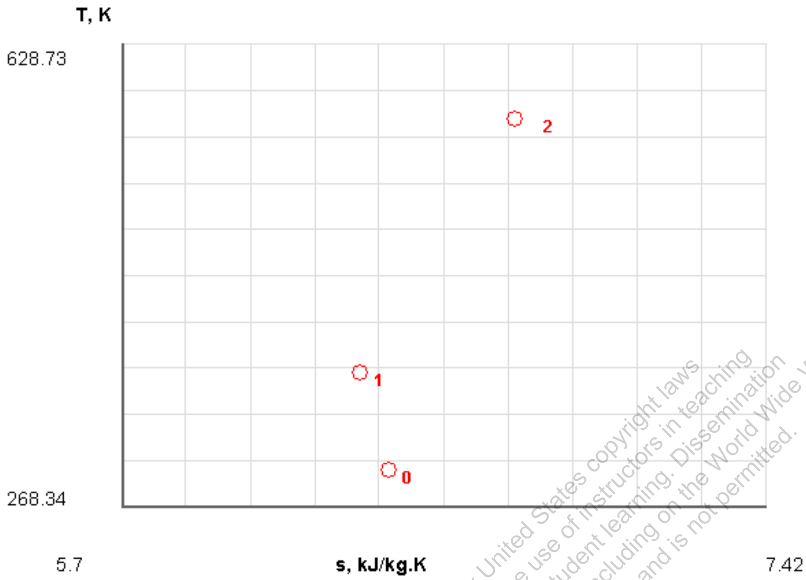
$$\Rightarrow \frac{I}{m} = \phi_1 - \phi_2 - w_u = 34.43 - 527.65 - (-2300.77) = 1807.55\ \frac{\text{kJ}}{\text{kg}}$$

TEST Solution:

Launch the PC closed-process TESTcalc and select H2O. Evaluate the dead, initial, and final states from the given information. In the process panel, analyze the process (load the initial and final states, enter Q as 0 and Calculate) to determine W_B. In the exergy panel, click Calculate to obtain all the exergy terms. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-13 [OEZ] An insulated piston cylinder device contains 20 L of O_2 (use the IG model) at 300 kPa and 100°C. It is then heated for 1 min by a 200 W resistance heater placed inside the cylinder. The pressure of O_2 is maintained constant during the process. Determine (a) the change in stored exergy ($\Delta\Phi$) and (b) the irreversibility during the process. Assume the surroundings to be at 100 kPa and 25°C. (c) What-if Scenario: What would the answer in part (b) be if the volume were 50 L instead?

SOLUTION



Use the IG closed-process TESTcalc or the manual approach to determine the dead state, State-0, the initial state, State-1, and the final state, State-2.

State-0 (given $p_0 = 100\text{ kPa}$ and $T_0 = 25^\circ\text{C}$):

$$v_0 = 0.775\ \frac{\text{m}^3}{\text{kg}};\quad u_0 = -78.1\ \frac{\text{kJ}}{\text{kg}};\quad s_0 = 6.412\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

State-1 (given $p_1 = 300\text{ kPa}$, $T_1 = 100^\circ\text{C}$, and $\cancel{V}_1 = 20\text{ L}$):

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.259)(373)}{100} = 0.323\ \frac{\text{m}^3}{\text{kg}};$$

$$m = \frac{\cancel{V}_1}{v_1} = \frac{(0.02)}{0.323} = 0.062\text{ kg};$$

$$u_1 = 114.2\ \frac{\text{kJ}}{\text{kg}};\quad h_1 = 68.8\ \frac{\text{kJ}}{\text{kg}};\quad s_1 = 6.333\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$\phi_1 = (u_1 - u_0) - T_0(s_1 - s_0) + p_0(v_1 - v_0) = 28.0\ \frac{\text{kJ}}{\text{kg}};$$

State-2 (given $p_2 = p_1$, $m_2 = m_1$)

The energy equation for the closed process yields:

$$\Delta U = \cancel{Q}^{0} - W_{\text{ext}} = -\left(W_{B,\text{out}} - W_{\text{el,in}}\right);$$

$$\Rightarrow \Delta U + W_B = W_{\text{el,in}};$$

$$\Rightarrow m\left(h_2 - h_1\right) = W_{\text{el,in}} = \frac{(200)(60)}{1000} = 12 \text{ kJ};$$

$$\Rightarrow h_2 = \frac{W_{\text{el,in}}}{m} + h_1 = \frac{12}{0.062} + 68.8 = 262.7 \ \frac{\text{kJ}}{\text{kg}};$$

$$\therefore T_2 = 571.6 \text{ K}; \quad \mathcal{V} = 0.031 \text{ m}^3;$$

$$v_2 = 0.495 \ \frac{\text{m}^3}{\text{kg}}; \quad u_2 = 114.2 \ \frac{\text{kJ}}{\text{kg}}; \quad s_2 = 6.75 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$\phi_2 = \left(u_2 - u_0\right) - T_0\left(s_2 - s_0\right) + p_0\left(v_2 - v_0\right) = 63.58 \ \frac{\text{kJ}}{\text{kg}};$$

(a) The exergy change

$$\Delta\Phi = m\left(\phi_2 - \phi_1\right) = 2.2 \text{ kJ}$$

(b) The entropy equation for the closed process is:

$$\Delta S = m\left(s_2 - s_1\right) = \frac{Q}{T_B} + S_{\text{gen.univ}} = \frac{Q}{T_0} + S_{\text{gen.univ}};$$

$$\Rightarrow I = T_0 S_{\text{gen.univ}} = T_0 \Delta S - Q = T_0 m\left(s_2 - s_1\right) - \cancel{Q}^{0};$$

$$\Rightarrow I = 7.67 \text{ kJ}$$

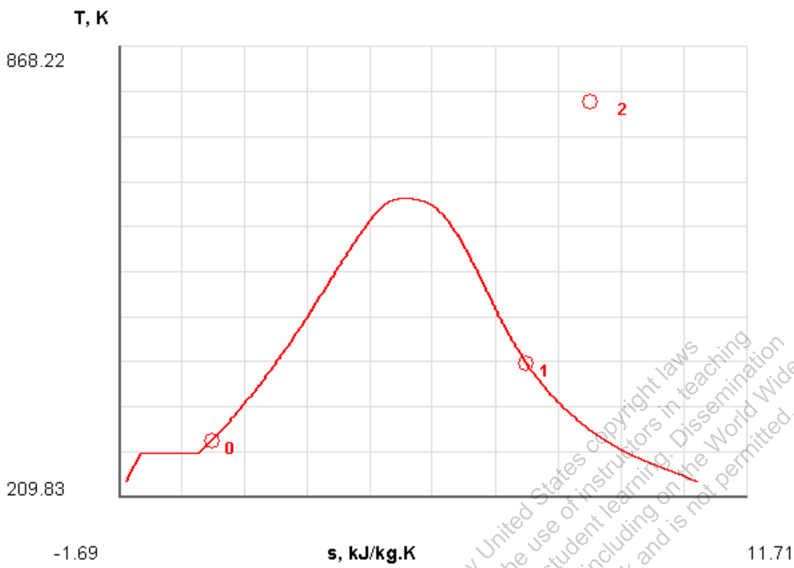
TEST Solution:

Launch the IG closed-process TESTcalc and select O2. Evaluate the dead, initial, and final states from the given information. In the process panel, analyze the process (load the initial and final states, enter Q as 0, W_O, and Calculate) to determine e2, which is posted back at State-2. Click Super-Calculate to update all results. In the exergy panel, click Calculate to obtain all the exergy terms. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

(c) Change Vol1 to 50 L and click Super-Calculate. The new answer for I (in the exergy panel) is displayed as 8.67 kJ.

6-2-14 [OEK] A piston-cylinder device initially contains 20 g of saturated water vapor at 300 kPa. A resistance heater is operated within the cylinder with a current of 0.4 A from a 240 V source until the volume doubles. At the same time a heat loss of 4 kJ occurs. Determine (a) the final temperature (T_2), (b) duration of the process and (c) second-law efficiency. Assume the surrounding temperature and pressure to be 20°C and 100 kPa, respectively. (d) What-if Scenario: What would the efficiency be if the heat loss were negligible during the process?

SOLUTION



Use the PC closed-process TESTcalc or the manual approach to determine the dead state, State-0, the beginning state, State-1, and the final state, State-2.

State-0 (given $p_0 = 100 \text{ kPa}$ and $T_0 = 20^{\circ}\text{C}$):

$$v_0 = 0.0010 \ \frac{\text{m}^3}{\text{kg}}; \quad u_0 = 83.96 \ \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 0.297 \ \frac{\text{kJ}}{\text{kg} \cdot \text{K}};$$

State-1 (given $p_1 = 300 \text{ kPa}$, $x_1 = 1$ and $m_1 = 20 \text{ g}$):

$$v_1 = 0.606 \ \frac{\text{m}^3}{\text{kg}}; \quad u_1 = 2543.5 \ \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 6.99 \ \frac{\text{kJ}}{\text{kg K}};$$

$$\phi_1 = (u_1 - u_0) - T_0 (s_1 - s_0) + p_0 (v_1 - v_0) = 557.4 \ \frac{\text{kJ}}{\text{kg}};$$

State-2 (given $p_2 = p_1$, $v_2 = 2v_1$):

$$v_2 = 1.212 \ \frac{\text{m}^3}{\text{kg}}; \quad u_2 = 3157.51 \ \frac{\text{kJ}}{\text{kg}}; \quad s_2 = 8.37 \ \frac{\text{kJ}}{\text{kg K}};$$

$$\phi_2 = (u_2 - u_0) - T_0 (s_2 - s_0) + p_0 (v_2 - v_0) = 828.6 \ \frac{\text{kJ}}{\text{kg}};$$

(a) $T_2 = 516.14^{\circ}\mathrm{C}$

The energy equation for the closed-process simplifies as:

$$\Delta E = Q - W_{\text{ext}}; \qquad \Rightarrow \Delta U = \left(-Q_{\text{loss}}\right) - \left(W_B - W_{\text{el,in}}\right);$$
$$\Rightarrow m\left(u_2 - u_1\right) = -Q_{\text{loss}} - p\left(V_2 - V_1\right) + W_{\text{el,in}};$$
$$\Rightarrow 0.02\left(3157.51 - 2543.5\right) = -4 - \left(300\right)\left(0.01212\right) + W_{\text{el,in}};$$
$$\Rightarrow W_{\text{el,in}} = 19.9 \text{ kJ};$$

(b) The duration of the process is

$$t = \frac{W_{\text{el,in}}}{\left(VI/1000\right)} = \frac{\left(19.9\right)\left(1000\right)}{\left(240\right)\left(0.4\right)} = 207.3 \text{ sec}$$

The exergy equation for the closed-process simplifies as:

$$\Delta\Phi = \sum_k Q_k\left(1 - \frac{T_0}{T_k}\right) - W_u - I = \sum_k Q_0 \cancelto{0}{\left(1 - \frac{T_0}{T_0}\right)} - W_{\text{rev}};$$
$$\Rightarrow W_{\text{rev}} = \Phi_1 - \Phi_2 = m\left(\phi_1 - \phi_2\right) = -5.41 \text{ kJ};$$
$$\Rightarrow W_{\text{rev,in}} = 5.41 \text{ kJ};$$

The useful work input is given as:

$$W_u = W_{\text{ext}} - W_0 = \left(W_B - W_{\text{el,in}}\right) - p_0\left(V_2 - V_1\right);$$
$$\Rightarrow W_u = p_1\left(V_2 - V_1\right) - p_0\left(V_2 - V_1\right) - W_{\text{el,in}} = \left(300 - 100\right)\left(0.01212\right) - 19.9;$$
$$\Rightarrow W_u = \left(300 - 100\right)\left(0.01212\right) - 19.9 = -17.5 \text{ kJ};$$
$$\Rightarrow W_{u,\text{in}} = 17.5 \text{ kJ};$$

(c) The second-law efficiency, which is the ratio of the minimum reversible work input to the useful work input can now be calculated:

$$\eta_{II} = \frac{\dot{W}_{\text{rev,in}}}{\dot{W}_{u,\text{in}}} = \frac{5.4}{17.5} = 0.308$$
$$\eta_{II} = 30.8\%$$

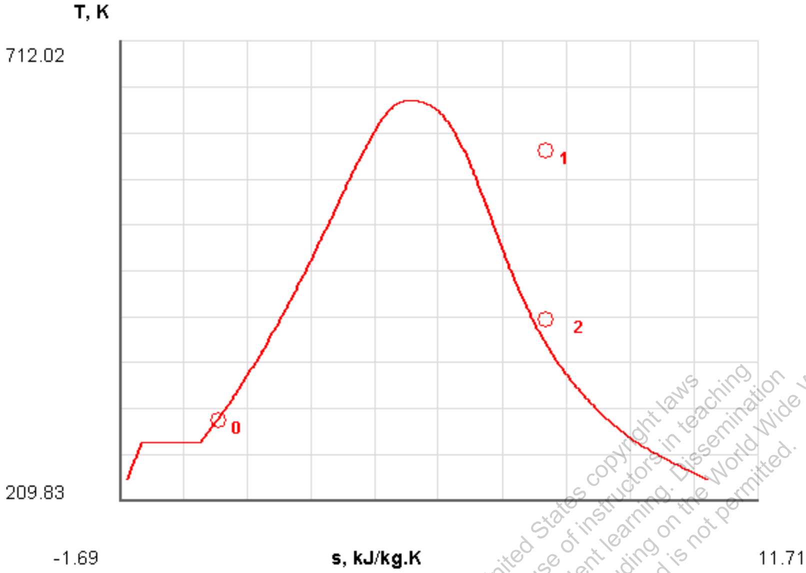
TEST Solution:

Launch the PC closed-process TESTcalc and select H2O. Evaluate the dead, initial, and final states from the given information. In the process panel, analyze the process (load the initial and final states, enter Q and T_B, and Calculate) to determine W_O. In the exergy panel, click Calculate to obtain all the exergy terms. Calculate eta_II in the I/O panel from W_rev and W_u. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

(d) Change Q to 0 in the process panel and click Super-Calculate. From the new values of W_rev and W_u, obtain eta_II = 5.42/13.5 = 40.1 %.

6-2-15 [OEP] A piston-cylinder device contains 0.1 kg of steam at 900 kPa and 320°C. Steam then expands to a final state of 180 kPa and 135°C, doing work. Heat losses from the system to the surroundings are estimated to be 4 kJ during this process. Assuming the surroundings to be at 25°C and 100 kPa, determine (a) the exergy of the steam at the initial and final states, (b) the exergy change ($\Delta\Phi$) of steam, (c) the exergy destroyed (I) and (d) the exergetic (second-law) efficiency.

SOLUTION



Use the PC closed-process TESTcalc or the manual approach to determine the dead state, State-0, the beginning state, State-1, and the final state, State-2.

State-0 (given $p_0 = 100$ kPa and $T_0 = 25$°C):

$$v_0 = 0.0010 \frac{\text{m}^3}{\text{kg}}; \quad u_0 = 104.87 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 0.367 \frac{\text{kJ}}{\text{kg K}};$$

State-1 (given $p_1 = 900$ kPa, $T_1 = 320^\circ$C and $m_1 = 0.1$ kg):

$$v_1 = 0.29818 \frac{\text{m}^3}{\text{kg}}; \quad u_1 = 2827.76 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 7.25 \frac{\text{kJ}}{\text{kg K}};$$

State-2 (given $p_2 = 180$ kPa, $T_2 = 135^\circ$C and $m_2 = m_1$):

$$v_2 = 1.02749 \frac{\text{m}^3}{\text{kg}}; \quad u_2 = 2554.38 \frac{\text{kJ}}{\text{kg}}; \quad s_2 = 7.254 \frac{\text{kJ}}{\text{kg K}};$$

(a) $\phi_1 = (u_1 - u_0) - T_0(s_1 - s_0) + p_0(v_1 - v_0);$

$$\Rightarrow \Phi_1 = m\phi_1;$$
$$\Rightarrow \Phi_1 = 0.1\left[\left(2827.76-104.87\right)-298\left(7.25-0.367\right)+100\left(0.29818-0.0010\right)\right];$$
$$\Rightarrow \Phi_1 = 70.1 \text{ kJ}$$

$$\phi_2 = \left(u_2-u_0\right)-T_0\left(s_2-s_0\right)+p_0\left(v_2-v_0\right);$$
$$\Rightarrow \Phi_2 = m\phi_2;$$
$$\Rightarrow \Phi_2 = 0.1\left[\left(2554.38-104.87\right)-298\left(7.254-0.367\right)+100\left(1.027-0.0010\right)\right];$$
$$\Rightarrow \Phi_2 = 49.9 \text{ kJ}$$

(b) The exergy change

$$\Delta\Phi = \Phi_2 - \Phi_1;$$
$$\Rightarrow \Delta\Phi = 49.9-70.1 = -20.2 \text{ kJ}$$

The exergy balance equation applied over the system yields

$$\Delta\Phi = \sum_k \cancel{Q_k}^{0}\left(1-\frac{T_0}{T_k}\right)-W_{rev};$$
$$\Rightarrow W_{\text{rev}} = 20.2 \text{ kJ};$$

(c) Using the entropy equation, we can obtain the exergy destroyed.

$$I = T_0 S_{gen};$$
$$\Rightarrow I = T_0\left(\Delta S - \frac{Q}{T_B}\right);$$
$$\Rightarrow I = 298\left[0.1\left(.004\right)-\frac{-4}{298}\right];$$
$$\Rightarrow I = 4.1 \text{ kJ}$$

(d) The exergetic efficiency is given as

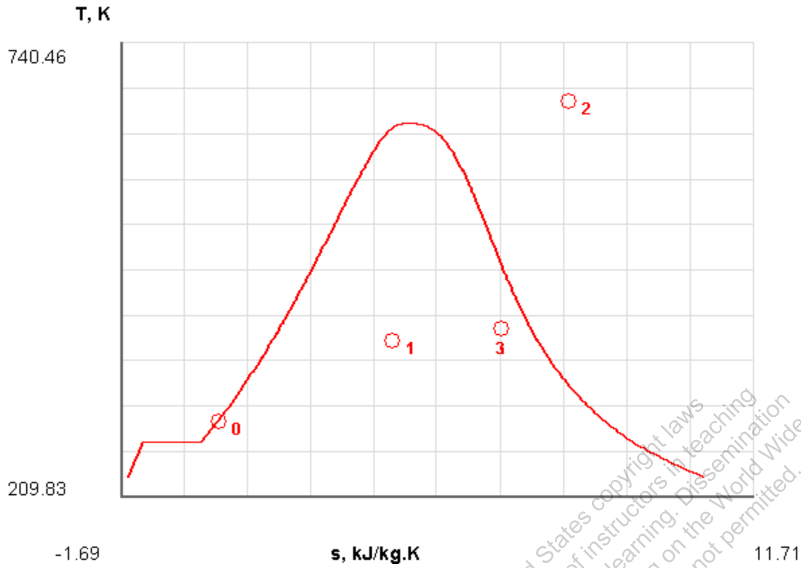
$$\eta_{II} = \frac{W_u}{W_{rev}} = \frac{W_{rev}-I}{W_{rev}} = \frac{20.2-4.1}{20.2} = 0.797;$$
$$\eta_{II} = 79.7\%$$

TEST Solution:

Launch the PC closed-process TESTcalc and select H2O. Evaluate the dead, initial, and final states from the given information. In the process panel, analyze the process (load the initial and final states, enter Q and T_B, and Calculate) to determine W_O. In the exergy panel, click Calculate to obtain all the exergy terms. Calculate eta_II in the I/O panel from W_rev and W_u. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-16 [OEC] Two insulated tanks are connected, both containing H_2O. Tank-A is at 200 kPa, v= 0.4 m^3/kg, V = 1 m^3 and tank B contains 3.5 kg at 0.5 MPa, 400^{o}C. The valve is then opened and the two tanks come to a uniform state. Determine (a) the final pressure (p_2), (b) temperature (T_2) and (c) irreversibility of the process. Assume the surroundings to be at 100 kPa and 25^{o}C.

SOLUTION



Use the PC mixing closed-process TESTcalc or the manual approach to determine the initial states, State-1 and State-2, and the final state, State-3.

State-1 $\left(\text{given } p_1 = 200 \text{ kPa}; v_1 = 0.4 \dfrac{\text{m}^3}{\text{kg}}; \text{ and } \cancel{V}_1 = 1 \text{ m}^3\right)$:

$$u_1 = 1417.1 \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 4.05 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}; \quad m_1 = \frac{\cancel{V}_1}{v1} = 2.5 \text{ kg};$$

State-2 (given $p_2 = 0.5$ MPa, $T_2 = 400^\circ$C and $m_2 = 3.5$ kg):

$$v_2 = 0.617 \frac{\text{m}^3}{\text{kg}}; \quad u_2 = 2963.17 \frac{\text{kJ}}{\text{kg}}; \quad s_2 = 7.79 \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$\cancel{V}_2 = m_2 v_2 = 2.16 \text{ m}^3;$$

State-3

$$m_3 = m_1 + m_2 = 2.5 + 3.5 = 6 \text{ kg};$$

$$\cancel{V}_3 = \cancel{V}_1 + \cancel{V}_2 = 1 + 2.16 = 3.16 \text{ m}^3;$$

$$\Rightarrow v_3 = \frac{3.16}{6} = 0.526 \frac{\text{m}^3}{\text{kg}};$$

The energy equation for the mixing closed process simplifies as:

$$\Delta E = Q - W_{\text{ext}}; \qquad \Rightarrow m_3u_3 - m_2u_2 - m_1u_1 = \cancel{Q}^{0} - \cancel{W_{\text{ext}}}^{0};$$

$$\Rightarrow u_3 = \frac{m_2u_2 + m_1u_1}{m_3} = \frac{(3.5)(2963.17)+(2.5)(1417.1)}{6} = 2318.97 \ \frac{\text{kJ}}{\text{kg}};$$

From v_3 and u_3:

$$s_3 = 6.376 \ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

(a) $p_3 = 302.52 \text{ kPa}$

(b) $T_3 = 134.2^{\circ}\text{C}$

Using the entropy equation

$$\Delta S = \frac{Q}{T_B} + S_{\text{gen,univ}}; \qquad \Rightarrow m_3s_3 - m_1s_1 - m_2s_2 = \cancel{\frac{Q}{T_B}}^{0} + S_{\text{gen,univ}};$$

$$\Rightarrow S_{\text{gen,univ}} = (6)(6.377)-(3.5)(7.794)-(2.5)(4.053) = 0.85 \ \frac{\text{kJ}}{\text{K}};$$

(c) The irreversibility is given by

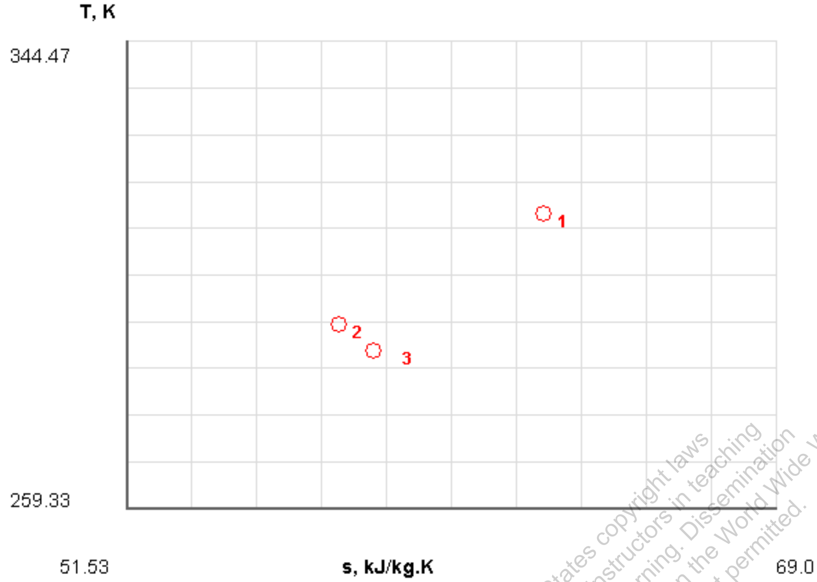
(d) $I = T_0 S_{\text{gen,univ}} = (298)(0.85) = 253.3 \text{ kJ}$

TEST Solution:

Launch the PC mixing closed-process TESTcalc and select H2O. Evaluate the initial, and final states from the given information. In the process panel, analyze the process (load the composite initial and final states, enter Q and W_ext as 0, and Calculate) to determine S_gen. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-17 [OEU] A 0.5 m^3 rigid tank containing hydrogen at 40^{o}C and 200 kPa is connected to another 1 m^3 rigid tank containing hydrogen at 20^{o}C and 600 kPa. The valve is opened and the system is allowed to reach thermal equilibrium with the surroundings at 15^{o}C. Determine the irreversibility in this process. Assume variable c_p.

SOLUTION



Use the IG mixing closed-process TESTcalc or the manual approach to determine the initial states, State-1 and State-2, and the final state, State-3.

State-1 (given $p_1 = 200$ kPa , $T_1 = 40^{o}$C, and $\cancel{V}_1 = 0.5$ m^3):

$$v_1 = 6.46\ \frac{\text{m}^3}{\text{kg}};\quad u_1 = \text{-}1076.6\ \frac{\text{kJ}}{\text{kg}};\quad s_1 = 62.73\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$m_1 = \frac{\cancel{V}_1}{v_1} = \frac{(0.5)}{6.44} = 0.077\ \text{kg};$$

State-2 (given $p_2 = 600$ kPa, $T_2 = 20^{o}$C, $\cancel{V}_2 = 1$ m^3):

$$v_2 = 2.01\ \frac{\text{m}^3}{\text{kg}};\quad u_2 = \text{-}1280.6\ \frac{\text{kJ}}{\text{kg}};\quad s_2 = 57.25\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

$$m_2 = \frac{\cancel{V}_2}{v_2} = \frac{(1)}{2.01} = 0.497\ \text{kg};$$

State-3 (given $T_3 = 15^{o}$C, $\cancel{V}_3 = \cancel{V}_2 + \cancel{V}_1$, $m_3 = m_2 + m_1$):

$$m_3 = 0.574\ \text{kg};\quad u_3 = -1331\ \frac{\text{kJ}}{\text{kg}};\quad s_3 = 58.15\ \frac{\text{kJ}}{\text{kg}\cdot\text{K}};$$

The energy equation for the mixing closed process simplifies as:

$$\Delta E = Q - \cancel{W_{\text{ext}}}^{0};$$

$$\Rightarrow m_3 u_3 - m_2 u_2 - m_1 u_1 = Q;$$

$$\Rightarrow Q = -45.0 \text{ kJ};$$

Using the entropy equation for this closed-process:

$$\Delta S = \frac{Q}{T_B} + S_{\text{gen,univ}}; \qquad \Rightarrow m_3 s_3 - m_1 s_1 - m_2 s_2 = \frac{Q}{T_0} + S_{\text{gen,univ}};$$

$$\Rightarrow S_{\text{gen,univ}} = (0.574)(58.15) - (0.077)(62.73) - (0.496)(57.25) - \frac{(-45)}{288} = 0.248 \ \frac{\text{kJ}}{\text{K}};$$

The irreversibility is given by

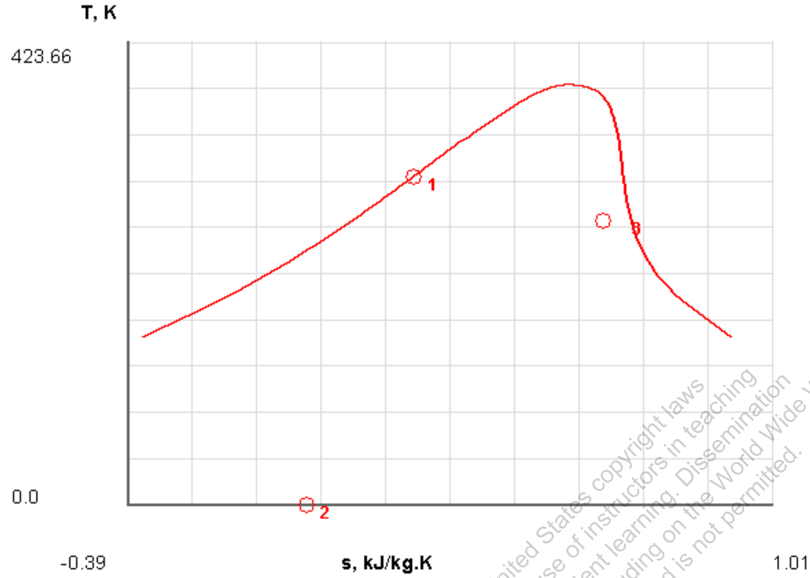
$$I = T_0 S_{\text{gen,univ}} = (288)(0.248) = 71.42 \text{ kJ}$$

TEST Solution:

Launch the IG mixing closed-process TESTcalc and select H2. Evaluate the initial, and final states from the given information. In the process panel, analyze the process (load the composite initial and final states, enter W_ext as 0 and T_B, and Calculate) to determine S_gen. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-18 [OEX] A tank whose volume is unknown is divided into two parts by a partition. One side contains 0.02 m^3 of saturated liquid R-12 at 0.7 MPa, while the other side is evacuated. The partition is removed, and R-12 fills up the entire volume. If the final state is 200 kPa and has a quality of 90%. Determine (a) the volume of the tank, (b) heat transfer (Q) and (c) the irreversible work. The atmospheric temperature is 30°C.

SOLUTION



Use the PC mixing closed-process TESTcalc or the manual approach to determine the initial states, State-1 and State-2, and the final state, State-3.

State-1 (given $p_1 = 0.7$ MPa, $x_1 = 0$ and $\cancel{V}_1 = 0.02\ \text{m}^3$):

$$T_1 = 27.65^\circ\text{C}; \quad u_1 = 61.76\ \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 0.232\ \frac{\text{kJ}}{\text{kg.K}}; \quad v_1 = 0.00077\ \frac{\text{m}^3}{\text{kg}};$$

$$m_1 = \frac{\cancel{V}_1}{v_1} = \frac{0.02}{0.00077} = 26\ \text{kg};$$

State-2 (given $p_2 = 0$ kPa; $\cancel{V}_2 = 0\ \text{m}^3$):

$$m_2 = 0\ \text{kg};$$

State-3 (given $p_3 = 200$ kPa; $x_3 = 90$ %):

$$T_3 = -12.52^\circ\text{C}; \quad u_3 = 151.26\ \frac{\text{kJ}}{\text{kg}}; \quad s_3 = 0.643\ \frac{\text{kJ}}{\text{kg.K}}; \quad v_3 = 0.0753\ \frac{\text{m}^3}{\text{kg}};$$

$$m_3 = m_1 + m_2 = 26\ \text{kg};$$

(a) The volume of the tank is

$$\cancel{V}_3 = mv_3 = (26)(0.0753) = 1.95\ \text{m}^3$$

(b) The energy equation for the mixing closed process simplifies as:

$$\Delta E = Q - W_{\text{ext}};$$

$$\Rightarrow m_3u_3 - \cancelto{0}{m_2}u_2 - m_1u_1 = Q - \cancelto{0}{W_{\text{ext}}};$$

$$\Rightarrow Q = m(u_3 - u_1) = 26(151.26 - 61.76) = 2327.3\ \text{kJ}$$

The entropy equation for the mixing closed process simplifies as:

$$\Delta S = \frac{Q}{T_B} + S_{\text{gen,univ}};$$

$$\Rightarrow m\left(s_3 - s_1 - \cancelto{0}{s_2}\right) = \frac{Q}{T_0} + S_{\text{gen,univ}};$$

$$S_{\text{gen,univ}} = 26(0.644 - 0.232) - \frac{2327.3}{303} = 3.0\ \frac{\text{kJ}}{\text{K}};$$

(c) The irreversibility is given by

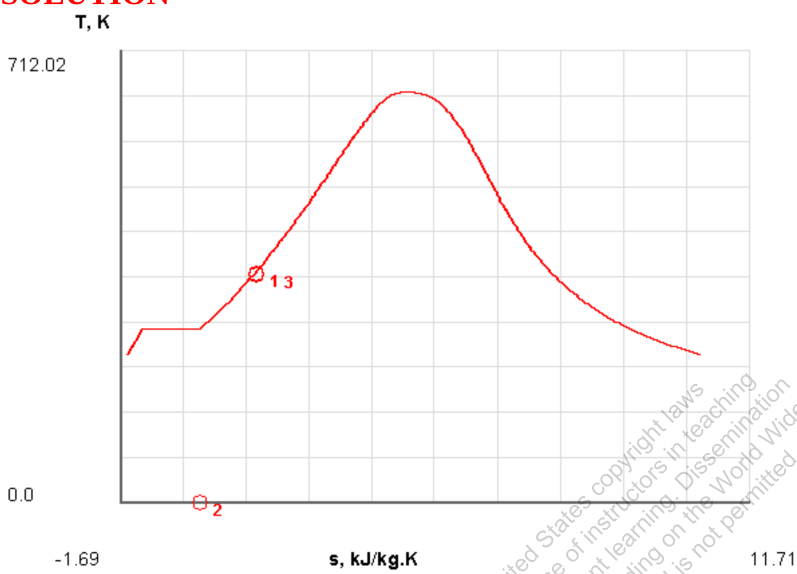
$$I = T_0S_{\text{gen,univ}} = (303)(3) = 909\ \text{kJ}$$

TEST Solution:

Launch the PC mixing closed-process TESTcalc and select R12. Evaluate the initial, and final states from the given information. To set a vacuum state in TEST, mass and either pressure or temperature (all zeros) are assigned. In the process panel, analyze the process (load the composite initial and final states, enter W_ext as 0 and T_B, and Calculate) to determine S_gen. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-19 [OEV] An insulated rigid tank has two compartments, one 10 times larger than the other, divided by a partition. At the beginning the smaller side contains 4 kg of H_2O at 200 kPa, 90°C and the other side is evacuated. The partition is removed and the water expands to a new equilibrium condition. (a) Determine the irreversibility during the process. Assume the surrounding conditions to be 100 kPa and 25°C.(b) What-if Scenario: What would the irreversibility be if the larger chamber were 100 times larger?

SOLUTION



Use the PC mixing closed-process TESTcalc or the manual approach to determine the initial states, State-1 and State-2, and the final state, State-3.

State-1 (given $p_1 = 200$ kPa, $T_1 = 90^\circ$C and $m_1 = 4$ kg):

$$v_1 = 0.00104\ \frac{\text{m}^3}{\text{kg}}; \quad u_1 = 376.85\ \frac{\text{kJ}}{\text{kg}}; \quad s_1 = 1.1925\ \frac{\text{kJ}}{\text{kg.K}};$$

$$\cancel{V}_1 = mv_1 = (4)(0.00104) = 0.00414\ \text{m}^3;$$

State-2 (given $p_2 = 0$ kPa, $m_2 = 0$ kg, $\cancel{V}_2 = 0.0414\ \text{m}^3$):

$$m_1 = 0\ \text{kg};$$

State-3 (given $m_3 = m_1$):

$$\cancel{V}_3 = \cancel{V}_1 + \cancel{V}_2 = 0.04554\ \text{m}^3;$$

$$v_3 = \frac{\cancel{V}_3}{m_1} = 0.0114\ \frac{\text{m}^3}{\text{kg}};$$

$$m_3 = m_1 + m_2 = 0.00414\ \text{kg};$$

The energy equation for the mixing closed process simplifies as:

$\Delta E = Q - W_{\text{ext}};$

$$\Rightarrow m_3 u_3 - \cancel{m_2}^0 u_2 - m_1 u_1 = \cancel{Q}^0 - \cancel{W_{\text{ext}}}^0;$$

$$\Rightarrow u_3 = \frac{m_1}{m_3} = u_1 \frac{m_1}{m_1} = u_1 = 376.85 \ \frac{\text{kJ}}{\text{kg}};$$

From v and u, we can determine:

$$s_3 = 1.19431 \ \frac{\text{kJ}}{\text{kg.K}}; \quad T_3 = 87.93^{\circ}\text{C}; \quad p_3 = 63.43 \text{ kPa};$$

The entropy equation for the mixing closed process simplifies as:

$$\Delta S = \frac{Q}{T_B} + S_{\text{gen,univ}}; \quad \Rightarrow m_3 s_3 - m_1 s_1 - \cancel{m_2 s_2}^0 = \frac{\cancel{Q}^0}{T_0} + S_{\text{gen,univ}};$$

$$\Rightarrow S_{\text{gen,univ}} = 4(1.19431 - 1.1925) = 0.00724 \ \frac{\text{kJ}}{\text{K}};$$

The irreversibility is given by

$I = T_0 S_{gen} = (298)(0.00724) = 2.157 \text{ kJ}$

TEST Solution:

Launch the PC mixing closed-process TESTcalc and select H2O. Evaluate the initial, and final states from the given information. To set a vacuum state in TEST, mass and either pressure or temperature (all zeros) are assigned. In the process panel, analyze the process (load the composite initial and final states, enter W_ext as 0 and T_B, and Calculate) to determine S_gen. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-20 [OEQ] A 40 kg aluminum block at 90°C is dropped into an insulated tank that contains 0.5 m^3 of liquid water at 20°C. Determine the irreversibility in the resulting process if the surrounding temperature is 27°C.

SOLUTION

Use the SL-SL non-mixing closed-process TESTcalc or the manual approach to determine the composite initial states, State-1 and State-2, and the final states, State-3 and State-4.

Material properties of water are $\rho_w = 997 \ \dfrac{\text{kg}}{\text{m}^3}$ and $c_{\text{v,w}} = 4.184 \ \dfrac{\text{kJ}}{\text{kg} \cdot \text{K}}$;

Material properties of aluminum are $\rho_a = 2700.0 \ \dfrac{\text{kg}}{\text{m}^3}$ and $c_{v,a} = 0.9 \ \dfrac{\text{kJ}}{\text{kg} \cdot \text{K}}$;

Let State-1 and State-3 be the initial and final state for aluminum and State-2 and State-4 be the initial and final states for water.

State-1 (Aluminum):

$T_1 = 90^\circ\text{C};$

$m_1 = 40 \text{ kg};$

State-2 (Water):

$T_2 = 20^\circ\text{C};$

$\mathcal{V}_2 = 0.5 \text{ m}^3;$

$m_2 = \rho_w \mathcal{V}_2 = (997)(0.5) = 498.5 \text{ kg};$

State-3 (Aluminum):

$m_3 = m_1;$

State-4 (Water):

$T_4 = T_3;$

$\mathcal{V}_4 = \mathcal{V}_2;$

$m_4 = m_2;$

The energy equation for the combined system going through a non-mixing closed process simplifies as:

$$\Delta E = Q - W_{\text{ext}}; \qquad \Rightarrow \Delta U = \cancel{Q}^0 - \cancel{W_{\text{ext}}}^0; \qquad \Rightarrow \Delta U_a + \Delta U_w = 0;$$

$$\Rightarrow \lfloor mc_{v,a}(T_3 - T_1) \rfloor + \lfloor mc_{v,w}(T_4 - T_2) \rfloor = 0;$$

$$\Rightarrow \left[(40)(0.9)(\mathrm{T}_3 - 363)\right] + \left[(498.5)(4.184)(T_4 - 293)\right] = 0;$$

$$\Rightarrow 36T_3 - 13068 + 2085.7T_3 - 611117.1;$$

$$\Rightarrow T_3 = T_4 = 294.2 \text{ K};$$

The entropy equation for this non-mixing closed process simplifies as:

$$\Delta S = \frac{Q}{T_B} + S_{\text{gen,univ}} = \frac{\cancel{Q}^0}{T_0} + S_{\text{gen,univ}};$$

$$\Rightarrow S_{\text{gen,univ}} = \Delta S = \Delta S_a + \Delta S_w;$$

$$\Rightarrow S_{\text{gen,univ}} = mc_{v,a} \ln\left(\frac{T_3}{T_1}\right) + mc_{v,w} \ln\left(\frac{T_4}{T_2}\right);$$

$$\Rightarrow S_{\text{gen,univ}} = (40)(0.9)\ln\left(\frac{294.2}{363}\right) + (498.5)(4.184)\ln\left(\frac{294.2}{293}\right) = 0.93 \ \frac{\text{kJ}}{\text{K}};$$

The irreversibilities in the process

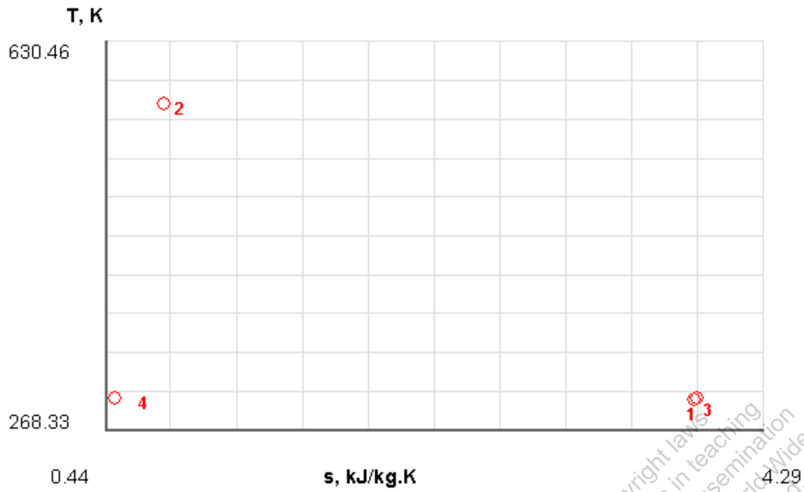
$\dot{I} = T_0 S_{\text{gen,univ}} = (300)(0.93) = 281.4 \text{ kJ}$

TEST Solution:

Launch the SL-SL non-mixing closed-process TESTcalc. Evaluate the initial, and final states from the given information. For each state select the working substance from the subsystem A or B menu. In the process panel, analyze the process (load the composite initial and final states, enter W_ext and Q as 0, T_B, and Calculate) to determine S_gen. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).

6-2-21 [OET] A 4 kg iron block initially at 300°C is dropped into an insulated tank that contains 80 kg of water at 25°C. Assuming the water that vaporizes during this process condenses back in the tank and the surroundings are at 20°C and 100 kPa. Determine (a) the final equilibrium temperature (T_f), (b) the exergy (Φ) of the combined system at initial and final states and (c) the wasted work potential during this process.

SOLUTION



Use the SL-SL non-mixing closed-process TESTcalc or the manual approach to determine the composite initial states, State-1 and State-2, and the final states, State-3 and State-4.

Material properties of water are $c_{v,w} = 4.184 \ \dfrac{\text{kJ}}{\text{kg.K}}$;

Material properties of aluminum are $c_{v,i} = 0.45 \ \dfrac{\text{kJ}}{\text{kg.K}}$;

Let State-1 and State-3 be the initial and final state for water and State-2 and State-4 be the initial and final states for iron.

(a) The energy equation for the combined system going through a non-mixing closed process simplifies as:

$$\Delta E = Q - W_{\text{ext}}; \quad \Rightarrow \quad \Delta U = \cancel{Q}^{0} - \cancel{W_{\text{ext}}}^{0}; \quad \Rightarrow \quad \Delta U_i + \Delta U_w = 0$$

$$\Rightarrow \lfloor m_w c_{v,w}(T_3 - T_1) \rfloor + \lfloor m_i c_{v,i}(T_4 - T_2) \rfloor = 0;$$

$$\Rightarrow 0 = \left[m_{water} C_{p,water}(T_3 - T_1) + m_{iron} C_{p,iron}(T_4 - T_2) \right];$$

$$\Rightarrow 0 = \left[(80)(4.18)(T_3 - 298) + (4)(0.45)(T_4 - 573) \right];$$

$$\Rightarrow T_{final} = T_3 = T_4 = 299.6 \text{ K} = 26.6^{\circ}\text{C}$$

The entropy equation for this non-mixing closed process simplifies as:

$$\Delta S = \frac{Q}{T_B} + S_{\text{gen,univ}} = \frac{\cancel{Q}^{0}}{T_0} + S_{\text{gen,univ}} = 0.456 \ \frac{\text{kJ}}{\text{K}};$$

(b) The irreversibilities in the process

$$\dot{I} = T_0 S_{\text{gen,univ}} = (293)(0.456) = 135.9 \text{ kJ}$$

TEST Solution:

Launch the SL-SL non-mixing closed-process TESTcalc. Evaluate the initial and final states from the given information. For each state select the working substance from the subsystem A or B menu. In the process panel, analyze the process (load the composite initial and final states, enter W_ext and Q as 0, T_B, and Calculate) to determine S_gen. The TEST-code can be found in the Problems module of TEST-Pro (at www.thermofluids.net).