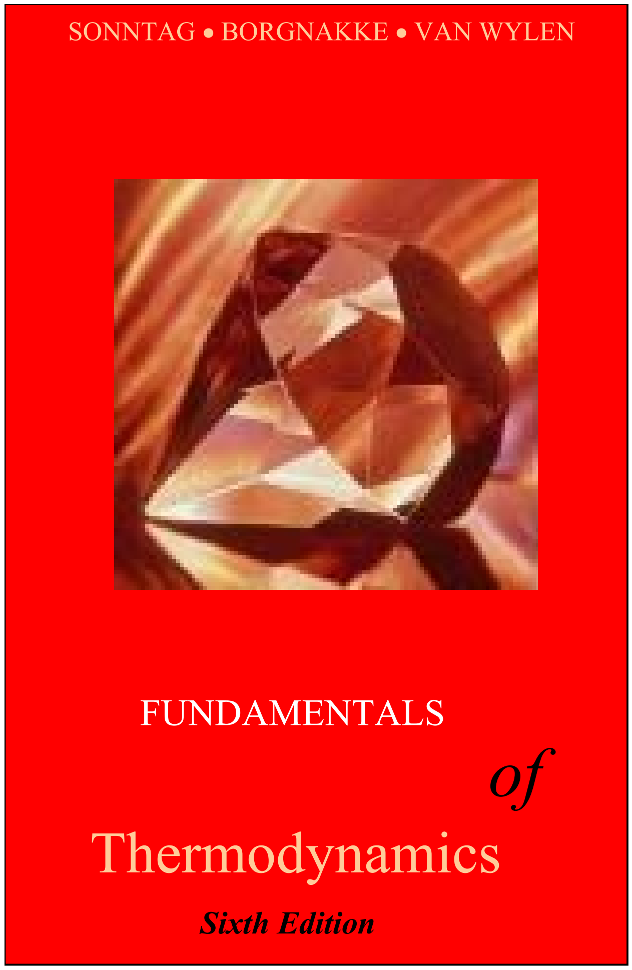
SOLUTION MANUAL
ENGLISH UNIT PROBLEMS
CHAPTER 10



CHAPTER 10

SUBSECTION	PROB NO.
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Correspondence List

The correspondence between the new English unit problem set and the previous 5th edition chapter 10 problem set with the current set of SI problems.

New	5th	SI	New	5th	SI	New	5th	SI
107	new	12	120	65	42	133	new	82
108	new	14	121	68	43	134	new	71
109	new	15	122	64	44	135	77mod	74
110	new	16	123	67	45	136	78	76
111	new	18	124	86b	50	137	79mod	78
112	new	20	125	70	51	138	81	79
113	69	22	126	73	52	139	new	87
114	62	24	127	74	53	140	new	89
115	new	23	128	76	61	141	61	96
116	66	32	129	new	63	142	80	97
117	86a	34	130	71	65	143	82	99
118	new	37	131	72	67	144	new	-
119	63	39	132	75	68	145	87	104

Concept-Study Guide Problems

10.107E

A flow of air at 150 psia, 540 R is throttled to 75 psia. What is the irreversibility? What is the drop in flow availability?

A throttle process is constant enthalpy if we neglect kinetic energies.

Process: $h_e = h_i$ so ideal gas => $T_e = T_i$

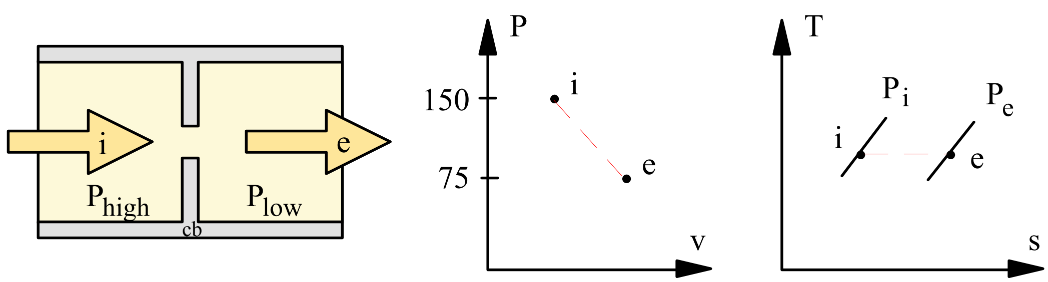
Entropy Eq.: $s_e - s_i = s_{gen} = s^o_{Te} - s^o_{Ti} - R \ln \frac{P_e}{P_i} = 0 - R \ln \frac{P_e}{P_i}$

$$s_{gen} = - \frac{53.34}{778} \ln \left(\frac{75}{150}\right) = 0.0475 \text{ Btu/lbm R}$$

Eq.10.11: $i = T_o\, s_{gen} = 536.7 \times 0.0475 =$ **25.49 Btu/lbm**

The drop in availability is exergy destruction, which is the irreversibility

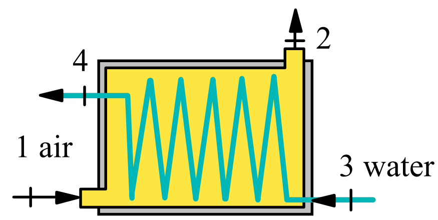
$\Delta\psi = i =$ **25.49 Btu/lbm**



10.108E

A heat exchanger increases the availability of 6 lbm/s water by 800 btu/lbm using 20 lbm/s air coming in at 2500 R and leaving with 250 Btu/lbm less availability. What are the irreversibility and the second law efficiency?

C.V. Heat exchanger, steady flow 1 inlet and 1 exit for air and water each. The two flows exchange energy with no heat transfer to/from the outside.



The irreversibility is the destruction of exergy (availability) so

$$\dot{I} = \dot{\Phi}_{destruction} = \dot{\Phi}_{in} - \dot{\Phi}_{out} = 20 \times 250 - 6 \times 800 = \mathbf{200\ Btu/s}$$

The second law efficiency, Eq.10.32

$$\eta_{II} = \dot{\Phi}_{out} / \dot{\Phi}_{in} = \frac{6 \times 800}{20 \times 250} = \mathbf{0.96}$$

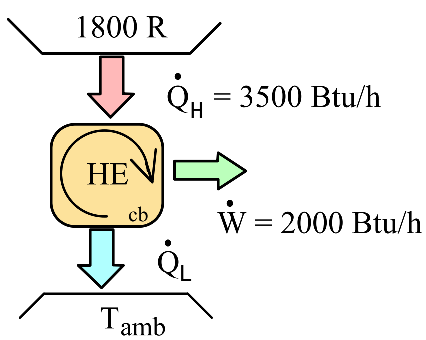
10.109E

A heat engine receives 3500 Btu/h heat transfer at 1800 R and gives out 2000 Btu/h as work with the rest as heat transfer to the ambient. What are the fluxes of exergy in and out?

Exergy flux in: $\dot{\Phi}_H = \left(1 - \frac{T_o}{T_H}\right) \dot{Q}_H = \left(1 - \frac{536.7}{1800}\right)$ 3500 Btu/h = **2456 btu/h**

Exergy flux out: $\dot{\Phi}_L = \left(1 - \frac{T_o}{T_L}\right) \dot{Q}_L = \mathbf{0}$ $\quad (T_L = T_o)$

The other exergy flux out is the power $\dot{\Phi}_{out} = \dot{W} =$ **2000 Btu/h**



10.110E

A heat engine receives 3500 Btu/h heat transfer at 1800 R and gives out 2000 Btu/h as work with the rest as heat transfer to the ambient. Find its first and second law efficiencies.

First law efficiency is based on the energies

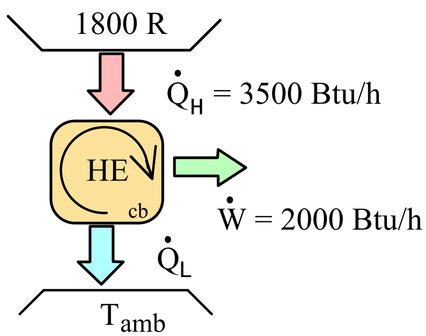
$$\eta_I = \dot{W}/\dot{Q}_H = \frac{2000}{3500} = \mathbf{0.6}$$

The second law efficiency is based on work out versus availability in

Exergy flux in: $\dot{\Phi}_H = \left(1 - \frac{T_o}{T_H}\right) \dot{Q}_H = \left(1 - \frac{536.7}{1800}\right) 3500 \text{ Btu/h} = \mathbf{2456\ btu/h}$

$$\eta_{II} = \frac{\dot{W}}{\dot{\Phi}_H} = \frac{2000}{2456} = \mathbf{0.814}$$

Notice the exergy flux in is equal to the Carnot heat engine power output given 3500 Btu/h at 1800 R and rejecting energy to the ambient.



10.111E

A heat pump has a coefficient of performance of 2 using a power input of 15000 Btu/h. Its low temperature is T_o, and the high temperature is 180 F, with ambient at T_o. Find the fluxes of exergy associated with the energy fluxes in and out.

First let us do the energies in and out

$$\text{COP} = \beta = \frac{\dot{Q}_H}{\dot{W}} \quad \Rightarrow \quad \dot{Q}_H = \beta\,\dot{W} = 2 \times 15\,000 \text{ Btu/h} = 30\,000 \text{ Btu/h}$$

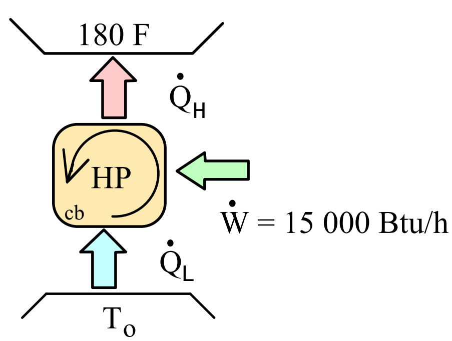
Energy Eq.: $\dot{Q}_L = \dot{Q}_H - \dot{W} = 30\,000 - 15\,000 = 15\,000$ Btu/h

Exergy flux in: $\dot{\Phi}_L = \left(1 - \frac{T_o}{T_L}\right)\dot{Q}_L = \mathbf{0} \qquad (T_L = T_o)$

Exergy flux in: $\dot{\Phi}_W = \dot{W} =$ **15 000 Btu/h**

Exergy flux out: $\dot{\Phi}_H = \left(1 - \frac{T_o}{T_H}\right)\dot{Q}_H = \left(1 - \frac{536.7}{639.7}\right) 30\,000 =$ **4830 Btu/h**

Remark: It destroys 15 000 – 4830 = 10 170 Btu/h of exergy.



10.112E

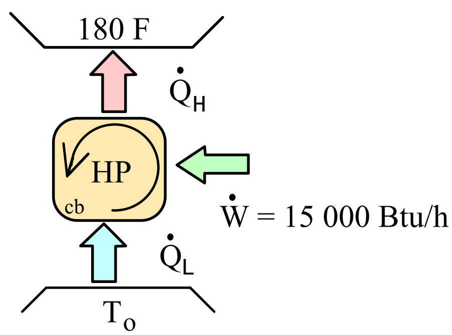
Find the second law efficiency of the heat pump in problem 10.111.

The second law efficiency is a ratio of exergies namely what we want out divided by what we have to put in. Exergy from first term on RHS Eq. 10.36

$$\dot{\Phi}_H = \left(1 - \frac{T_o}{T_H}\right) \dot{Q}_H;$$

$$\dot{Q}_H = \beta\, \dot{W} = 2 \times 15\,000 \text{ Btu/h} = 30\,000 \text{ Btu/h}$$

$$\eta_{II} = \frac{\dot{\Phi}_H}{\dot{W}} = \left(1 - \frac{T_o}{T_H}\right) \frac{\dot{Q}_H}{\dot{W}} = \left(1 - \frac{536.7}{639.7}\right) \frac{30\,000}{15\,000} = \mathbf{0.32}$$



Available Energy, Reversible work

10.113E

A control mass gives out 1000 Btu of energy in the form of

a. Electrical work from a battery
b. Mechanical work from a spring
c. Heat transfer at 700 F

Find the change in availability of the control mass for each of the three cases.

Solution:

a) Work is availability $\Delta\Phi = -W_{el} = \mathbf{-1000\ Btu}$

b) Work is availability $\Delta\Phi = -W_{spring} = \mathbf{-1000\ Btu}$

c) Give the heat transfer to a Carnot heat engine and W is availability

$$\Delta\Phi = -\left(1 - \frac{T_0}{T_H}\right) Q_{out} = -\left(1 - \frac{537}{1160}\right) 1000 = \mathbf{-537\ Btu}$$

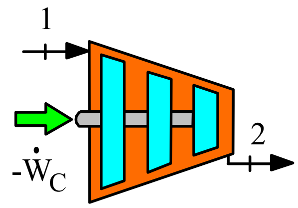
10.114E

The compressor in a refrigerator takes refrigerant R-134a in at 15 lbf/in.^{2}, 0 F and compresses it to 125 lbf/in.^{2}, 100 F. With the room at 70 F find the reversible heat transfer and the minimum compressor work.

Solution:

C.V. Compressor out to ambient. Minimum work in is the reversible work.

Steady flow, 1 inlet and 2 exit



Energy Eq.: $w_c = h_1 - h_2 + q^{rev}$

Entropy Eq.: $s_2 = s_1 + \int dq/T + s_{gen} = s_1 + q^{rev}/T_o + 0$

$\Rightarrow \quad q^{rev} = T_o(s_2 - s_1)$

$q^{rev} = 529.67 \times (0.41262 - 0.42288) =$ **-5.43 Btu/lbm**

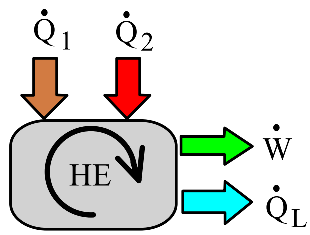
$w_{c\ min} = h_1 - h_2 + T_o(s_2 - s_1) = 167.193 - 181.059 - 5.43 =$ **-19.3 Btu/lbm**

10.115E

A heat engine receives 15 000 btu/h at 1400 R and 30 000 btu/h at 1800 R rejecting energy by heat transfer at 900 R. Assume it is reversible and find the power output. How much power could be produced if it could reject energy at T_o = 540 R?

Solution:

C.V. The heat engine, this is in steady state.



Energy Eq.: $0 = \dot{Q}_1 + \dot{Q}_2 - \dot{Q}_L - \dot{W}$

Entropy Eq.: $0 = \frac{\dot{Q}_1}{T_1} + \frac{\dot{Q}_2}{T_2} - \frac{\dot{Q}_L}{T_L} + 0$

Now solve for $\dot{Q}_L$ from the entropy equation

$$\dot{Q}_L = \frac{T_L}{T_1}\dot{Q}_1 + \frac{T_L}{T_2}\dot{Q}_2 = \frac{900}{1400} \times 15\,000 + \frac{900}{1800} \times 30\,000 = 24\,643 \text{ Btu/h}$$

Substitue into the enrgy equation and solve for the work term

$$\dot{W} = \dot{Q}_1 + \dot{Q}_2 - \dot{Q}_L = 15\,000 + 30\,000 - 24\,643 = \mathbf{20\,357\ Btu/h}$$

For a low temperature of 540 R we can get

$$\dot{Q}_{L2} = \frac{540}{900}\dot{Q}_L = 14\,786 \text{ btu/h}$$

$$\dot{W} = \dot{Q}_1 + \dot{Q}_2 - \dot{Q}_L = 15\,000 + 30\,000 - 14\,786 = \mathbf{30\,214\ Btu/h}$$

Remark: Notice the large increase in the power output.

10.116E

Air flows through a constant pressure heating device as shown in Fig. P10.32. It is heated up in a reversible process with a work input of 85 Btu/lbm air flowing. The device exchanges heat with the ambient at 540 R. The air enters at 540 R, 60 lbf/in.^{2}. Assuming constant specific heat develop an expression for the exit temperature and solve for it.

C.V. Total out to T_0

Energy Eq.: $h_1 + q_0^{rev} - w^{rev} = h_2$

Entropy Eq.: $s_1 + q_0^{rev}/T_0 = s_2 \quad \Rightarrow \quad q_0^{rev} = T_0(s_2 - s_1)$

$h_2 - h_1 = T_0(s_2 - s_1) - w^{rev}$ (same as Eq. 10.12)

Constant C_p gives: $C_p(T_2 - T_1) = T_0C_p \ln (T_2/T_1) + 85$

The energy equation becomes

$$\mathbf{T_2 - T_0 ln(T_2/T_1) = T_1 + 85/C_p}$$

$T_1 = 540$ R, $C_p = 0.24$ Btu/lbm R, $T_0 = 540$ R

$T_2 - 540 \ln (T_2/540) = 540 + (85/0.24) = 894.17$ R

Now trial and error on T_2

At 1400 R LHS = 885.56 R(too low)

At 1420 R LHS = 897.9 R

Interpolate to get $\mathbf{T_2 = 1414\ R}$ (LHS = 894.19 R **OK**)

10.117E

A rock bed consists of 12 000 lbm granite and is at 160 F. A small house with lumped mass of 24 000 lbm wood and 2000 lbm iron is at 60 F. They are now brought to a uniform final temperature with no external heat transfer by connecting the house and rock bed through some heat engines. If the process is reversible, find the final temperature and the work done during the process.

Take C.V. Total (rockbed and heat engine)

Energy Eq.: $m_{rock}(u_2 - u_1) + m_{wood}(u_2 - u_1) + m_{Fe}(u_2 - u_1) = -{}_1W_2$

Entropy Eq.: $m_{rock}(s_2 - s_1) + m_{wood}(s_2 - s_1) + m_{Fe}(s_2 - s_1) = \emptyset$

$$(mC)_{rock}\ln\frac{T_2}{T_1} + (mC)_{wood}\ln\frac{T_2}{T_1} + (mC)_{Fe}\ln\frac{T_2}{T_1} = \emptyset$$

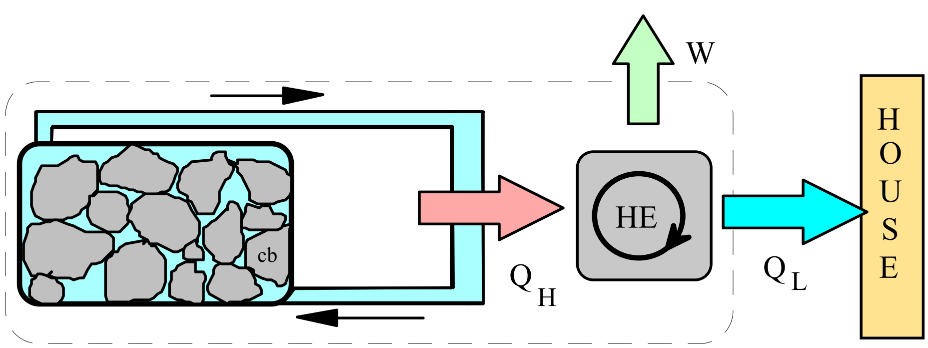
$$12000 \times 0.212 \ln (T_2/619.67) + 24000 \times 0.33 \ln (T_2/519.67) + 2000 \times 0.11 \ln (T_2/519.67) = \emptyset$$

$\Rightarrow$ $\mathbf{T_2 = 541.9\ R}$

Now from the energy equation

$$-{}_1W_2 = 12\,000 \times 0.212(541.9 - 619.67) + (24\,000 \times 0.33 + 2000 \times 0.11)(541.9 - 519.67)$$

$\Rightarrow$ ${}_1W_2 = \mathbf{16\ 895\ Btu}$



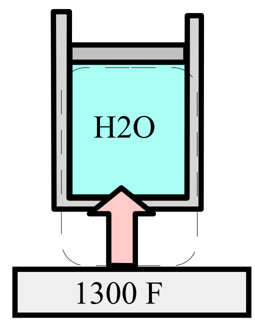
Irreversibility

10.118E

A constant pressure piston/cylinder contains 4 lbm of water at 1000 psia and 200 F. Heat is added from a reservoir at 1300 F to the water until it reaches 1300 F. We want to find the total irreversibility in the process.

Solution:

C.V. Piston cylinder out to the reservoir (incl. the walls).



Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = {}_1Q_2/T_{res} + {}_1S_{2\ gen}$

State 1: $h_1 = 168.07$ Btu/lbm, $s_1 = 0.294$ Btu/lbm R

State 2: $h_2 = 1676.53$ Btu/lbm, $s_2 = 1.7593$ Btu/lbm R

Process: $P = C \quad \Rightarrow \quad {}_1W_2 = P(V_2 - V_1)$

From the energy equation we get

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m(h_2 - h_1)$$

$$= 4(1676.53 - 168.07) = 6033.8 \text{ Btu}$$

From the entropy equation we get

$${}_1S_{2\ gen} = m(s_2 - s_1) - \frac{{}_1Q_2}{T_{res}} = 4(1.7593 - 0.294) - \frac{6033.8}{459.7 + 1300}$$

$$= 2.4323 \text{ Btu/R}$$

Now the irreversibility is from Eq. 10.19

$${}_1I_2 = m\ {}_1i_2 = T_o\ {}_1S_{2\ gen} = 536.7 \text{ R} \times 2.4323 \text{ Btu/R} = \mathbf{1305\ Btu}$$

10.119E

A supply of steam at 14.7 lbf/in.^{2}, 320 F is needed in a hospital for cleaning purposes at a rate of 30 lbm/s. A supply of steam at 20 lbf/in.^{2}, 500 F is available from a boiler and tap water at 14.7 lbf/in.^{2}, 60 F is also available. The two sources are then mixed in a mixing chamber to generate the desired state as output. Determine the rate of irreversibility of the mixing process.

C.V. Mixing chamber

Continuity Eq.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$

Entropy Eq.: $\dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{S}_{gen} = \dot{m}_3 s_3$

Table properties

F.7.1 $h_1 = 28.08$ Btu/lbm, $s_1 = 0.05555$ Btu/lbm R

F.7.2 $h_2 = 1286.8$ Btu/lbm, $s_2 = 1.8919$ Btu/lbm R

F.7.2 $h_3 = 1202.1$ Btu/lbm, $s_3 = 1.828$ Btu/lbm R

From the energy equation we get

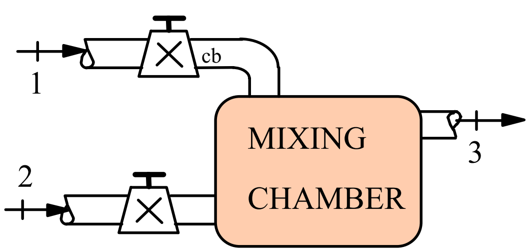
$$\dot{m}_2/\dot{m}_3 = (h_3 - h_1)/(h_2 - h_1) = \frac{1202.1 - 28.08}{1286.8 - 28.08} = 0.9327$$

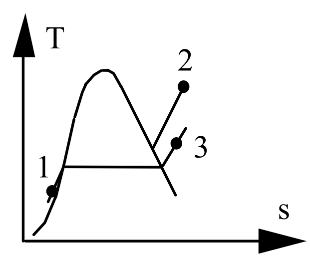
$$\dot{m}_2 = 27.981 \text{ lbm/s}, \quad \dot{m}_1 = 2.019 \text{ lbm/s}$$

From the entropy equation we get

$$\dot{I} = T_0 \dot{S}_{gen} = T_0(\dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2)$$

$$= 536.67 \times (30 \times 1.828 - 2.019 \times 0.05555 - 27.981 \times 1.8919) = \mathbf{961\ Btu/s}$$





10.120E

Fresh water can be produced from saltwater by evaporation and subsequent condensation. An example is shown in Fig. P10.42 where 300-lbm/s saltwater, state 1, comes from the condenser in a large power plant. The water is throttled to the saturated pressure in the flash evaporator and the vapor, state 2, is then condensed by cooling with sea water. As the evaporation takes place below atmospheric pressure, pumps must bring the liquid water flows back up to P_0. Assume that the saltwater has the same properties as pure water, the ambient is at 68 F, and that there are no external heat transfers. With the states as shown in the table below find the irreversibility in the throttling valve and in the condenser.

State	1	2	3	4	5	6	7	8
T [F]	86	77	77	--	74	--	63	68

C.V. Valve: $\dot{m}_1 = m_{ex} = \dot{m}_2 + \dot{m}_3$,

Energy Eq.: $h_1 = h_e$; Entropy Eq.: $s_i + s_{gen} = s_e$

$h_1 = 54.08$ $s_i = 0.1043$ Btu/lbm R, $P_2 = P_{sat}(T_2 = T_3) = 0.4641$ psia

$h_e = h_1 \Rightarrow x_e = (54.08 - 45.08)/1050.0 = 0.008571$

$\Rightarrow s_e = 0.08769 + 0.008571 \times 1.9565 = 0.1045$ Btu/lbm R

$$\dot{m}_2 = (1 - x_e)\, \dot{m}_i = (1 – 0.008571)\, 300 = 297.44 \text{ lbm/s}$$

$s_{gen} = s_e - s_i = 0.1045 - 0.1043 = 0.0002$ Btu/lbm R

$\dot{I} = \dot{m} T_0 s_{gen} = 300 \times 528 \times 0.0002 = 31.68$ Btu/s

C.V. Condenser.

State	2	5	7	8
h Btu/lbm	1095.1	42.09	31.08	36.09
s Btu/lbm R	2.044	0.0821	0.0613	0.0708

Energy Eq.: $\dot{m}_2 h_2 + \dot{m}_7 h_7 = \dot{m}_2 h_5 + \dot{m}_7 h_8 \Rightarrow$

$$\dot{m}_7 = \dot{m}_2 \times (h_2 - h_5)/(h_8 - h_7) = 297.44\, \frac{1095.1 - 42.09}{36.09 - 31.08} = 62516\, \frac{\text{lbm}}{\text{s}}$$

Entropy Eq.: $\dot{m}_2 s_2 + \dot{m}_7 s_7 + \dot{S}_{gen} = \dot{m}_2 s_5 + \dot{m}_7 s_8$

$$\dot{I} = T_0 \dot{S}_{gen} = T_0\left[\dot{m}_2(s_5 - s_2) + \dot{m}_7(s_8 - s_7)\right]$$

$$= 528\left[297.44(0.0821 - 2.044) + 62516(0.0708 - 0.0613)\right]$$

$$= 528 \times 10.354 = \mathbf{5467\ Btu/s}$$

10.121E

Calculate the irreversibility for the process described in Problem 6.175, assuming that the heat transfer is with the surroundings at 61 F.

C.V. Cylinder volume.

Continuity Eq.6.15: $m_2 - m_1 = m_{in}$

Energy Eq.6.16: $m_2u_2 - m_1u_1 = m_{in}h_{line} + {}_1Q_2 - {}_1W_2$

Process: P_1 is constant to stops, then constant V to state 2 at P_2

State 1: P_1, T_1 $\quad m_1 = \frac{P_1V}{RT_1} = \frac{45 \times 9 \times 144}{53.34 \times 519.7} = 2.104$ lbm

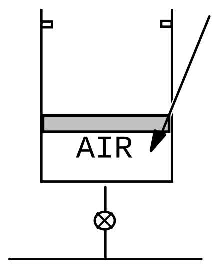
Open to: $P_2 = 60$ lbf/in^2

Table F.5:

$h_i = 266.13$ btu/lbm

$u_1 = 88.68$ Btu/lbm

$u_2 = 107.62$ Btu/lbm



$P = P_1$ until $V = V_{stop}$ then constant V

$${}_1W_2 = \int PdV = P_1(V_{stop} - V_1) = 45 \times (36 - 9)\frac{144}{778} = 224.9 \text{ Btu}$$

$$m_2 = P_2V_2/RT_2 = \frac{60 \times 36 \times 144}{53.34 \times 630} = 9.256 \text{ lbm}, \quad m_i = 7.152 \text{ lbm}$$

$${}_1Q_2 = m_2u_2 - m_1u_1 - m_i h_i + {}_1W_2$$

$$= 9.256 \times 107.62 - 2.104 \times 88.68 - 7.152 \times 266.13 + 224.9$$

$$= -868.9 \text{ Btu}$$

$I = T_o S_{gen}$ so apply 2nd law out to $T_o = 61$ F $= 520.7$ R

$$m_2 s_2 - m_1s_1 = m_is_i + {}_1Q_2 / T_o + {}_1S_{2gen}$$

$$T_oS_{gen} = T_o (m_2 s_2 - m_1s_1 - m_i s_i) - {}_1Q_2$$

Use from table F.4: $C_p = 0.24$, $R = 53.34 / 778 = 0.06856$ Btu/lbm R,

$$T_oS_{gen} = I = T_o [m_1 (s_2 - s_1) + m_i (s_2 - s_i)] - {}_1Q_2$$

$$= 520.7[2.104(C_p \ln \frac{630}{519.7} - R \ln \frac{60}{45}) + 7.152(C_p\ln \frac{630}{1100} - R \ln \frac{60}{75})] - (- 868.9)$$

$$= 520.7 (0.05569 - 0.8473) + 868.9$$

$= \mathbf{456.7 \text{ Btu}}$

10.122E

A 4-lbm piece of iron is heated from room temperature 77 F to 750 F by a heat source at 1100 F. What is the irreversibility in the process?

C.V. Iron out to 1100 F source, which is a control mass.

Energy Eq.: $m_{Fe}(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m_{Fe}(s_2 - s_1) = {}_1Q_2/T_{res} + {}_1S_{2\ gen}$

Process: Constant pressure => ${}_1W_2 = Pm_{Fe}(v_2 - v_1)$

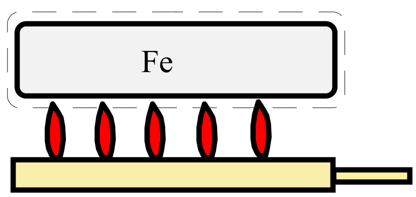
$\Rightarrow {}_1Q_2 = m_{Fe}(h_2 - h_1) = m_{Fe}C(T_2 - T_1)$

${}_1Q_2 = 4 \times 0.107 \times (750 - 77) = 288.04$ Btu

${}_1S_{2\ gen} = m_{Fe}(s_2 - s_1) - {}_1Q_2/T_{res} = m_{Fe}C \ln (T_2/T_1) - {}_1Q_2/T_{res}$

$$= 4 \times 0.107 \times \ln \frac{1209.67}{536.67} - \frac{288.04}{1559.67} = 0.163 \text{ Btu/R}$$

${}_1I_2 = T_o ({}_1S_{2\ gen}) = 536.67 \times 0.163 =$ **87.57 Btu**



A real flame may be more than 1100 F, but a little away from it where the gas has mixed with some air it may be 1100 F.

10.123E

Air enters the turbocharger compressor of an automotive engine at 14.7 lbf/in^2, 90 F, and exits at 25 lbf/in^2, as shown in Fig. P10.45. The air is cooled by 90 F in an intercooler before entering the engine. The isentropic efficiency of the compressor is 75%. Determine the temperature of the air entering the engine and the irreversibility of the compression-cooling process.

Solution:

a) Compressor. First ideal which is reversible adiabatic, constant s:

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 550\left(\frac{25}{14.7}\right)^{0.286} = 640.2 \text{ R}$$

$$-w_s = C_{P0}(T_{2s} - T_1) = 0.24(640.2 - 550) = 21.65 \text{ Btu/lbm}$$

Now the actual compressor

$$-w = - w_s/\eta_s = 21.65/0.75 = 28.87 = C_{P0}(T_2 - T_1) = 0.24(T_2 - 550)$$

$$=> \quad T_2 = 670.3 \text{ R}$$

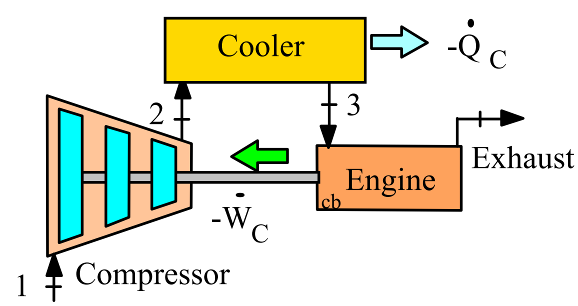
Cool down 90 F $\Rightarrow$ $T_3 = 670.3 - 90 =$ **580.3 R**

b) Irreversibility from Eq.10.13 with rev. work from Eq.10.12, ($q = 0$ at T_H)

$$s_3 - s_1 = 0.24 \ln\frac{580.3}{550} - \frac{53.34}{778} \ln\frac{25}{14.7} = -0.0235 \text{ Btu/lbm R}$$

$$i = T(s_3 - s_1) - (h_3 - h_1) - w = T(s_3 - s_1) - C_P(T_3 - T_1) - C_P(T_1 - T_2)$$

$$= 550(-0.0235) - 0.24(-90) = +8.7 \text{ Btu/lbm}$$



10.124E

A rock bed consists of 12 000 lbm granite and is at 160 F. A small house with lumped mass of 24 000 lbm wood and 2000 lbm iron is at 60 F. They are now brought to a uniform final temperature by circulating water between the rock bed and the house. Find the final temperature and the irreversibility in the process assuming an ambient at 60 F.

C.V. Total Rockbed and house. No work, no Q irreversible process.

Energy eq.: $m_{rock}(u_2 - u_1) + m_{wood}(u_2 - u_1) + m_{Fe}(u_2 - u_1) = 0$

Entropy Eq.: $m_{rock}(s_2 - s_1) + m_{wood}(s_2 - s_1) + m_{Fe}(s_2 - s_1) = S_{gen}$

$$(mC)_{rock}\ln\frac{T_2}{T_1} + (mC)_{wood}\ln\frac{T_2}{T_1} + (mC)_{Fe}\ln\frac{T_2}{T_1} = S_{gen}$$

Energy eq.: $(mC)_{rock}(T_2 - 160) + (mC_{wood} + mC_{Fe})(T_2 - 60) = 0$

$$12\,000 \times 0.212\,(T_2 - 160) + (24\,000 \times 0.33 + 2000 \times 0.11)(T_2 - 60) = 0$$

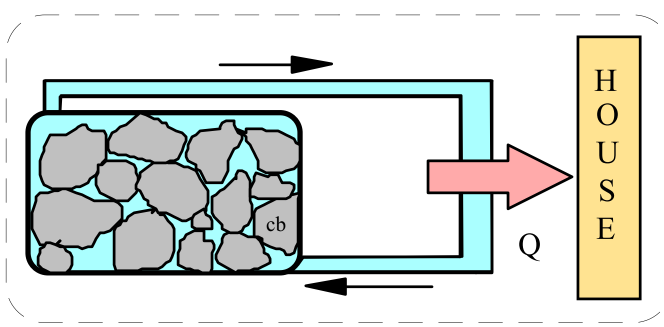
$$2544\,(T_2 - 160) + (7920 + 220)(T_2 - 60) = 0$$

T_2 = **83.8 F = 543.5 R**

$$S_{gen} = \sum m_i(s_2 - s_1)_i = (mC)_{rock}\ln\frac{T_2}{T_1} + (mC)_{wood}\ln\frac{T_2}{T_1} + (mC)_{Fe}\ln\frac{T_2}{T_1}$$

$$= 2544 \ln\frac{543.5}{619.67} + (7920 + 220)\ln\frac{543.5}{519.67} = 35.26 \text{ Btu/R}$$

${}_1I_2 = T_0 S_{gen} = 519.67 \times 35.26 =$ **18324 Btu**

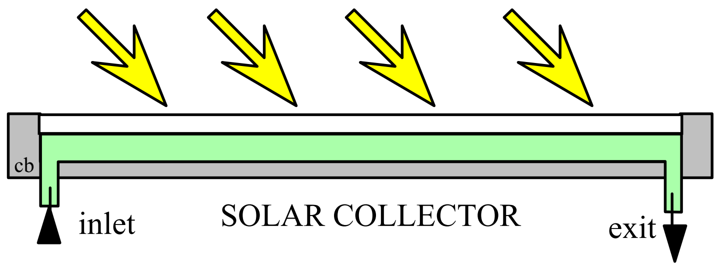


Availability (exergy)

10.125E

A steady stream of R-22 at ambient temperature, 50 F, and at 110 lbf/in.^{2} enters a solar collector. The stream exits at 180 F, 100 lbf/in.^{2}. Calculate the change in availability of the R-22 between these two states.

Solution:



Inlet Table F.9.1 (liquid): h_i = 24.275 Btu/lbm, s_i = 0.0519 Btu/lbm R

Exit Table F.9.2 (sup. vap.): h_e = 132.29 Btu/lbm, s_e = 0.2586 Btu/lbm R

From Eq.10.24 or 10.37

$$\Delta\psi_{ie} = \psi_e - \psi_i = (h_e - h_i) - T_0(s_e - s_i)$$
$$= (132.29 - 24.275) – 510\ (0.2586 - 0.0519)$$
$$= \mathbf{2.6\ Btu/lbm}$$

10.126E

Consider the springtime melting of ice in the mountains, which gives cold water running in a river at 34 F while the air temperature is 68 F. What is the availability of the water relative to the temperature of the ambient?

$\psi = h_1 - h_0 - T_0(s_1 - s_0)$ flow availability from Eq.10.19

Approximate both states as saturated liquid

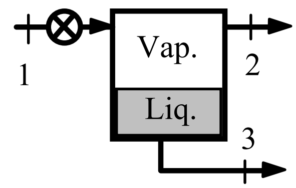
$\psi = 1.9973 - 36.088 - 527.67 \times (0.00405 - 0.07081) =$ **1.136 Btu/lbm**

Why is it positive? As the water is brought to 68 F it can be heated with q_L from a heat engine using q_H from atmosphere $T_H = T_0$ thus giving out work.

10.127E

A geothermal source provides 20 lbm/s of hot water at 80 lbf/in.^{2}, 300 F flowing into a flash evaporator that separates vapor and liquid at 30 lbf/in.^{2}. Find the three fluxes of availability (inlet and two outlets) and the irreversibility rate.

C.V. Flash evaporator chamber. Steady flow with no work or heat transfer.



Cont. Eq.: $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$;

Energy Eq.: $\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3$

Entropy Eq.: $\dot{m}_1 s_1 + \dot{S}_{gen} = \dot{m}_2 s_2 + \dot{m}_3 s_3$

Properties from Table F.7.1

$h_o = 45.08,\ \ h_1 = 269.73,\ \ h_2 = 1164.3,\ \ h_3 = 218.9$ Btu/lbm

$s_o = 0.08769,\ \ s_1 = 0.4372,\ \ s_2 = 1.6997,\ \ s_3 = 0.36815$ Btu/lbm R

$$h_1 = xh_2 + (1 - x)\, h_3 \quad \Rightarrow \quad x = \dot{m}_2/\dot{m}_1 = \frac{h_1 - h_3}{h_2 - h_3} = 0.05376$$

$$\dot{m}_2 = x\dot{m}_1 = 1.075 \text{ lbm/s} \qquad \dot{m}_3 = (1\text{-}x)\dot{m}_1 = 18.925 \text{ lbm/s}$$

$$\dot{S}_{gen} = 1.075 \times 1.6997 + 18.925 \times 0.36815 - 20 \times 0.4372 = 0.0504 \text{ Btu/s-R}$$

Flow availability Eq.10.22: $\psi = (h - T_o s) - (h_o - T_o s_o) = h - h_o - T_o(s - s_o)$

$\psi_1 = 269.73 - 45.08 - 537 \times (0.4372 - 0.08769) = 36.963$ Btu/lbm

$\psi_2 = 1164.3 - 45.08 - 537 \times (1.6997 - 0.08769) = 253.57$ Btu/lbm

$\psi_3 = 218.9 - -45.08 - 537 \times (0.36815 - 0.08769) = 23.21$ Btu/lbm

$\dot{m}_1\, \psi_1 =$ **739.3 Btu/s** $\quad \dot{m}_2\psi_2 =$ **272.6 Btu/s** $\quad \dot{m}_3\psi_3 =$ **439.3 Btu/s**

$\dot{I} = \dot{m}_1\, \psi_1 - \dot{m}_2\, \psi_2 - \dot{m}_3\psi_3 =$ **27.4 Btu/s**

10.128E

An air compressor is used to charge an initially empty 7-ft^3 tank with air up to 750 lbf/in.^{2}. The air inlet to the compressor is at 14.7 lbf/in.^{2}, 60 F and the compressor isentropic efficiency is 80%. Find the total compressor work and the change in energy of the air.

C.V. Tank + compressor (constant inlet conditions)

Continuity: $m_2 - 0 = m_{in}$ Energy: $m_2u_2 = m_{in}h_{in} - {}_1W_2$

Entropy: $m_2s_2 = m_{in}s_{in} + {}_1S_{2\,GEN}$

To use isentropic efficiency we must calc. ideal device

Reversible compressor: ${}_1S_{2\,GEN} = 0 \;\Rightarrow\; s_2 = s_{in}$

$$\Rightarrow s^o_{T2} = s^o_{Tin} + R\ln\left(\frac{P_2}{P_{in}}\right) = 1.6307 + \frac{53.34}{778} \times \ln\left(\frac{750}{14.7}\right) = 1.9003\ \frac{\text{Btu}}{\text{lbm R}}$$

$\Rightarrow T_{2,s} = 1541$ R $u_{2,s} = 274.49$ Btu/lbm

$\Rightarrow {}_1w_{2,s} = h_{in} - u_{2,s} = 124.38 - 274.49 = -150.11$ Btu/lbm

Actual compressor: ${}_1w_{2,AC} = {}_1w_{2,s}/\eta_c = -187.64$ Btu/lbm

$u_{2,AC} = h_{in} - {}_1w_{2,AC} = 312 \;\Rightarrow\; T_{2,AC} = 1729$ R

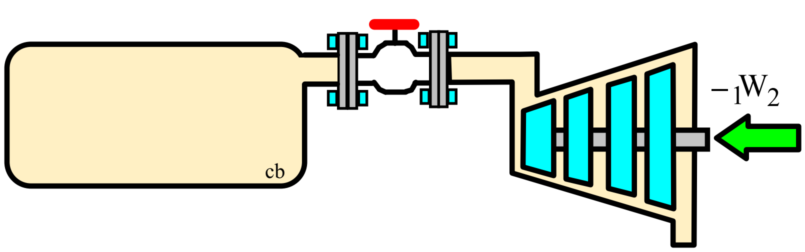
Final state 2 [u, P] $\Rightarrow v_2 = RT_2/P_2 = 0.854$ ft^3/lbm

$m_2 = V_2/v_2 = 8.2$ lbm

$\Rightarrow {}_1W_2 = m_2({}_1W_{2,AC}) =$ **-1539 Btu**

$m_2(\phi_2 - \phi_1) = m_2\,[u_2 - u_1 + P_0(v_2 - v_1) - T_0(s_2 - s_1)\,]$

$$= 8.2\left[312 - 88.733 + 14.7(0.854 - 13.103)\frac{144}{778} - 520\left(1.9311 - 1.63074 - \frac{53.34}{778}\ln\frac{750}{14.7}\right)\right] = 8.2 \times 173.94 = \mathbf{1426.3\ Btu}$$



10.129E

An electric stove has one heating element at 600 F getting 500 W of electric power. It transfers 90% of the power to 2 lbm water in a kettle initially at 70 F, 1 atm, the rest 10% leaks to the room air. The water at a uniform T is brought to the boiling point. At the start of the process what is the rate of availability transfer by: a) electrical input b) from heating element and c) into the water at T_{water}.

We take here the reference T to be the room 70 F = 529.67 R

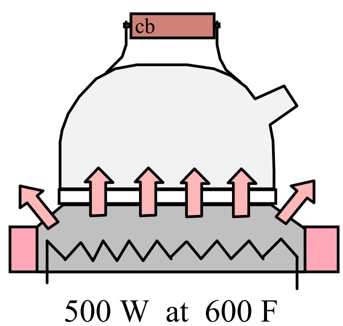
a) Work is availability $\dot{\Phi} = \dot{W} = \mathbf{500\ W}$

b) Heat transfer at 600 F is only partly availability

$$\dot{\Phi} = \left(1 - \frac{T_o}{T_H}\right)\dot{Q} = \left(1 - \frac{529.67}{459.67 + 600}\right) 500 = \mathbf{250\ W}$$

c) Water receives heat transfer at 70 F as 90% of 500 W = 450 W

$$\dot{\Phi} = \left(1 - \frac{T_o}{T_{water}}\right)\dot{Q} = \left(1 - \frac{529.67}{459.67 + 70}\right) 450 = \mathbf{0\ W}$$



10.130E

A 20-lbm iron disk brake on a car is at 50 F. Suddenly the brake pad hangs up, increasing the brake temperature by friction to 230 F while the car maintains constant speed. Find the change in availability of the disk and the energy depletion of the car's gas tank due to this process alone. Assume that the engine has a thermal efficiency of 35%.

All the friction work is turned into internal energy of the disk brake.

$$m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 \;\Rightarrow\; {}_1Q_2 = m_{Fe}C_{Fe}(T_2 - T_1)$$

$${}_1Q_2 = 20 \times 0.107 \times (230 - 50) = 385.2 \text{ Btu}$$

Neglect the work to the surroundings at P_0

$$m(s_2 - s_1) = mC \ln(T_2 / T_1) = 20 \times 0.107 \times \ln\left(\frac{690}{510}\right) = 0.6469 \text{ Btu/R}$$

No change in kinetic or potential energy and no volume change so

$$\Delta\phi = m(u_2 - u_1) - T_0 m(s_2 - s_1) = 385.2 - 510 \times 0.6469 = \mathbf{55.28\ Btu}$$

$$W_{engine} = \eta_{th}Q_{gas} = {}_1Q_2 = \text{Friction work}$$

$$Q_{gas} = {}_1Q_2/\eta_{th} = 385.2/0.35 = \mathbf{1100\ Btu}$$

10.131E

Calculate the availability of the system (aluminum plus gas) at the initial and final states of Problem 8.183, and also the irreversibility.

State 1: $T_1 = 400$ F $\quad v_1 = 2/2.862 = 0.6988 \qquad P_1 = 300$ psi

Ideal gas $\quad v_2 = v_1(300 / 220)(537 / 860) = 0.595 \;;\; v_o = 8.904 = RT_o / P_o$

The metal does not change volume so the terms as Eq.10.22 are added

$$\phi_1 = m_{gas}\phi_{gas} + m_{Al}\phi_{Al}$$

$$= m_{gas}C_v (T_1 - T_o) - m_{gas}T_o [C_p \ln \frac{T_1}{T_o} - R \ln \frac{P_1}{P_o}] + m_{gas}P_o (v_1 - v_o)$$

$$+ m_{Al} [C (T_1 - T_o) - T_oC \ln (T_1 / T_o)]_{Al}$$

$$\phi_1 = 2.862[0.156(400\text{-}77) - 537(0.201 \ln \frac{860}{537} - \frac{35.1}{778} \ln \frac{300}{14.7})$$

$$+ 14.7 (0.6988 - 8.904)(\frac{144}{778})] + 8 \times 0.21 [400 -77 - 537 \ln \frac{860}{537}]$$

$$= 143.96 + 117.78 = \mathbf{261.74\ Btu}$$

$$\phi_2 = 2.862[0.156(77 - 77) - 537 (0.201 \ln \frac{537}{537} - \frac{35.1}{778} \ln \frac{220}{14.7})$$

$$+ 14.7(0.595 - 8.904)(\frac{144}{778})] + 8 \times 0.21 [77 -77 - 537 \ln \frac{537}{537}]$$

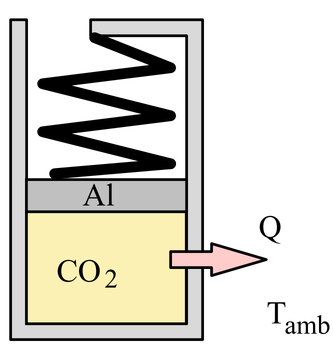
$$= 122.91 + 0 = \mathbf{122.91\ Btu}$$

$${}_1I_2 = \phi_1 - \phi_2 + (1 - T_o/T_H)\,{}_1Q_2 - {}_1W_2^{AC} + P_om(V_2 - V_1)$$

$$= 261.74 - 122.91 + 0 - (-14.29) + 14.7 \times 2.862 \times \frac{144}{778} (0.595 - 0.6988)$$

$$= \mathbf{152.3\ Btu}$$

[($S_{gen} = 0.2837$ Btu/R $\qquad T_oS_{gen} = 152.3$ so OK]

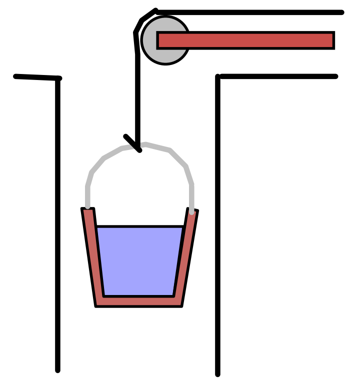


10.132E

A wood bucket (4 lbm) with 20 lbm hot liquid water, both at 180 F, is lowered 1300 ft down into a mineshaft. What is the availability of the bucket and water with respect to the surface ambient at 70 F?

C.V. Bucket and water. Both thermal availability and potential energy terms.

$v_1 \approx v_0$ for both wood and water so work to atm. is zero.



Use constant heat capacity table F.2 for wood and table F.7.1 (sat. liquid) for water.
From Eq.10.27

$$\phi_1 - \phi_0 = m_{wood}[u_1 - u_0 - T_0(s_1 - s_0)] + m_{H_2O}[u_1 - u_0 - T_0(s_1 - s_0)] + m_{tot}g(z_1 - z_0)$$

$$= 4[0.3(180 - 70) - 0.3 \times 530 \ln \frac{640}{530}] + 20[147.76 - 38.09$$

$$- 530(0.263 - 0.074)] + 24 \times 32.174 \times (-1300 / 25\ 037)$$

$$= 12.05 + 199.3 - 40.1 = \mathbf{171.25\ Btu}$$

Recall 1 Btu/lbm = 25 037 ft^2/s^2

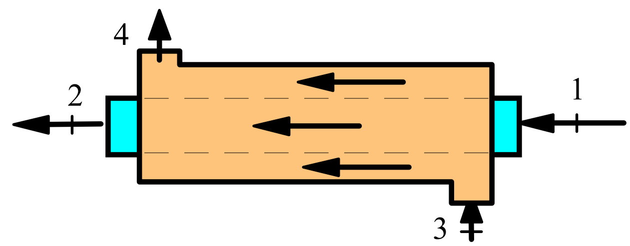
Device 2nd Law Efficiency

10.133E

A coflowing (same direction) heat exchanger has one line with 0.5 lbm/s oxygen at 68 F and 30 psia entering and the other line has 1.2 lbm/s nitrogen at 20 psia and 900 R entering. The heat exchanger is long enough so that the two flows exit at the same temperature. Use constant heat capacities and find the exit temperature and the second law efficiency for the heat exchanger assuming ambient at 68 F.

Solution:

C.V. Heat exchanger, steady 2 flows in and two flows out.



Energy Eq.6.10: $\dot{m}_{O2}h_1 + \dot{m}_{N2}h_3 = \dot{m}_{O2}h_2 + \dot{m}_{N2}h_4$

Same exit tempearture so $T_4 = T_2$ with values from Table F.4

$$\dot{m}_{O2}C_{P\ O2}T_1 + \dot{m}_{N2}C_{P\ N2}T_3 = (\dot{m}_{O2}C_{P\ O2} + \dot{m}_{N2}C_{P\ N2})T_2$$

$$T_2 = \frac{0.5 \times 0.22 \times 527.7 + 1.2 \times 0.249 \times 900}{0.5 \times 0.22 + 1.2 \times 0.249} = \frac{326.97}{0.4088} = \mathbf{800\ R}$$

The second law efficiency for a heat exchanger is the ratio of the availability gain by one fluid divided by the availability drop in the other fluid. For each flow availability is Eq.10.24 include mass flow rate as in Eq.10.36

For the oxygen flow:

$$\dot{m}_{O2}(\psi_2 - \psi_1) = \dot{m}_{O2}\ [\ h_2 - h_1 - T_o\ (\ s_2 - s_1\ )\ ]$$

$$= \dot{m}_{O2}\ [\ C_P(T_2 - T_1) - T_o\ [\ C_P \ln(T_2 / T_1) - R \ln(P_2 / P_1)\ ]$$

$$= \dot{m}_{O2}C_P\ [\ T_2 - T_1 - T_o \ln(T_2 / T_1)\ ]$$

$$= 0.5 \times 0.22\ [\ 800 - 527.7 - 536.7 \ln(800/527.7)\ ]$$

$$= 5.389 \text{ Btu/s}$$

For the nitrogen flow

$$\dot{m}_{N2}(\psi_3 - \psi_4) = \dot{m}_{N2}C_P\ [\ T_3 - T_4 - T_o \ln(T_3 / T_4)\ ]$$

$$= 1.2 \times 0.249\ [\ 900 - 800 - 536.7 \ln(900/800)\ ]$$

$$= 10.992 \text{ Btu/s}$$

From Eq.10.30

$$\eta_{2^{nd}\ Law} = \frac{\dot{m}_{O2}(\psi_1 - \psi_2)}{\dot{m}_{N2}(\psi_3 - \psi_4)} = \frac{5.389}{10.992} = \mathbf{0.49}$$

10.134E

A steam turbine has an inlet at 600 psia, and 900 F and actual exit of 1 atm with x = 1.0. Find its first law (isentropic) and the second-law efficiencies

Solution:

C.V. Steam turbine

Energy Eq.6.13: $w = h_i - h_e$

Entropy Eq.9.8: $s_e = s_i + s_{gen}$

Inlet state: Table F.7.2 h_i = 1462.92 Btu/lbm; s_i = 1.6766 Btu/lbm R

Exit (actual) state: F.7.2 h_e = 1150.49 Btu/lbm; s_e = 1.7567 Btu/lbm R

Actual turbine energy equation

$$w = h_i - h_e = 312.43 \text{ Btu/lbm}$$

Ideal turbine reversible process so $s_{gen} = 0$ giving

$$s_{es} = s_i = 1.6766 = 0.3121 + x_{es} \times 1.4446$$

$$x_{es} = 0.94455, \; h_{es} = 180.13 + 0.94455 \times 970.35 = 1096.67$$

The energy equation for the ideal gives

$$w_s = h_i - h_{es} = 366.25 \text{ Btu/lbm}$$

The first law efficiency is the ratio of the two work terms

$$\eta_s = w/w_s = 312.43/366.25 = \mathbf{0.853}$$

The reversible work for the actual turbine states is, Eq.10.9

$$w^{rev} = (h_i - h_e) + T_o(s_e - s_i)$$

$$= 312.43 + 536.7(1.7567 - 1.6766)$$

$$= 312.43 + 42.99 = 355.4 \text{ Btu/lbm}$$

Second law efficiency Eq.10.29

$$\eta_{2^{nd}\,Law} = w/w_{rev} = 312.43/355.4 = \mathbf{0.879}$$

10.135E

A compressor is used to bring saturated water vapor at 103 lbf/in.^{2} up to 2000 lbf/in.^{2}, where the actual exit temperature is 1200 F. Find the irreversibility and the second law efficiency.

Inlet state: Table F.7.1 h_i = 1188.4 Btu/lbm, s_i = 1.601 Btu/lbm R

Actual compressor F.7.2: h_e = 1598.6 Btu/lbm, s_e = 1.6398 Btu/lbm R

Energy Eq. actual compressor: $-w_{c,ac} = h_e - h_i$ = 410.2 Btu/lbm

Eq.10.14: $i = T_0(s_e - s_i) = 536.67 \times (1.6398 - 1.601) =$ **20.82 Btu/lbm**

Eq.10.13: $w_{rev} = i + w_{c,ac} = 20.82 + (-410.2) = -389.4$ Btu/lbm

$\eta_{II} = -w_{rev}/(-w_{c,ac}) = 389.4 / 410.2 =$ **0.949**

10.136E

The simple steam power plant in Problem 6.167, shown in Fig P6.99 has a turbine with given inlet and exit states. Find the availability at the turbine exit, state 6. Find the second law efficiency for the turbine, neglecting kinetic energy at state 5.

Properties from Problem 6.167 and s values from F.7.2.

$h_6 = 1029$, $h_5 = 1455.6$, $h_o = 45.08$ all in Btu/lbm

$s_5 = 1.6408$, $s_6 = 1.8053$, $s_o = 0.08769$ all in Btu/lbm R

Kinetic energy at state 6: $KE_6 = 0.5\mathbf{V}_6^2 = 600^2 /(2 \times 25\,037) = 7.19$ Btu/lbm

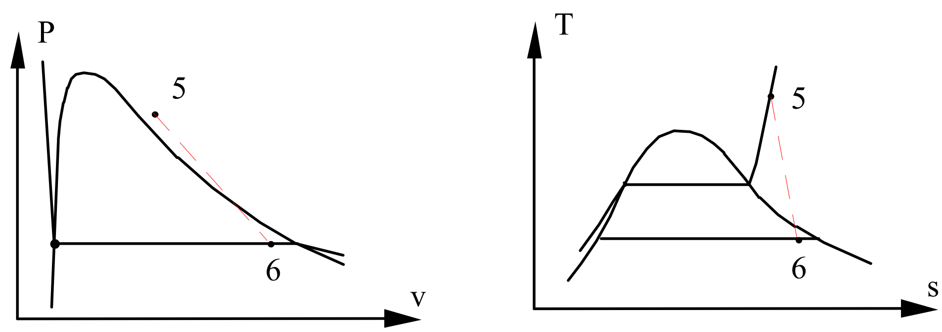
Recall 1 Btu/lbm = 25 037 ft^2/s^2

$\psi_6 = h_6 + KE_6 - h_o - T_o (s_6 - s_o) = 61.26$ Btu/lbm

$w^{rev} = \psi_5 - \psi_6 = h_5 - h_6 - T_o(s_5 - s_6) = 515.2$ Btu/lbm

$w^{AC} = h_5 - h_6 = 426.9$ Btu/lbm

$\eta_{II} = w^{ac} / w^{rev} = 426.9 / 515.2 = \mathbf{0.829}$



10.137E

Steam is supplied in a line at 400 lbf/in.^{2}, 1200 F. A turbine with an isentropic efficiency of 85% is connected to the line by a valve and it exhausts to the atmosphere at 14.7 lbf/in.^{2}. If the steam is throttled down to 300 lbf/in.^{2} before entering the turbine find the actual turbine specific work. Find the change in availability through the valve and the second law efficiency of the turbine.

C.V. Valve: Energy Eq.: $h_2 = h_1 = 1631.79$ Btu/lbm,

Entropy Eq.: $s_2 > s_1 = 1.8327$ Btu/lbm R,

State 2: $h_2, P_2 \Rightarrow s_2 = 1.86407$ Btu/lbm R

Ideal turbine: $s_3 = s_2 \Rightarrow h_{3s} = 1212.28$ Btu/lbm

$w_{T,s} = h_2 - h_{3s} = 419.51$ Btu/lbm

Actual turbine: $w_{T,ac} = \eta_T w_{T,s} =$ **356.58 Btu/lbm**

$h_{3ac} = h_2 - w_{Tac} = 1275.21$ Btu/lbm $\Rightarrow s_{3ac} = 1.9132$ Btu/lbm R

$\psi_2 - \psi_1 = h_2 - h_1 - T_0(s_2 - s_1)$

$= 0 - 536.67(1.86407 - 1.8327) = -16.835$ Btu/lbm

$w^{rev} = \psi_2 - \psi_3 = 1631.79 - 1275.21 - 536.67(1.86407 - 1.9132)$

$= 382.95$ Btu/lbm

$\eta_{II} = w_{ac}/w^{rev} = 356.58/382.95 =$ **0.931**

10.138E

Air flows into a heat engine at ambient conditions 14.7 lbf/in.^{2}, 540 R, as shown in Fig. P10.79. Energy is supplied as 540 Btu per lbm air from a 2700 R source and in some part of the process a heat transfer loss of 135 Btu per lbm air happens at 1350 R. The air leaves the engine at 14.7 lbf/in.^{2}, 1440 R. Find the first- and the second-law efficiencies.

C.V. Engine out to reservoirs

$$h_i + q_H = q_L + h_e + w$$

Table F.5: $h_i = 129.18$ Btu/lbm, $s^o_{Ti} = 1.63979$ Btu/lbm R

$h_e = 353.483$ Btu/lbm, $s^o_{Te} = 1.88243$ Btu/lbm R

$$w_{ac} = 129.18 + 540 - 135 - 353.483 = 180.7 \text{ Btu/lbm}$$

$$\eta_{TH} = w/q_H = 180.7/540 = \mathbf{0.335}$$

For second law efficiency also a q to/from ambient

$$s_i + (q_H/T_H) + (q_0/T_0) = (q_{loss}/T_m) + s_e$$

$$q_0 = T_0\left[s_e - s_i + (q_{loss}/T_m) - (q_H/T_H)\right]$$

$$= 540\left(1.88243 - 1.63979 + \frac{135}{1350} - \frac{540}{2700}\right) = 77.02 \text{ Btu/lbm}$$

$$w_{rev} = h_i - h_e + q_H - q_{loss} + q_0 = w_{ac} + q_0 = 257.7 \text{ Btu/lbm}$$

$$\eta_{II} = w_{ac}/w_{rev} = 180.7/257.7 = \mathbf{0.70}$$

Exergy Balance Equation

10.139E

A heat engine operating with an evironment at 540 R produces 17 000 Btu/h of power output with a first law efficiency of 50%. It has a second law efficiency of 80% and T_L = 560 R. Find all the energy and exergy transfers in and out.

Solution:

From the definition of the first law efficiency

$$\dot{Q}_H = \dot{W} / \eta = \frac{17\,000}{0.5} = \mathbf{34\,000\ Btu/h}$$

Energy Eq.: $\dot{Q}_L = \dot{Q}_H - \dot{W} = 34\,000 - 17\,000 = \mathbf{17\,000\ Btu/h}$

$$\dot{\Phi}_W = \dot{W} = \mathbf{17\,000\ Btu/h}$$

From the definition of the second law efficiency $\eta = \dot{W}/\dot{\Phi}_H$

$$\dot{\Phi}_H = (1 - \frac{T_o}{T_H})\,\dot{Q}_H = \frac{17\,000}{0.8} = \mathbf{21\,250\ Btu/h}$$

$$\dot{\Phi}_L = (1 - \frac{T_o}{T_L})\,\dot{Q}_L = (1 - \frac{540}{560})\ 17\,000 = \mathbf{607\ Btu/h}$$

Notice from the $\dot{\Phi}_H$ form we could find the single characteristic T_H as

$$(1 - \frac{T_o}{T_H}) = 21\,250\ \text{Btu/h} / \dot{Q}_H = 0.625 \quad => \quad T_H = 1440\ \text{R}$$

10.140E

The condenser in a power plant cools 20 lbm/s water at 120 F, quality 90% so it comes out as saturated liquid at 120 F. The cooling is done by ocean-water coming in at 60 F and returned to the ocean at 68 F. Find the transfer out of the water and the transfer into the ocean-water of both energy and exergy (4 terms).

Solution:

C.V. Water line. No work but heat transfer out.

Energy Eq.: $\dot{Q}_{out} = \dot{m}\,(h_1 - h_2) = 20(1010.99 - 87.99) = \mathbf{18\ 460\ Btu/s}$

C.V. Ocean water line. No work but heat transfer in equals water heattransfer out

Energy Eq.: $q = h_4 - h_3 = 36.09 - 28.08 = 8.0$ Btu/lbm

$$\dot{m}_{ocean} = \dot{Q}_{out}/q = 18\ 460 / 8.0 = 2308 \text{ kg/s}$$

Exergy out of the water follows Eq.10.37 (we will use $T_o = 60$ F)

$$\dot{\Phi}_{out} = \dot{m}(\psi_1 - \dot{m}\psi_2) = \dot{m}\,[\, h_1 - h_2 - T_o\,(\, s_1 - s_2)\,]$$

$$= 20\,[\, 1010.99 - 87.99 - 519.7(1.7567 - 0.1646)]$$

$$= \mathbf{1912\ Btu/s}$$

Exergy into the ocean water

$$\dot{\Phi}_{ocean} = \dot{m}_{ocean}(\psi_4 - \psi_3) = \dot{m}_{ocean}\,[\, h_4 - h_3 - T_o(s_4 - s_3)]$$

$$= 2308\,[\, 8.0 - 519.7(0.0708 - 0.0555)]$$

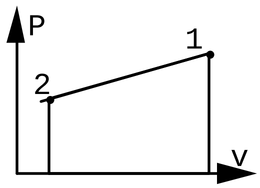
$$= \mathbf{112\ Btu/s}$$

Notice there is a large amount of energy exchanged, but very little exergy.

Review Problems

10.141E

Calculate the reversible work and irreversibility for the process described in Problem 5.168, assuming that the heat transfer is with the surroundings at 68 F.



Linear spring gives

$${}_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2$$

Equation of state: PV = mRT

$$\text{State 1: } V_1 = mRT_1/P_1 = \frac{4 \times 35.1 \times (750 + 460)}{70 \times 144} = 16.85 \text{ ft}^3$$

$$\text{State 2: } V_2 = mRT_2/P_2 = \frac{4 \times 35.1 \times (75 + 460)}{45 \times 144} = 11.59 \text{ ft}^3$$

$${}_1W_2 = \frac{1}{2}(70 + 45)(11.59 - 16.85) \times 144/778 = -55.98 \text{ Btu}$$

From Table F.6

$C_p(T_{avg}) = [(6927\text{-}0)/(1200\text{-}537)]/M = 10.45/44.01 = 0.2347$ Btu/lbm R

$\Rightarrow\ C_V = C_p - R = 0.2375 - 35.10/778 = 0.1924$

${}_1Q_2 = mC_V(T_2 - T_1) + {}_1W_2 = 4\times 0.1924(75 - 750) - 55.98 = -575.46$ Btu

$${}_1W_2^{rev} = T_o(S_2 - S_1) - (U_2 - U_1) + {}_1Q_2(1 - T_o/T_H) = T_o m(s_2 - s_1) + {}_1W_2^{ac} - {}_1Q_2 T_o/T_o$$

$$= T_o m[C_P \ln(T_2 / T_1) - R \ln(P_2 / P_1)] + {}_1W_2^{ac} - {}_1Q_2$$

$$= 527.7 \times 4 [\ 0.2347 \ln(535/1210) - 0.0451 \ln(45/70)] - 55.98 + 575.46$$

$$= -362.24 - 55.98 + 575.46 = \mathbf{157.2\ Btu}$$

$${}_1I_2 = {}_1W_2^{rev} - {}_1W_2^{ac} = 157.2 - (-55.98) = \mathbf{213.2\ Btu}$$

10.142E

A piston/cylinder arrangement has a load on the piston so it maintains constant pressure. It contains 1 lbm of steam at 80 lbf/in.^{2}, 50% quality. Heat from a reservoir at 1300 F brings the steam to 1000 F. Find the second-law efficiency for this process. Note that no formula is given for this particular case, so determine a reasonable expression for it.

1: $P_1, x_1 \;\Rightarrow\; v_1 = 2.7458 \text{ ft}^3/\text{lbm}, \quad h_1 = 732.905 \text{ Btu/lbm},$

$s_1 = 1.0374 \text{ Btu/lbm R}$

2: $P_2 = P_1, T_2 \;\Rightarrow\; v_2 = 10.831 \text{ ft}^3/\text{lbm}, \;\; h_2 = 1532.6 \text{ Btu/lbm},$

$s_2 = 1.9453 \text{ Btu/lbm R}$

$$m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = {}_1Q_2 - P(V_2 - V_1)$$

$${}_1Q_2 = m(u_2 - u_1) + Pm(v_2 - v_1) = m(h_2 - h_1) = 799.7 \text{ Btu}$$

$${}_1W_2 = Pm(v_2 - v_1) = 119.72 \text{ Btu}$$

$${}_1W_{2 \text{ to atm}} = P_0 m(v_2 - v_1) = 22 \text{ Btu}$$

$$\text{Useful work out} = {}_1W_2 - {}_1W_{2 \text{ to atm}} = 119.72 - 22 = 97.72 \text{ Btu}$$

$$\Delta\phi_{\text{reservoir}} = \left(1 - \frac{T_0}{T_{\text{res}}}\right) {}_1Q_2 = \left(1 - \frac{536.67}{1759.67}\right) 799.7 = 556 \text{ Btu}$$

$$n_{II} = W_{\text{net}}/\Delta\phi = \mathbf{0.176}$$

Remark: You could argue that the stored availability (exergy) should be accounted for in the second law efficiency, but it is not available from this device alone.

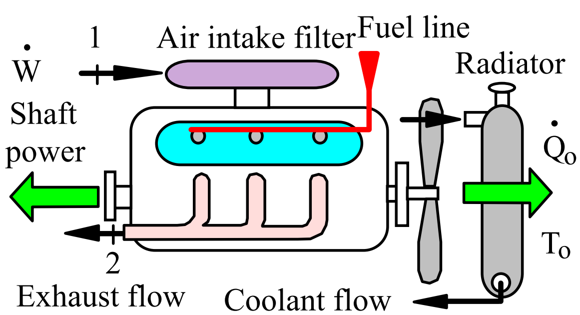
10.143E

Consider a gasoline engine for a car as a steady flow device where air and fuel enters at the surrounding conditions 77 F, 14.7 lbf/in.^{2} and leaves the engine exhaust manifold at 1800 R, 14.7 lbf/in.^{2} as products assumed to be air. The engine cooling system removes 320 Btu/lbm air through the engine to the ambient. For the analysis take the fuel as air where the extra energy of 950 Btu/lbm of air released in the combustion process, is added as heat transfer from a 3240 R reservoir. Find the work out of the engine, the irreversibility per pound-mass of air, and the first- and second-law efficiencies.

C.V. Total out to reservoirs

Energy Eq.: $\dot{m}_a h_1 + \dot{Q}_H = \dot{m}_a h_2 + \dot{W} + \dot{Q}_{out}$

Entropy Eq.: $\dot{m}_a s_1 + \dot{Q}_H/T_H + \dot{S}_{gen} = \dot{m}_a s_s + \dot{Q}_{out}/T_0$



Burning of the fuel releases $\dot{Q}_H$ at T_H.

From the air Table F.5

	Btu/lbm	Btu/lbm R
	$h_1 = 128.381$	$s^o_{T1} = 1.63831$
	$h_2 = 449.794$	$s^o_{T1} = 1.94209$

$w_{ac} = \dot{W}/\dot{m}_a = h_1 - h_2 + q_H - q_{out} = 128.38 - 449.794 + 950 - 320 = 308.6$ Btu/lbm

$\eta_{TH} = w/q_H = 308.6/950 = \mathbf{0.325}$

$i_{tot} = (T_0)s_{gen} = T_0(s_2 - s_1) + q_{out} - q_H T_0/T_H$

$= 536.67(1.94209 - 1.63831) + 320 - 950 \left(\frac{536.67}{3240}\right) = \mathbf{325.67\ Btu/lbm}$

For reversible case have $s_{gen} = 0$ and q_0^R from T_0, no q_{out}

$q^R_{0,in} = T_0(s_2 - s_1) - (T_0/T_H)q_H = i_{tot} - q_{out} = 5.67$ Btu/lbm

$w^{rev} = h_1 - h_2 + q_H + q^R_{0,in} = w_{ac} + i_{tot} = 634.3$ Btu/lbm

$\eta_{II} = w_{ac}/w^{rev} = \mathbf{0.486}$

10.144E

The exit nozzle in a jet engine receives air at 2100 R, 20 psia with negligible kinetic energy. The exit pressure is 10 psia and the actual exit temperature is 1780 R. What is the actual exit velocity and the second law efficiency?

Solution:

C.V. Nozzle with air has no work, no heat transfer.

Energy eq.: $h_i = h_e + \frac{1}{2}\mathbf{V}_{ex}^2$

Entropy Eq.: $s_i + s_{gen} = s_e$

$$\frac{1}{2}\mathbf{V}_{ex}^2 = h_i - h_e = 532.57 - 444.36 = 88.21 \text{ Btu/lbm}$$

$$\mathbf{V}_{ex} = \sqrt{2 \times 88.21 \times 25\,037} = \mathbf{2102\ ft\ s^{-1}}$$

Recall 1 Btu/lbm = 25 037 ft^2/s^2. This was the actual nozzle. Now we can do the reversible nozzle, which then must have a q.

Energy eq.: $h_i + q = h_e + \frac{1}{2}\mathbf{V}_{ex\ rev}^2$

Entropy Eq.: $s_i + q/T_o = s_e$ => $q = T_o\,(s_e - s_i)$

$$q = T_o[\ C \ln \frac{T_e}{T_i} - R \ln \frac{P_e}{P_i}\ ] = 536.7 \left[0.24 \ln \frac{1780}{2100} - \frac{53.34}{778.17} \ln \frac{10}{20}\right]$$

$$= 4.198 \text{ Btu/lbm}$$

$$\frac{1}{2}\mathbf{V}_{ex\ rev}^2 = h_i + q - h_e = 88.21 + 4.198 = 92.408 \text{ Btu/lbm}$$

$$\eta_{II} = \frac{1}{2}\mathbf{V}_{ex}^2 \Big/ \frac{1}{2}\mathbf{V}_{ex\ rev}^2 = 88.21 / 92.408 = \mathbf{0.95}$$

Notice the reversible nozzle is not isentropic (there is a heat transfer).

10.145E

Air in a piston/cylinder arrangement, shown in Fig. P10.104, is at 30 lbf/in.^{2}, 540 R with a volume of 20 ft^3. If the piston is at the stops the volume is 40 ft^3 and a pressure of 60 lbf/in.^{2} is required. The air is then heated from the initial state to 2700 R by a 3400 R reservoir. Find the total irreversibility in the process assuming surroundings are at 70 F.

Solution:

Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq,: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen}$

Process: $P = P_0 + \alpha(V-V_0)$ if $V \le V_{stop}$

Information: $P_{stop} = P_0 + \alpha(V_{stop}-V_0)$

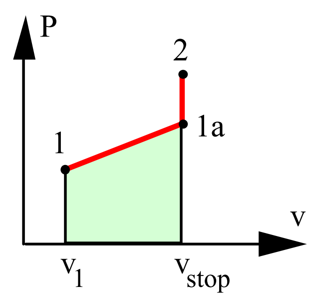
Eq. of state $\Rightarrow$ $T_{stop} = T_1P_{stop}V_{stop}/P_1V_1 = 2160 < T_2$

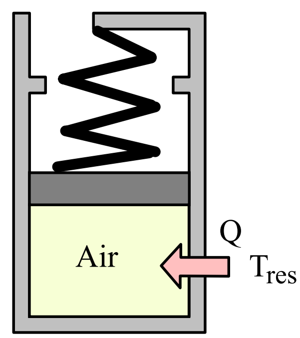
So the piston will hit the stops => $V_2 = V_{stop}$

$$P_2 = (T_2/T_{stop})\ P_{stop} = (2700/2160)\ 60 = 75 \text{ psia} = 2.5\ P_1$$

State 1:

$$m_2 = m_1 = \frac{P_1V_1}{RT_1} = \frac{30 \times 20 \times 144}{53.34 \times 540} = 3.0 \text{ lbm}$$





$${}_1W_2 = \tfrac{1}{2}(P_1 + P_{stop})(V_{stop} - V_1) = \tfrac{1}{2}(30 + 60)(40 - 20) = 166.6 \text{ Btu}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 3(518.165 - 92.16) + 166.6 = 1444.6 \text{ Btu}$$

$$s_2 - s_1 = s^o_{T2} - s^o_{T1} - R\ln(P_2/P_1)$$

$$= 2.0561 - 1.6398 - (53.34/778)\ \ln(2.5) = 0.3535 \text{ Btu/lbm R}$$

Take control volume as total out to reservoir at T_{RES}

$${}_1S_{2\ gen\ tot} = m(s_2 - s_2) - {}_1Q_2/T_{RES} = \mathbf{0.6356\ Btu/R}$$

$${}_1I_2 = T_0\left({}_1S_{2\ gen}\right) = 530 \times 0.6356 = \mathbf{337\ Btu}$$