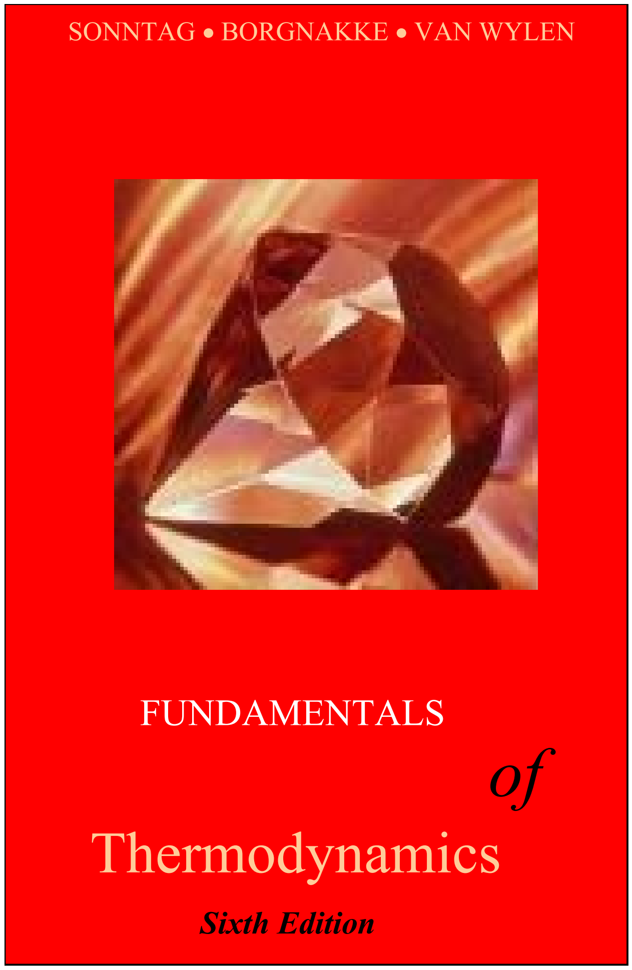
SOLUTION MANUAL
SI UNIT PROBLEMS
CHAPTER 10



CONTENT

Correspondence List

CHAPTER 10 **6th edition** **Sonntag/Borgnakke/Wylen**

The correspondence between the new problem set and the previous 5th edition chapter 10 problem set.

Study guide problems 10.1-10.20 are all new.

New	Old	New	Old	New	Old
21	new	51	25	81	new
22	23	52	30	82	new
23	new	53	32	83	new
24	3	54	new	84	new
25	new	55	33	85	19
26	4	56	new	86	new
27	5	57	26	87	new
28	new	58	18	88	new
29	6	59	new	89	new
30	9	60	31	90	new
31	13	61	36	91	new
32	15	62	20	92	new
33	14	63	new	93	new
34	57a	64	24	94	new
35	new	65	27	95	new
36	new	66	28	96	1
37	new	67	29	97	46
38	2	68	34	98	48
39	7	69	37	99	49
40	new	70	43	100	new
41	8	71	new	101	52
42	12	72	45	102	55
43	21	73	38	103	58
44	10	74	39	104	59
45	16	75	40	105	new
46	11	76	42	106	new
47	17	77	new		
48	22	78	44		
49	35	79	47		
50	57b	80	50		

The English unit problems are:

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

10.1

Can I have any energy transfer as heat transfer that is 100% available?

By definition the possible amount of work that can be obtained equals the exergy (availability). The maximum is limited to that out of a reversible heat engine, if constant T then that is the Carnot heat engine

$$W = (1 - \frac{T_o}{T})Q$$

So we get a maximum for an infinite high temperature T, where we approach an efficiency of one. In practice you do not have such a source (the closest would be solar radiation) and secondly no material could contain matter at very high T so a cycle process can proceed (the closest would be a plasma suspended by a magnetic field as in a tokamak).

10.2

Is energy transfer as work 100% available?

Yes. By definition work is 100% exergy or availability.

10.3

We cannot create nor destroy energy, but how about available energy?

Yes. Every process that is irreversible to some degree destroys exergy. This destruction is directly proportional to the entropy generation.

10.4

Energy can be stored as internal energy, potential energy or kinetic energy. Are those energy forms all 100% available?

The internal energy is only partly available, a process like an expansion can give out work or if it cools by heat transfer out it is a Q out that is only partly available as work. Potential energy like from gravitation, mgH, or a compressed spring or a charged battery are forms that are close to 100% available with only small losses present. Kinetic energy like in a fly-wheel or motion of a mass can be transferred to work out with losses depending on the mechanical system.

10.5

All the energy in the ocean is that available?

No. Since the ocean is at the ambient T (it **is** the ambient) it is not possible to extract any work from it. You can extract wave energy (wind generated kinetic energy) or run turbines from the tide flow of water (moon generated kinetic energy). However, since the ocean temperature is not uniform there are a few locations where cold and warmer water flows close to each other like at different depths. In that case a heat engine can operate due to the temperature difference.

10.6

Does a reversible process change the availability if there is no work involved?

Yes. There can be heat transfer involved and that has an availability associated with it, which then equals the change of availability of the substance.

10.7

Is the reversible work between two states the same as ideal work for the device?

No. It depends on the definition of ideal work. The ideal device does not necessarily have the same exit state as the actual device. An ideal turbine is approximated as a reversible adiabatic device so the ideal work is the isentropic work. The reversible work is between the inlet state and the actual exit state that do not necessarily have the same entropy.

10.8

When is the reversible work the same as the isentropic work?

That happens when the inlet and exit states (or beginning and end states) have the same entropy.

10.9

If I heat some cold liquid water to T_o, do I increase its availability?

No. You decrease its availability by bringing it closer to T_o, where it has zero availability, if we neglect pressure effects. Any substance at a T different from ambient (higher or lower) has a positive availability since you can run a heat engine using the two temperatures as the hot and cold reservoir, respectively. For a T lower than the ambient it means that the ambient is the hot side of the heat engine.

10.10

Are reversible work and availability (exergy) connected?

Yes. They are very similar. Reversible work is usually defined as the reversible work that can be obtained between two states, inlet-exit or beginning to end. Availability is a property of a given state and defined as the reversible work that can be obtained by changing the state of the substance from the given state to the dead state (ambient).

10.11

Consider availability (exergy) associated with a flow. The total exergy is based on the thermodynamic state, the kinetic and potential energies. Can they all be negative?

No. By virtue of its definition kinetic energy can only be positive. The potential energy is measured from a reference elevation (standard sea level or a local elevation) so it can be negative. The thermodynamic state can only have a positive exergy the smallest it can be is zero if it is the ambient dead state.

10.12

A flow of air at 1000 kPa, 300 K is throttled to 500 kPa. 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 => $T_e = T_i$

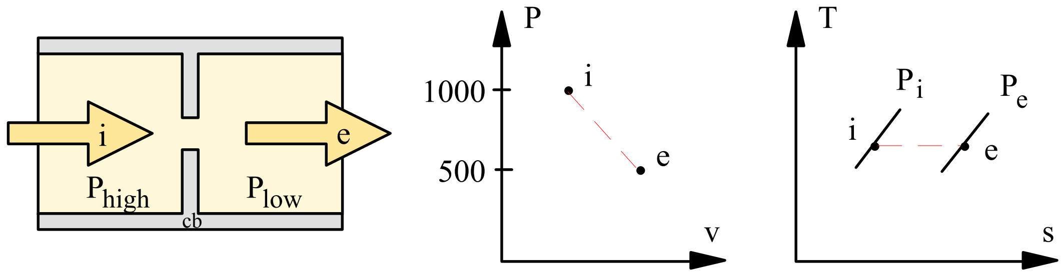
Entropy Eq.: $s_e - s_i = s_{gen} = s^o_{Te} - s^o_{Ti} - R \ln \frac{P_e}{P_i} = 0 - R \ln \frac{P_e}{P_i}$

$$s_{gen} = - 0.287 \ln (500 / 1000) = 0.2 \text{ kJ/kg K}$$

Eq.10.11: $i = T_o \, s_{gen} = 298 \; 0.2 =$ **59.6 kJ/kg**

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

$\Delta\psi = i =$ **59.6 kJ/kg**



10.13

A steam turbine inlet is at 1200 kPa, 500°C. The actual exit is at 300 kPa with an actual work of 407 kJ/kg. What is its second law efficiency?

The second law efficiency is the actual work out measured relative to the reversible work out, Eq. 10.29.

Steam turbine $T_o = 25°C = 298.15$ K

Inlet state: Table B.1.3 $h_i = 3476.28$ kJ/kg; $s_i = 7.6758$ kJ/kg K

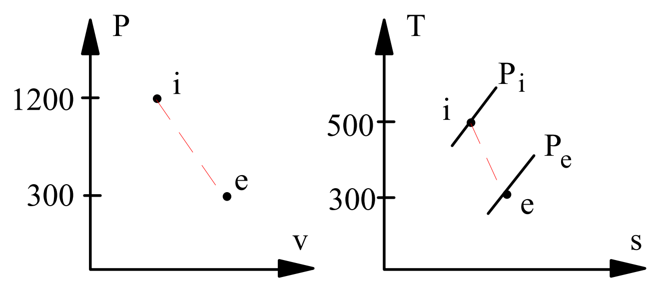
Actual turbine energy Eq.: $h_e = h_i - w_{ac} = 3476.28 – 407 = 3069.28$ kJ/kg

Actual exit state: Table B.1.3 $T_e = 300°C$; $s_e = 7.7022$ kJ/kg K

From Eq.10.9,

$$w^{rev} = (h_i - T_o s_i) – (h_e - T_o s_e) = (h_i - h_e) + T_o(s_e - s_i)$$
$$= (3476.28 – 3069.28) + 298.15(7.7022 – 7.6758)$$
$$= 407 + 7.87 = 414.9 \text{ kJ/kg}$$

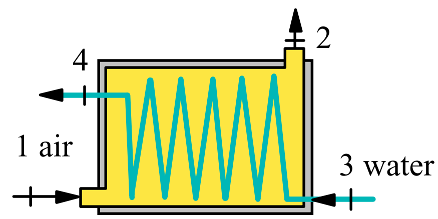
$$\eta_{II} = w_{ac}/w^{rev} = 407 / 414.9 = \mathbf{0.98}$$



10.14

A heat exchanger increases the availability of 3 kg/s water by 1650 kJ/kg using 10 kg/s air coming in at 1400 K and leaving with 600 kJ/kg 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

$$\dot{I} = \dot{\Phi}_{destruction} = \dot{\Phi}_{in} - \dot{\Phi}_{out} = 10 \times 600 - 3 \times 1650 = \mathbf{1050\ kW}$$

The second law efficiency, Eq.10.32

$$\eta_{II} = \dot{\Phi}_{out} / \dot{\Phi}_{in} = \frac{3 \times 1650}{10 \times 600} = \mathbf{0.825}$$

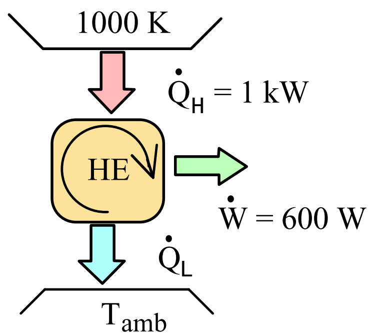
10.15

A heat engine receives 1 kW heat transfer at 1000 K and gives out 600 W as work with the rest as heat transfer to the ambient. What are the fluxes of exergy in and out?

Exergy flux in: $\dot{\Phi}_H = \left(1 - \frac{T_o}{T_H}\right) \dot{Q}_H = \left(1 - \frac{298.15}{1000}\right) 1 \text{ kW} = \mathbf{0.702\ kW}$

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 $\dot{\Phi}_{out} = \dot{W} = \mathbf{0.6\ kW}$



10.16

A heat engine receives 1 kW heat transfer at 1000 K and gives out 600 W 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

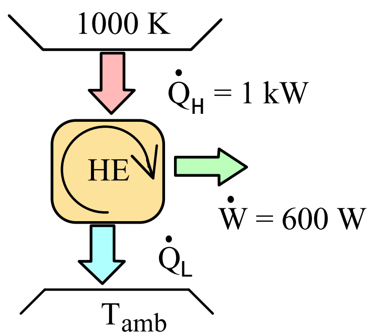
$$\eta_I = \dot{W}/\dot{Q}_H = \frac{0.6}{1} = \mathbf{0.6}$$

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

Exergy flux in: $\dot{\Phi}_H = \left(1 - \frac{T_o}{T_H}\right) \dot{Q}_H = \left(1 - \frac{298.15}{1000}\right) 1 \text{ kW} = 0.702 \text{ kW}$

$$\eta_{II} = \frac{\dot{W}}{\dot{\Phi}_H} = \frac{0.6}{0.702} = \mathbf{0.855}$$

Notice the exergy flux in is equal to the Carnot heat engine power output given 1 kW at 1000 K and rejecting energy to the ambient.



10.17

Is the exergy equation independent of the energy and entropy equations?

No. The exergy equation is derived from the other balance equations by defining the exergy from the state properties and the reference dead state.

10.18

A heat pump has a coefficient of performance of 2 using a power input of 2 kW. Its low temperature is T_o and the high temperature is 80^{o}C, with an 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

$$COP = \beta = \frac{\dot{Q}_H}{\dot{W}} \quad => \quad \dot{Q}_H = \beta\, \dot{W} = 2 \times 2 \text{ kW} = 4 \text{ kW}$$

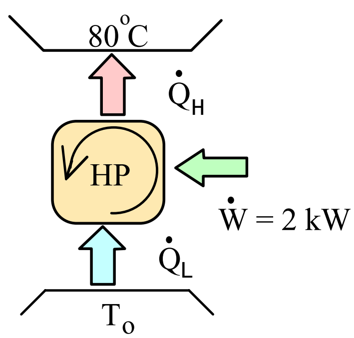
Energy Eq.: $\dot{Q}_L = \dot{Q}_H - \dot{W} = 4 - 2 = 2 \text{ kW}$

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

Exergy flux in: $\dot{\Phi}_W = \dot{W} = \mathbf{2\ kW}$

Exergy flux out: $\dot{\Phi}_H = \left(1 - \frac{T_o}{T_H}\right) \dot{Q}_H = \left(1 - \frac{298.15}{353.15}\right) 4 \text{ kW} = \mathbf{0.623\ kW}$

Remark: The process then destroys (2 – 0.623) kW of exergy.



10.19

Use the exergy balance equation to find the efficiency of a steady state Carnot heat engine operating between two fixed temperature reservoirs?

The exergy balance equation, Eq.10.36, for this case looks like

$$0 = \left(1 - \frac{T_o}{T_H}\right) \dot{Q}_H - \left(1 - \frac{T_o}{T_L}\right) \dot{Q}_L - \dot{W} + 0 + 0 - 0 - 0$$

Steady state (LHS = 0 and dV/dt = 0, no mass flow terms, Carnot cycle so reversible and the destruction is then zero. From the energy equation we have

$$0 = \dot{Q}_H - \dot{Q}_L - \dot{W}$$

which we can subtract from the exergy balance equation to get

$$0 = -\frac{T_o}{T_H} \dot{Q}_H + \frac{T_o}{T_L} \dot{Q}_L$$

Solve for one heat transfer in terms of the other

$$\dot{Q}_L = \frac{T_L}{T_H} \dot{Q}_H$$

The work from the energy equation is

$$\dot{W} = \dot{Q}_H - \dot{Q}_L = \dot{Q}_H \left[1 - \frac{T_L}{T_H} \right]$$

from which we can read the Carnot cycle efficiency as we found in Chapter 7.

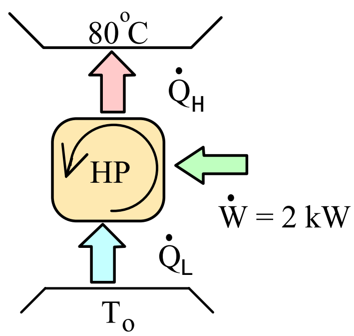
10.20

Find the second law efficiency of the heat pump in problem 10.18.

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

$$\dot{\Phi}_H = \left(1 - \frac{T_o}{T_H}\right)\dot{Q}_H; \qquad \dot{Q}_H = \beta\,\dot{W} = 2 \times 2\text{ kW} = 4\text{ kW}$$

$$\eta_{II} = \frac{\dot{\Phi}_H}{\dot{W}} = \left(1 - \frac{T_o}{T_H}\right)\frac{\dot{Q}_H}{\dot{W}} = \left(1 - \frac{298.15}{353.15}\right)\frac{4}{2} = \mathbf{0.31}$$



Available Energy, Reversible work

10.21

Find the availability of 100 kW delivered at 500 K when the ambient is 300 K.

Solution:

The availability of an amount of heat transfer equals the possible work that can be extracted. This is the work out of a Carnot heat engine with heat transfer to the ambient as the other reservoir. The result is from Chapter 7 as also shown in Eq. 10.1 and Eq. 10.36

$$\dot{\Phi} = \dot{W}_{rev\ HE} = (1 - \frac{T_o}{T})\dot{Q} = (1 - \frac{300}{500})\ 100\ \text{kW} = \mathbf{40\ kW}$$

10.22

A control mass gives out 10 kJ of energy in the form of

a. Electrical work from a battery

b. Mechanical work from a spring

c. Heat transfer at 500°C

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

Solution:

a) Work is availability $\Delta\Phi = -W_{el} = \mathbf{-10\ kJ}$

b) Work is availability $\Delta\Phi = -W_{spring} = \mathbf{-10\ kJ}$

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

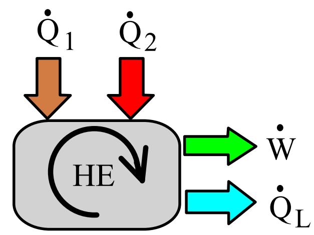
$$\Delta\Phi = -\left[1 - \frac{T_0}{T_H}\right] Q_{out} = -\left(1 - \frac{298.15}{773.15}\right) 10 = \mathbf{-6.14\ kJ}$$

10.23

A heat engine receives 5 kW at 800 K and 10 kW at 1000 K rejecting energy by heat transfer at 600 K. Assume it is reversible and find the power output. How much power could be produced if it could reject energy at T_o = 298 K?

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

$$\dot{Q}_L = \frac{T_L}{T_1}\dot{Q}_1 + \frac{T_L}{T_2}\dot{Q}_2 = \frac{600}{800} \times 5 + \frac{600}{1000} \times 10 = 9.75 \text{ kW}$$

Substitue into the enrgy equation and solve for the work term

$$\dot{W} = \dot{Q}_1 + \dot{Q}_2 - \dot{Q}_L = 5 + 10 - 9.75 = \mathbf{5.25\ kW}$$

For a low temperature of 298 K we can get

$$\dot{Q}_{L2} = \frac{298}{600}\dot{Q}_L = 4.843 \text{ kW}$$

$$\dot{W} = \dot{Q}_1 + \dot{Q}_2 - \dot{Q}_L = 5 + 10 - 4.843 = \mathbf{10.16\ kW}$$

Remark: Notice the large increase in the power output.

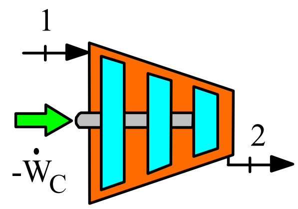
10.24

The compressor in a refrigerator takes refrigerant R-134a in at 100 kPa, –20°C and compresses it to 1 MPa, 40°C. With the room at 20°C find 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.: $s_2 = s_1 + \int dq/T + s_{gen} = s_1 + q^{rev}/T_o + 0$

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

$$w_{c\ min} = h_1 - h_2 + T_o(s_2 - s_1)$$

$$= 387.22 - 420.25 + 293.15 \times (1.7148 - 1.7665)$$

$$= \mathbf{-48.19\ kJ/kg}$$

10.25

Find the specific reversible work for a steam turbine with inlet 4 MPa, 500°C and an actual exit state of 100 kPa, x = 1.0 with a 25°C ambient.

Solution:

Steam turbine T_o = 25°C = 298.15 K

Inlet state: Table B.1.3 h_i = 3445.2 kJ/kg; s_i = 7.090 kJ/kg K

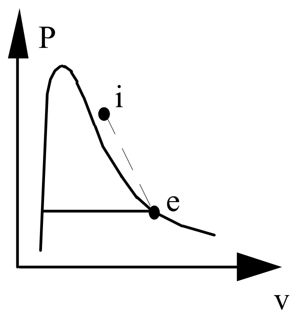
Exit state: Table B.1.2 h_e = 2675.5 kJ/kg; s_e = 7.3593 kJ/kg K

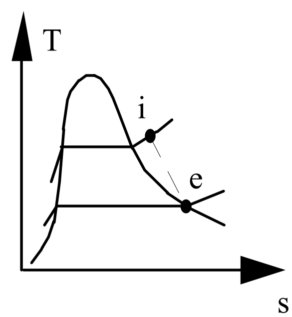
From Eq.9.39,

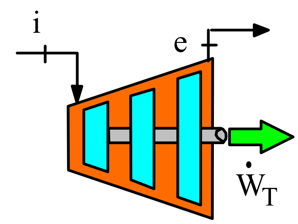
$$w^{rev} = (h_i - T_o s_i) – (h_e - T_o s_e) = (h_i - h_e) + T_o(s_e - s_i)$$

$$= (3445.2 – 2675.5) + 298.2(7.3593 – 7.0900)$$

$$= 769.7 + 80.3 = \mathbf{850.0\ kJ/kg}$$





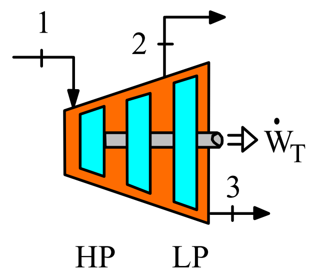


10.26

Calculate the reversible work out of the two-stage turbine shown in Problem 6.82, assuming the ambient is at 25°C. Compare this to the actual work which was found to be 18.08 MW.

C.V. Turbine. Steady flow, 1 inlet and 2 exits.

Use Eq. 10.12 for each flow stream with q = 0 for adiabatic turbine.



Supply state 1: 20 kg/s at 10 MPa, 500°C

Process steam 2: 5 kg/s, 0.5 MPa, 155°C,

Exit state 3: 20 kPa, x = 0.9

Table B.1.3: $h_1 = 3373.7$, $h_2 = 2755.9$ kJ/kg,

$s_1 = 6.5966$, $s_2 = 6.8382$ kJ/kg K

Table B.1.2: $h_3 = 251.4 + 0.9 \times 2358.3 = 2373.9$ kJ/kg,

$s_3 = 0.8319 + 0.9 \times 7.0766 = 7.2009$ kJ/kg K

$$\dot{W}^{rev} = (\dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3) - T_0(\dot{m}_1 s_1 - \dot{m}_2 s_2 - \dot{m}_3 s_3)$$

$$= 20 \times 3373.7 - 5 \times 2755.9 - 15 \times 2373.9$$

$$- 298.15\ (20 \times 6.5966 - 5 \times 6.8382 + 15 \times 7.2009)$$

$$= \mathbf{21.14\ MW} = \dot{W}^{ac} + \dot{Q}^{rev} = 18084 \text{ kW} + 3062.7 \text{ kW}$$

10.27

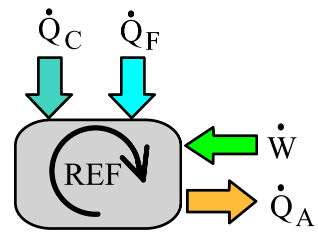
A household refrigerator has a freezer at T_F and a cold space at T_C from which energy is removed and rejected to the ambient at T_A as shown in Fig. P10.27. Assume that the rate of heat transfer from the cold space, $\dot{Q}_C$, is the same as from the freezer, $\dot{Q}_F$, find an expression for the minimum power into the heat pump. Evaluate this power when $T_A = 20°C$, $T_C = 5°C$, $T_F = -10°C$, and $\dot{Q}_F = 3$ kW.

Solution:

C.V. Refrigerator (heat pump), Steady, no external flows except heat transfer.

Energy Eq.: $\dot{Q}_F + \dot{Q}_c + \dot{W} = \dot{Q}_A$

(amount rejected to ambient)



Reversible gives minimum work in as from Eq. 10.1 or 10.9 on rate form.

$$\dot{W} = \dot{Q}_F \left[1 - \frac{T_A}{T_F}\right] + \dot{Q}_c \left[1 - \frac{T_A}{T_C}\right] = 3\left[1 - \frac{293.15}{263.15}\right] + 3\left[1 - \frac{293.15}{278.15}\right]$$

= **-0.504 kW** (negative so work goes in)

10.28

Find the specific reversible work for a R-134a compressor with inlet state of –20°C, 100 kPa and an exit state of 600 kPa, 50°C. Use a 25°C ambient temperature.

Solution:

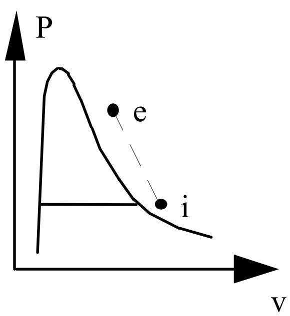
This is a steady state flow device for which the reversible work is given by Eq.10.9. The compressor is also assumed to be adiabatic so q = 0

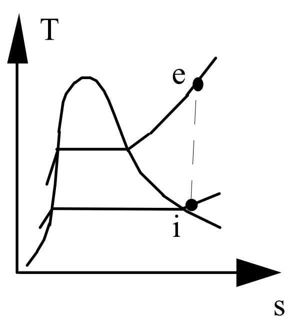
$$w^{rev} = T_o(s_e - s_i) - (h_e - h_i)$$

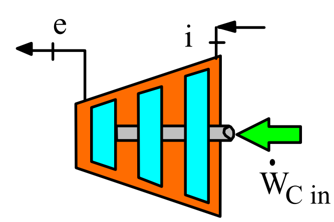
Table B.5.2: $h_i = 387.22$ kJ/kg; $s_i = 1.7665$ kJ/kg K

$h_e = 438.59$ kJ/kg; $s_e = 1.8084$ kJ/kg K

$w^{rev} = 298.15\ (1.8084 - 1.7665) - (438.59 - 387.22) =$ **-38.878 kJ/kg**







10.29

An air compressor takes air in at the state of the surroundings 100 kPa, 300 K. The air exits at 400 kPa, 200°C at the rate of 2 kg/s. Determine the minimum compressor work input.

C.V. Compressor, Steady flow, minimum work in is reversible work.

$\psi_1 = 0$ at ambient conditions

$s_0 - s_2 = s^\circ_{T_0} - s^\circ_{T_2} - R \ln(P_0/P_2)$

$= 6.86926 - 7.3303 - 0.287 \ln(100/400) = -0.06317$ kJ/kg K

$\psi_2 = h_2 - h_0 + T_0(s_0 - s_2) = 475.79 - 300.473 + 300\ (-0.06317)$

$= 156.365$ kJ/kg

$\mathbf{-\dot{W}^{REV} = \dot{m}(\psi_2 - \psi_1) = 312.73\ kW = \dot{W}_c}$

10.30

A steam turbine receives steam at 6 MPa, 800°C. It has a heat loss of 49.7 kJ/kg and an isentropic efficiency of 90%. For an exit pressure of 15 kPa and surroundings at 20°C, find the actual work and the reversible work between the inlet and the exit.

C.V. Reversible adiabatic turbine (isentropic)

$w_T = h_i - h_{e,s}$; $s_{e,s} = s_i = 7.6566$ kJ/kg K, $h_i = 4132.7$ kJ/kg

$x_{e,s} = (7.6566 - 0.7548)/7.2536 = 0.9515,$

$h_{e,s} = 225.91 + 0.9515 \times 2373.14 = 2483.9$ kJ/kg

$w_{T,s} = 4132.7 - 2483.9 = 1648.79$ kJ/kg

C.V. Actual turbine

$w_{T,ac} = \eta w_{T,s} =$ **1483.91 kJ/kg**

$= h_i - h_{e,ac} - q_{loss} \Rightarrow$

$h_{e,ac} = h_i - q_{loss} - w_{T,ac} = 4132.7 - 49.7 - 1483.91 = 2599.1$ kJ/kg

Actual exit state: P,h $\Rightarrow$ sat. vap., $s_{e,ac} = 8.0085$ kJ/kg K

C.V. Reversible process, work from Eq.10.12

$$q^R = T_0(s_{e,ac} - s_i) = 293.15 \times (8.0085 - 7.6566) = 103.15 \ \frac{kJ}{kg}$$

$w^R = h_i - h_{e,ac} + q^R = 4132.7 - 2599.1 + 103.16 =$ **1636.8 kJ/kg**

10.31

An air compressor receives atmospheric air at T_0 = 17°C, 100 kPa, and compresses it up to 1400 kPa. The compressor has an isentropic efficiency of 88% and it loses energy by heat transfer to the atmosphere as 10% of the isentropic work. Find the actual exit temperature and the reversible work.

C.V. Compressor

Isentropic: $w_{c,in,s} = h_{e,s} - h_i$; $s_{e,s} = s_i$

From table A.7.1 and entropy equation we get

$$s^o_{Te\ s} = s^o_{Ti} + R \ln (P_e/P_i) = 6.83521 + 0.287 \ln(14) = 7.59262$$

Back interpolate in Table A.7: $\Rightarrow$ $h_{e,s}$ = 617.23 kJ/kg

$$w_{c,in,s} = 617.23 - 290.43 = 326.8 \text{ kJ/kg}$$

Actual: $w_{c,in,ac} = w_{c,in,s}/\eta_c = 371.36$; $q_{loss} = 32.68$ kJ/kg

$$w_{c,in,ac} + h_i = h_{e,ac} + q_{loss}$$

$$\Rightarrow h_{e,ac} = 290.43 + 371.36 - 32.68 = 629.1 \text{ kJ/kg}$$

$$\Rightarrow T_{e,ac} = \mathbf{621\ K}$$

Reversible: $w^{rev} = h_i - h_{e,ac} + T_0(s_{e,ac} - s_i)$

$$= 290.43 - 629.1 + 290.15 \times (7.6120 - 6.8357)$$

$$= -338.67 + 225.38 = \mathbf{-113.3\ kJ/kg}$$

Since q_{loss} is also to the atmosphere it is the net q exchanged with the ambient that explains the change in s.

10.32

Air flows through a constant pressure heating device, shown in Fig. P10.32. It is heated up in a reversible process with a work input of 200 kJ/kg air flowing. The device exchanges heat with the ambient at 300 K. The air enters at 300 K, 400 kPa. Assuming constant specific heat develop an expression for the exit temperature and solve for it by iterations.

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: $C_p(T_2 - T_1) = T_0 C_p \ln (T_2/T_1) + 200$

The energy equation becomes

$$\mathbf{T_2 - T_0 \ln\left(\frac{T_2}{T_1}\right) = T_1 + \frac{200}{C_p}}$$

$T_1 = 300$ K, $C_p = 1.004$ kJ/kg K, $T_0 = 300$ K

$$T_2 - 300 \ln\left(\frac{T_2}{300}\right) = 300 + \frac{200}{1.004} = 499.3 \text{ K}$$

Now trial and error on T_2

At 600 K LHS = 392 (too low)

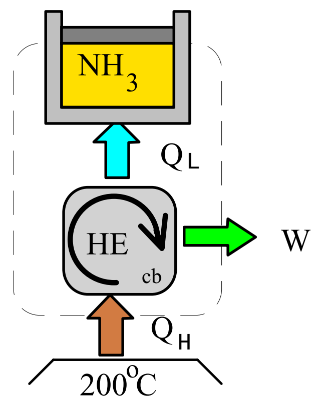
At 800 K LHS = 505.75

Linear interpolation gives $\mathbf{T_2 = 790\ K}$ (LHS = 499.5 **OK**)

10.33

A piston/cylinder has forces on the piston so it keeps constant pressure. It contains 2 kg of ammonia at 1 MPa, 40°C and is now heated to 100°C by a reversible heat engine that receives heat from a 200°C source. Find the work out of the heat engine.

C.V. Ammonia plus heat engine



Energy: $m_{am}(u_2 - u_1) = {}_1Q_{2,200} - W_{H.E.} - {}_1W_{2,pist}$

Entropy: $m_{am}(s_2 - s_1) = {}_1Q_2/T_{res} + 0$

$\Rightarrow \; {}_1Q_2 = m_{am}(s_2 - s_1)T_{res}$

Process: $P = \text{const.} \Rightarrow {}_1W_2 = P(v_2 - v_1)m_{am}$

Substitute the piston work term and heat transfer into the energy equation

$W_{H.E.} = m_{am}(s_2 - s_1)T_{res} - m_{am}(h_2 - h_1)$

Table B.2.2: $h_1 = 1508.5$ kJ/kg, $s_1 = 5.1778$ kJ/kg K,

$h_2 = 1664.3$ kJ/kg, $s_2 = 5.6342$ kJ/kg K

$$W_{H.E.} = 2 \times \left[(5.6342 - 5.1778)473.15 - (1664.3 - 1508.5)\right] = \mathbf{120.3\ kJ}$$

10.34

A rock bed consists of 6000 kg granite and is at 70°C. A small house with lumped mass of 12000 kg wood and 1000 kg iron is at 15°C. 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 in the process.

Solution:

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

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

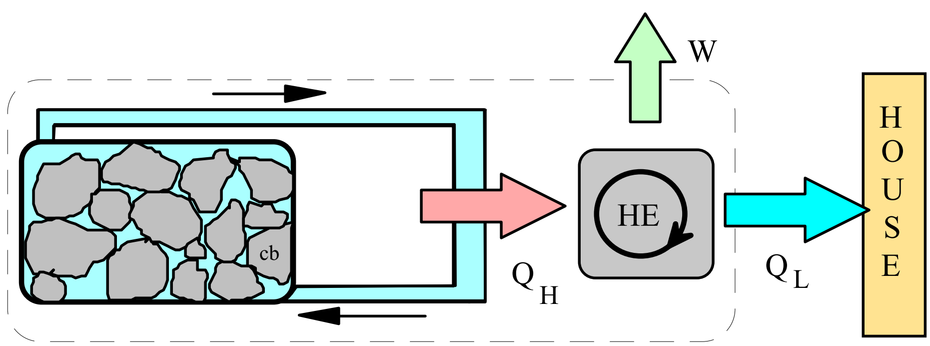
$$6000 \times 0.89 \ln (T_2/343.15) + 12000 \times 1.26 \ln (T_2/288.15) + 1000 \times 0.46 \ln (T_2/288.15) = \emptyset$$

$\Rightarrow$ $\mathbf{T_2 = 301.3\ K}$

Now from the energy equation

$$-{}_1W_2 = 6000 \times 0.89(301.3 - 343.15) + (12000 \times 1.26 + 460)(301.3 - 288.15)$$

$\Rightarrow {}_1W_2 =$ **18 602 kJ**



10.35

An air flow of 5 kg/min at 1500 K, 125 kPa goes through a constant pressure heat exchanger, giving energy to a heat engine shown in Figure P10.35. The air exits at 500 K and the ambient is at 298 K, 100 kPa. Find the rate of heat transfer delivered to the engine and the power the engine can produce.

Solution:

C.V. Heat exchanger

Continuity eq.: $\dot{m}_1 = \dot{m}_2$;

Energy Eq.6.12: $\dot{m}_1 h_1 = \dot{m}_1 h_2 + \dot{Q}_H$

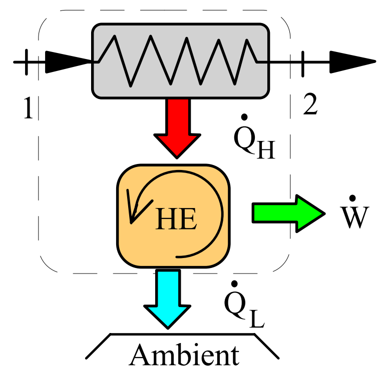


Table A.7.1: h_1 = 1635.8 kJ/kg,

h_2 = 503.36 kJ/kg, s_1 = 8.61209 kJ/kg K

s_2 = 7.38692 kJ/kg K

$$\dot{Q}_H = \dot{m}(h_1 - h_2) = \frac{5}{60}\frac{kg}{s}(1635.8 - 503.36)\frac{kJ}{kg} = \mathbf{94.37\ kW}$$

C.V. Total system for which we will write the second law.

Entropy Equation 9.8: $\dot{m}\, s_1 + \dot{S}_{gen} = \dot{m}\, s_2 + \dot{Q}_L/T_o$

Process: Assume reversible $\dot{S}_{gen} = 0$, and P = C for air

$$\dot{Q}_L = T_o\, \dot{m}\, (s_1 - s_2) = 298\ K\ \frac{5}{60}\frac{kg}{s}(8.61209 - 7.38692)\frac{kJ}{kg\ K}$$

$$= 30.425\ kW$$

Energy equation for the heat engine gives the work as

$$\dot{W} = \dot{Q}_H - \dot{Q}_L = 94.37 - 30.425 = \mathbf{63.9\ kW}$$

Irreversibility

10.36

Calculate the irreversibility for the condenser in Problem 9.53 assuming an ambient temperature at 17°C.

Solution:

C.V. Condenser. Steady state with no shaft work term.

Energy Equation 6.12: $\dot{m}\, h_i + \dot{Q} = \dot{m} h_e$

Entropy Equation 9.8: $\dot{m}\, s_i + \dot{Q}/T + \dot{S}_{gen} = \dot{m}\, s_e$

Properties are from Table B.1.2

$h_i = 225.91 + 0.9 \times 2373.14 = 2361.74$ kJ/kg , $h_e = 225.91$ kJ/kg

$s_i = 0.7548 + 0.9 \times 7.2536 = 7.283$ kJ/kg K, $s_e = 0.7548$ kJ/kg K

From the energy equation

$\dot{Q}_{out} = -\dot{Q} = \dot{m}\,(h_i - h_e) = 5(2361.74 - 225.91) = 10679$ kW

From the entropy equation

$\dot{S}_{gen} = \dot{m}\,(s_e - s_i) + \dot{Q}_{out}/T = 5(0.7548 - 7.283) + 10679/(273 + 17)$

$= -35.376 + 36.824 = 1.448$ kW/K

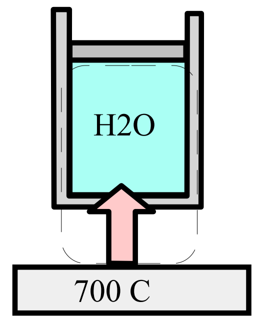
From Eq.10.11 times $\dot{m}$,

$\dot{I} = T_o\, \dot{S}_{gen} = 290 \times 1.448 =$ **419.9 kW**

10.37

A constant pressure piston/cylinder contains 2 kg of water at 5 MPa and 100°C. Heat is added from a reservoir at 700°C to the water until it reaches 700°C. 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: $h_1 = 422.71$ kJ/kg, $s_1 = 1.303$ kJ/kg K

State 2: $h_2 = 3900.13$ kJ/kg, $s_2 = 7.5122$ kJ/kg K

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

From the energy equation we get

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m(h_2 - h_1) = 2(3900.13 - 422.71) = 6954.8 \text{ kJ}$$

From the entropy equation we get

$${}_1S_{2\,gen} = m(s_2 - s_1) - \frac{{}_1Q_2}{T_{res}} = 2(7.5122 - 1.303) - \frac{6954.8}{273 + 700} = 5.2717 \frac{\text{kJ}}{\text{K}}$$

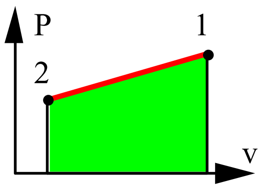
Now the irreversibility is from Eq. 10.19

$${}_1I_2 = m\ {}_1i_2 = T_o\ {}_1S_{2\,gen} = 298.15 \text{ K} \times 5.2717 \frac{\text{kJ}}{\text{K}} = \mathbf{1572\ kJ}$$

10.38

Calculate the reversible work and irreversibility for the process described in Problem 5.97, assuming that the heat transfer is with the surroundings at 20°C.

Solution:



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: $PV = mRT$

State 1: $V_1 = mRT_1/P_1 = 2 \times 0.1889 \times 673.15 /500 = 0.5087 \text{ m}^3$

State 2: $V_2 = mRT_2/P_2 = 2 \times 0.1889 \times 313.15 /300 = 0.3944 \text{ m}^3$

$${}_1W_2 = \frac{1}{2}(500 + 300)(0.3944 - 0.5087) = -45.72 \text{ kJ}$$

From Figure 5.11: $C_p(T_{avg}) = 5.25\ R = 0.99 \Rightarrow C_V = 0.803 = C_p - R$

For comparison the value from Table A.5 at 300 K is $C_V = 0.653$ kJ/kg K

$${}_1Q_2 = mC_V(T_2 - T_1) + {}_1W_2 = 2 \times 0.803(40 - 400) - 45.72 = -623.9 \text{ kJ}$$

$${}_1W_2^{rev} = T_o(S_2 - S_1) - (U_2 - U_1) + {}_1Q_2\,(1 - T_o/T_H)$$

$$= T_o m(s_2 - s_1) + {}_1W_2^{ac} - {}_1Q_2\,T_o/T_o$$

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

$$= 293.15 \times 2\ [\ 0.99 \ln(313/673) - 0.1889 \ln(300/500)] - 45.72 + 623.9$$

$$= -387.8 - 45.72 + 623.9 = \mathbf{190.4\ kJ}$$

$${}_1I_2 = {}_1W_2^{rev} - {}_1W_2^{ac} = 190.4 - (-45.72) = \mathbf{236.1\ kJ}$$

10.39

A supply of steam at 100 kPa, 150°C is needed in a hospital for cleaning purposes at a rate of 15 kg/s. A supply of steam at 150 kPa, 250°C is available from a boiler and tap water at 100 kPa, 15°C 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, Steady flow

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

B.1.1: $h_1 = 62.99$ kJ/kg, $s_1 = 0.2245$ kJ/kg K

B.1.3: $h_2 = 2972.7$ kJ/kg, $s_2 = 7.8437$ kJ/kg K

B.1.3: $h_3 = 2776.4$ kJ/kg, $s_3 = 7.6133$ kJ/kg K

From the energy equation we get

$$\dot m_2/\dot m_3 = (h_3 - h_1)/(h_2 - h_1) = \frac{2776.4 - 62.99}{2972.7 - 62.99} = 0.9325$$

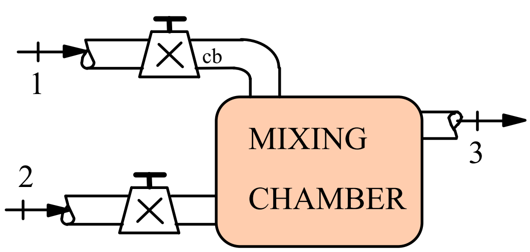
$$\dot m_2 = 13.988 \text{ kg/s}, \qquad \dot m_1 = 1.012 \text{ kg/s}$$

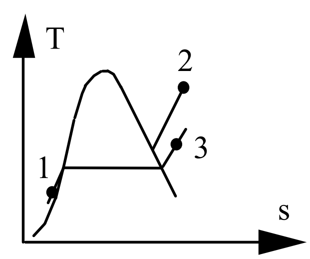
From the entropy equation we get

$$\dot I = T_0 \dot S_{gen} = T_0(\dot m_3 s_3 - \dot m_1 s_1 - \dot m_2 s_2)$$

$$= 298.15 \times (15 \times 7.6133 - 1.012 \times 0.2245 - 13.988 \times 7.8437)$$

$= \mathbf{1269\ kW}$





10.40

The throttle process in Example 6.5 is an irreversible process. Find the reversible work and irreversibility assuming an ambient temperature at 25°C.

Solution:

C.V. Throttle. Steady state, adiabatic q = 0 and no shaft work w = 0.

Inlet state: B.2.1 $h_i = 346.8$ kJ/kg; $s_i = 1.2792$ kJ/kg K

Energy Eq.6.13: $h_e = h_i$

Exit state: B.2.1 P = 291 kPa, $h_e = h_i$ which is two-phase

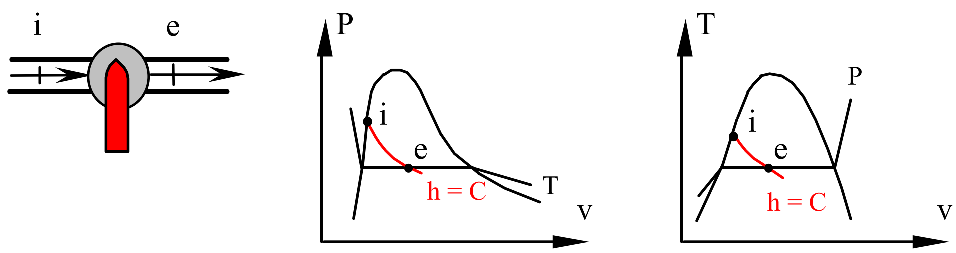
$$s_e = s_f + xs_{fg} = 0.5408 + 0.1638 \times 4.9265 = 1.3478 \text{ kJ/kg K}$$

The reversible work is the difference in availability also equal to the expression in Eq.10.9 or 10.36 and 10.37

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

$$= 0 + 298.15\ (1.2792 - 1.3478) = \mathbf{20.45\ kJ/kg}$$

$$i = w^{rev} - w = 20.45 - 0 = \mathbf{20.45\ kJ/kg}$$



10.41

Two flows of air both at 200 kPa of equal flow rates mix in an insulated mixing chamber. One flow is at 1500 K and the other is at 300 K. Find the irreversibility in the process per kilogram of air flowing out.

C.V. Mixing chamber

Continuity Eq..: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3 = 2\,\dot{m}_1$

Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_1 h_2 = 2\,\dot{m}_1 h_3$

Entropy Eq.: $\dot{m}_1 s_1 + \dot{m}_1 s_2 + \dot{S}_{gen} = 2\,\dot{m}_1 s_3$

Properties from Table A.7

$h_3 = (h_1 + h_2)/2 = (300.473 + 1635.8)/2 = 968.14$ kJ/kg

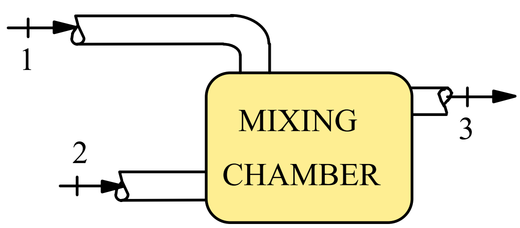
$\Rightarrow\ s^{\circ}_{T3} = 8.0474$ kJ/kg K

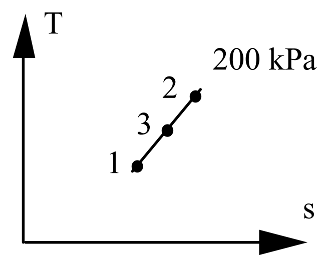
From the entropy equation

$\dot{S}_{gen}/2\dot{m}_1 = s_3 - (s_1 + s_2)/2 = 8.0474 - (6.86926 + 8.61208)/2$

$= 0.30673$ kJ/kg K

$i = \dot{I}/2\dot{m}_1 = T\,\dot{S}_{gen}/2\dot{m}_1 = 298.15 \times 0.30673$ = **91.45 kJ/kg**





10.42

Fresh water can be produced from saltwater by evaporation and subsequent condensation. An example is shown in Fig. P10.42, where 150-kg/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 20°C 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 [°C]	30	25	25	--	23	--	17	20
h [kJ/kg]	125.77	2547.2			96.5		71.37	83.96
s [kJ/kg K]	0.4369	8.558			0.3392		0.2535	0.2966

C.V. Valve. $P_2 = P_{sat}(T_2 = T_3) = 3.169$ kPa

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

Energy Eq.: $h_1 = h_e$; Entropy Eq.: $s_1 + s_{gen} = s_e$

$h_e = h_1 \;\Rightarrow\; x_e = (125.77 - 104.87)/2442.3 = 0.008558$

$\Rightarrow\; s_e = 0.3673 + 0.008558 \times 8.1905 = 0.4374$ kJ/kg K

$\dot{m}_2 = (1 - x_e)\dot{m}_1 = 148.716$ kg/s

$s_{gen} = s_e - s_1 = 0.4374 - 0.4369 = 0.000494$ kJ/kg K

$\dot{I} = \dot{m}T_0 s_{gen} = 150 \times 293.15 \times 0.000494 = \mathbf{21.72\ kW}$

C.V. Condenser.

Energy Eq.: $\dot{m}_2h_2 + \dot{m}_7h_7 = \dot{m}_2h_5 + \dot{m}_7h_8 \;\Rightarrow$

$$\dot{m}_7 = \dot{m}_2 \times (h_2 - h_5)/(h_8 - h_7) = 148.716 \times \frac{2547.2 - 96.5}{83.96 - 71.37} = 28\,948\ \frac{kg}{s}$$

Entropy Eq.: $\dot{m}_2s_2 + \dot{m}_7s_7 + \dot{S}_{gen} = \dot{m}_2s_5 + \dot{m}_7s_8$

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

$= 293.15[148.716(0.3392 - 8.558) + 28948(0.2966 - 0.2535)]$

$= 293.15 \times 25.392 = \mathbf{7444\ kW}$

10.43

Calculate the irreversibility for the process described in Problem 6.133, assuming that heat transfer is with the surroundings at 17°C.

Solution:

C.V. Cylinder volume out to $T_o = 17\ ^oC$.

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

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

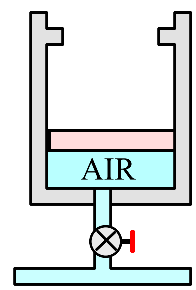
Entropy Eq.9.12: $m_2 s_2 - m_1s_1 = m_is_i + {}_1Q_2 / T_o + {}_1S_{2\ gen}$

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

State 1: P_1, T_1 $\quad m_1 = \dfrac{P_1V}{RT_1} = \dfrac{300 \times 0.25}{0.287 \times 290.2} = 0.90$ kg

State 2:

Open to $P_2 = 400$ kPa, $T_2 = 350$ K



$$m_2 = \frac{400 \times 1}{0.287 \times 350} = 3.982 \text{ kg}$$

$$m_i = 3.982 - 0.90 = 3.082 \text{ kg}$$

Only work while constant P

$${}_1W_2 = P_1(V_2 - V_1) = 300(1 - 0.25) = 225 \text{ kJ}$$

Energy eq.:

$${}_1Q_2 = m_2u_2 - m_1u_1 + {}_1W_2 - m_ih_i$$
$$= 3.982 \times 0.717 \times 350 - 0.90 \times 0.717 \times 290.2 + 225$$
$$- 3.082 \times 1.004 \times 600 = -819.2 \text{ kJ}$$

Entropy eq. gives

$$T_o\ {}_1S_{2\ gen} = I = T_o\ [\ m_1\ (s_2 - s_1) + m_i\ (s_2 - s_i)] - {}_1Q_2$$

$$= 290.15[0.9(C_p \ln \frac{350}{290} - R \ln \frac{400}{300}) + 3.082(C_p \ln \frac{350}{600} - R \ln \frac{400}{500})]$$
$$- (- 819.2 \text{ kJ})$$

$$= 290.15\ (0.0956 - 1.4705) + 819.2$$

$$= \mathbf{420.3\ kJ}$$

10.44

A 2-kg piece of iron is heated from room temperature 25°C to 400°C by a heat source at 600°C. What is the irreversibility in the process?

Solution:

C.V. Iron out to 600°C source, which is a control mass.

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

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

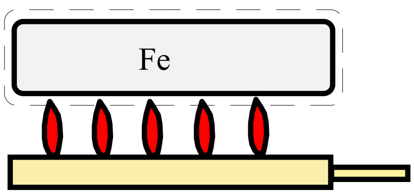
Process: Constant pressure => ${}_1W_2 = Pm_{Fe}(v_2 - v_1)$

$\Rightarrow\ {}_1Q_2 = m_{Fe}(h_2 - h_1) = m_{Fe}C(T_2 - T_1) = 2 \times 0.42 \times (400 - 25) = 315$ kJ

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

$$= 2 \times 0.42 \times \ln \frac{673.15}{298.15} - \frac{315}{873.15} = 0.3233 \text{ kJ/K}$$

${}_1I_2 = T_o\,({}_1S_{2\,gen}) = 298.15 \times 0.3233 =$ **96.4 kJ**



A real flame may be more than 600°C, but a little away from it where the gas has mixed with some air it may be 600°C.

10.45

Air enters the turbocharger compressor (see Fig. P10.45), of an automotive engine at 100 kPa, 30°C, and exits at 170 kPa. The air is cooled by 50°C 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:

$$T_{2S} = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 303.2\left(\frac{170}{100}\right)^{0.286} = 352.9 \text{ K}$$

$$w_S = C_{P0}(T_1 - T_{2S}) = 1.004(303.2 - 352.9) = -49.9 \text{ kJ/kg}$$

Now the actual compressor

$$w = w_S/\eta_S = -49.9/0.75 = -66.5 \text{ kJ/kg} = C_P(T_1 - T_2)$$

$$\Rightarrow T_2 = 369.5 \text{ K}$$

$$T_3(\text{to engine}) = T_2 - \Delta T_{INTERCOOLER} = 369.5 - 50$$

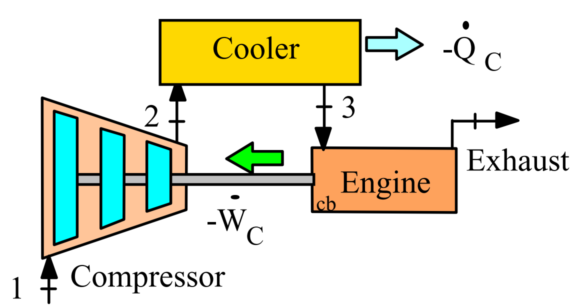
$$= 319.5 \text{ K} = \mathbf{46.3°C}$$

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

$$s_3 - s_1 = 1.004 \ln\left(\frac{319.4}{303.2}\right) - 0.287 \ln\left(\frac{170}{100}\right) = -0.1001 \frac{\text{kJ}}{\text{kg K}}$$

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

$$= 303.2(-0.1001) - 1.004(-50) = \mathbf{+19.8 \text{ kJ/kg}}$$



10.46

A 2-kg/s flow of steam at 1 MPa, 700°C should be brought to 500°C by spraying in liquid water at 1 MPa, 20°C in an steady flow. Find the rate of irreversibility, assuming that surroundings are at 20°C.

C.V. Mixing chamber, Steady flow. State 1 is superheated vapor in, state 2 is compressed liquid in, and state 3 is flow out. No work or heat transfer.

Continuity Eq.6.9: $\dot{m}_3 = \dot{m}_1 + \dot{m}_2$

Energy Eq.6.10: $\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$

Entropy Eq.9.7: $\dot{m}_3 s_3 = \dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{S}_{gen}$

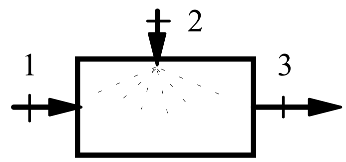


Table B.1.3: $h_1 = 3923.1$ kJ/kg, $s_1 = 8.2731$ kJ/kg K,

$h_3 = 3478.5$ kJ/kg, $s_3 = 7.7622$ kJ/kg K,

For state 2 interpolate between, saturated liquid 20°C table B.1.1 and, compressed liquid 5 MPa, 20°C from Table B.1.4: $h_2 = 84.9$, $s_2 = 0.2964$

$$x = \dot{m}_2/\dot{m}_1 = (h_3 - h_1)/(h_2 - h_3) = 0.13101$$

$$\Rightarrow \dot{m}_2 = 2 \times 0.131 = 0.262 \text{ kg/s} ; \qquad \dot{m}_3 = 2 + 0.262 = 2.262 \text{ kg/s}$$

$$\dot{S}_{gen} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2 = 0.9342 \text{ kW/K}$$

$$\dot{I} = \dot{W}^{rev} - \dot{W}^{ac} = \dot{W}^{rev} = T_o \dot{S}_{gen} = 293.15 \times 0.9342 = \mathbf{273.9\ kW}$$

10.47

A car air-conditioning unit has a 0.5-kg aluminum storage cylinder that is sealed with a valve and it contains 2 L of refrigerant R-134a at 500 kPa and both are at room temperature 20°C. It is now installed in a car sitting outside where the whole system cools down to ambient temperature at –10°C. What is the irreversibility of this process?

C.V. Aluminum and R-134a

Energy Eq.: $m_{Al}(u_2 - u_1)_{Al} + m_R(u_2 - u_1)_R = {}_1Q_2 - {}_1W_2 \quad ({}_1W_2 = 0)$

Entropy Eq.: $m_{AL}(s_2 - s_1)_{Al} + m_R(s_2 - s_1)_R = {}_1Q_2/T_0 + {}_1S_{2\,gen}$

$(u_2 - u_1)_{Al} = C_{v,Al}(T_2 - T_1) = 0.9(-10 - 20) = -27$ kJ/kg

$(s_2 - s_1)_{Al} = C_{p,Al} \ln(T_2/T_1) = 0.9 \ln(263.15/293.15) = -0.09716$ kJ/kg K

Table B.5.2: $v_1 = 0.04226$ m^3/kg, $u_1 = 390.5$ kJ/kg,

$s_1 = 1.7342$ kJ/kg K, $m_{R134a} = V/v_1 = 0.0473$ kg

$v_2 = v_1 = 0.04226$ & T_2 => $x_2 = (0.04226 - 0.000755)/0.09845 = 0.4216$

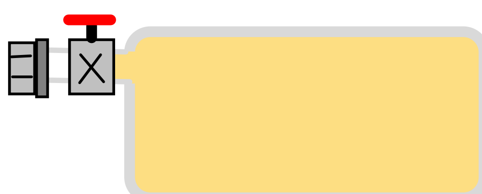
$u_2 = 186.57 + 0.4216 \times 185.7 = 264.9$ kJ/kg,

$s_2 = 0.9507 + 0.4216 \times 0.7812 = 1.2801$ kJ/kg K

${}_1Q_2 = 0.5 \times (-27) + 0.0473(264.9 - 390.5) = -19.44$ kJ

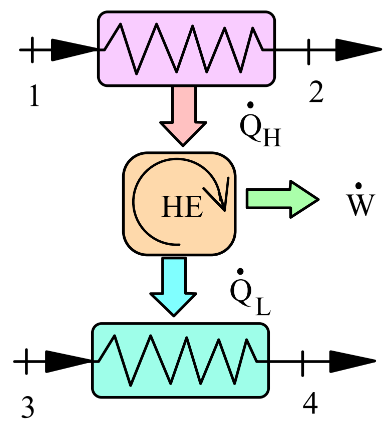
$${}_1S_{2\,gen} = 0.5\,(-0.09716) + 0.0473(1.2801 - 1.7342) + \frac{19.44}{263.15} = 0.003815 \text{ kJ/K}$$

${}_1I_2 = T_0\,(\,{}_1S_{2\,gen}\,) = 263.15 \times 0.003815 =$ **1.0 kJ**



10.48

The high-temperature heat source for a cyclic heat engine is a steady flow heat exchanger where R-134a enters at 80°C, saturated vapor, and exits at 80°C, saturated liquid at a flow rate of 5 kg/s. Heat is rejected from the heat engine to a steady flow heat exchanger where air enters at 150 kPa and ambient temperature 20°C, and exits at 125 kPa, 70°C. The rate of irreversibility for the overall process is 175 kW. Calculate the mass flow rate of the air and the thermal efficiency of the heat engine.



C.V. R-134a Heat Exchanger,

$\dot{m}_{R134a}$ = 5 kg/s, Table B.5.1

Inlet: $T_1 = 80^oC$, sat. vapor $x_1 = 1.0$,

$h_1 = h_g = 429.189$ kJ/kg,

$s_1 = s_g = 1.6862$ kJ/kg-K

Exit: $T_2 = 80^oC$, sat. liquid $x_2 = 0.0$

$h_2 = h_f = 322.794$ kJ/kg,

$s_2 = s_f = 1.3849$ kJ/kg-K

C.V. Air Heat Exchanger, $C_p = 1.004$ kJ/kg-K, R = 0.287 kJ/kg-K

Inlet: $T_3 = 20^oC$, $P_3 = 150$ kPa   Exit: $T_4 = 70^oC$, $P_4 = 125$ kPa

$$s_4 - s_3 = C_p \ln\left(\frac{T_4}{T_3}\right) - R \ln\left(\frac{P_4}{P_3}\right) = 0.2103 \text{ kJ/kg-K}$$

2nd Law for the total system as control volume (since we know $\dot{I}$):

$$\dot{I} = T_o \dot{S}_{net} = \dot{m}_{R134a}(s_2 - s_1) + \dot{m}_{air}(s_4 - s_3)$$

$$\dot{m}_{air} = [\dot{I} - \dot{m}_{R134a}(s_2 - s_1)]/(s_4 - s_3) = \mathbf{10.0\ kg/s}$$

1st Law for each line: $\dot{Q} + \dot{m}h_{in} = \dot{m}h_{ex} + \dot{W}$; $\dot{W} = 0$

R-134a: ${}_1\dot{Q}_2 = -\dot{Q}_H = \dot{m}_{R134a}(h_2 - h_1) = -532$ kW

Air: $\dot{Q}_L = {}_3\dot{Q}_4 = \dot{m}_{air}(h_4 - h_3) = \dot{m}_{air} C_p(T_4 - T_3) = 501.8$ kW

Control volume heat engine

$$\dot{W}_{net} = \dot{Q}_H - \dot{Q}_L = 532 - 501.8 = 30.2 \text{ kW};$$

$$\eta_{th} = \dot{W}_{net} / \dot{Q}_H = \mathbf{0.057}, \quad \textbf{or 5.7\%}$$

10.49

A rigid container with volume 200 L is divided into two equal volumes by a partition. Both sides contains nitrogen, one side is at 2 MPa, 300°C, and the other at 1 MPa, 50°C. The partition ruptures, and the nitrogen comes to a uniform state at 100°C. Assuming the surroundings are at 25°C find the actual heat transfer and the irreversibility in the process.

Solution:

C.V. Total container

Continuity Eq.: $m_2 - m_A - m_B = 0$

Energy Eq.: $m_A(u_2 - u_1)_A + m_B(u_2 - u_1)_B = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m_A(s_2 - s_1)_A + m_B(s_2 - s_1)_B = {}_1Q_2/T_{sur} + {}_1S_{s\ gen}$

Process: $V = C \quad => \quad {}_1W_2 = 0$

From the initial state we get the mass as

$$m_2 = m_A + m_B = \frac{P_{A1}V_A}{RT_{A1}} + \frac{P_{B1}V_B}{RT_{B1}}$$

$$= \frac{2000 \times 0.1}{0.2968 \times 573.15} + \frac{1000 \times 0.1}{0.2968 \times 323.15} = 1.176 + 1.043 = 2.219 \text{ kg}$$

$$P_2 = m_2RT_2/V_{tot} = 2.219 \times 0.2968 \times 373.15/0.2 = 1228.8 \text{ kPa}$$

From the energy equation we get the heat transfer as the change in U

$${}_1Q_2 = m_AC_v(T_2 - T_1)_A + m_BC_v(T_2 - T_1)_B$$

$$= 1.176 \times 0.745 \times (100 - 300) + 1.043 \times 0.745 \times (100 - 50)$$

$$= \mathbf{-136.4\ kJ}$$

The entropy changes are found from Eq.8.25

$$(s_2 - s_1)_A = 1.042 \times \ln\frac{373.15}{573.15} - 0.2968 \times \ln\frac{1228.8}{2000} = -0.09356 \text{ kJ/kg K}$$

$$(s_2 - s_1)_B = 1.042 \times \ln\frac{373.15}{323.15} - 0.2968 \times \ln\frac{1228.8}{1000} = 0.0887 \text{ kJ/kg K}$$

The entropy generation follows from the entropy equation

$${}_1S_{2,gen} = 1.176\times (-0.09356) + 1.043\times 0.0887 + 136.4/298.15 = 0.4396 \text{ kJ/K}$$

Now the irreversibility comes from Eq. 10.19

$${}_1I_2 = T_0 \times {}_1S_{2,gen} = \mathbf{131.08\ kJ}$$

10.50

A rock bed consists of 6000 kg granite and is at 70°C. A small house with lumped mass of 12000 kg wood and 1000 kg iron is at 15°C. 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 of the process, assuming an ambient at 15°C.

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

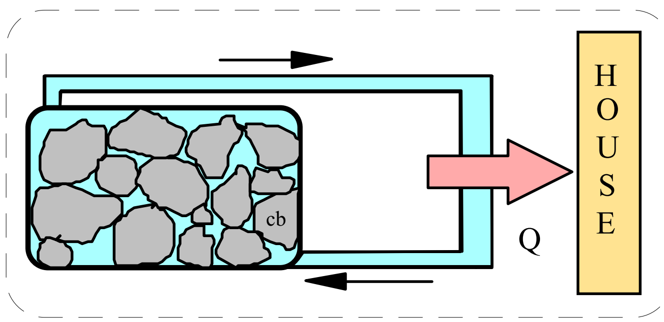
Energy Eq.: $(mC)_{rock}(T_2 - 70) + (mC_{wood} + mC_{Fe})(T_2 - 15) = \emptyset$

$T_2 = \mathbf{29.0°C = 302.2\ K}$

Entropy Eq.: $S_2 – S_1 = \sum m_i(s_2 - s_1)_i = 0 + S_{gen}$

$$S_{gen} = \sum m_i(s_2 - s_1)_i = 5340 \ln \frac{302.2}{343.15} + 15580 \ln \frac{302.2}{288.15} = 63.13 \text{ kJ/K}$$

$_1I_2 = (T_0)_1S_{2,gen} = 288.15 \times 63.13 = \mathbf{18191\ kJ}$

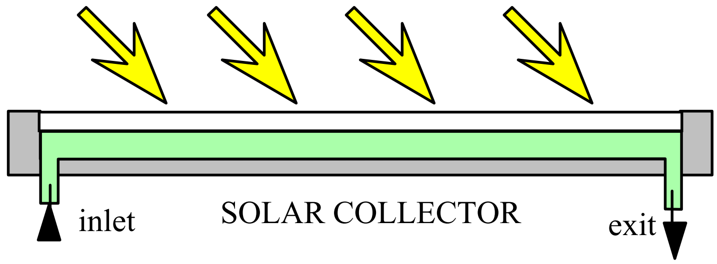


Availability (exergy)

10.51

A steady stream of R-22 at ambient temperature, 10°C, and at 750 kPa enters a solar collector. The stream exits at 80°C, 700 kPa. Calculate the change in availability of the R-22 between these two states.

Solution:



Inlet (T,P) Table B.4.1 (liquid): $h_i = 56.46$ kJ/kg, $s_i = 0.2173$ kJ/kg K

Exit (T,P) Table B.4.2 (sup. vap.): $h_e = 305.91$ kJ/kg, $s_e = 1.0761$ kJ/kg K

From Eq.10.24 or 10.37

$$\Delta\psi_{ie} = \psi_e - \psi_i = (h_e - h_i) - T_0(s_e - s_i) = (305.912 - 56.463)$$

$$- 283.2(1.0761 - 0.2173) = \mathbf{6.237\ kJ/kg}$$

10.52

Consider the springtime melting of ice in the mountains, which gives cold water running in a river at 2°C while the air temperature is 20°C. What is the availability of the water relative to the temperature of the ambient?

Solution:

$\psi = h_1 - h_0 - T_0(s_1 - s_0)$ flow availability from Eq.10.24

Approximate both states as saturated liquid from Table B.1.1

$\psi = 8.392 - 83.96 - 293.15(0.03044 - 0.2966) =$ **2.457 kJ/kg**

Why is it positive? As the water is brought to 20°C it can be heated with q_L from a heat engine using q_H from atmosphere $T_H = T_0$ thus giving out work.

10.53

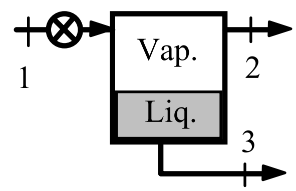
A geothermal source provides 10 kg/s of hot water at 500 kPa, 150°C flowing into a flash evaporator that separates vapor and liquid at 200 kPa. Find the three fluxes of availability (inlet and two outlets) and the irreversibility rate.

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



B.1.1: $h_o = 104.87$, $s_o = 0.3673$, $h_1 = 632.18$, $s_1 = 1.8417$

B.1.2: $h_2 = 2706.63$, $s_2 = 7.1271$, $h_3 = 504.68$, $s_3 = 1.530$

$$h_1 = xh_2 + (1 - x)\, h_3 \;\; => \;\; x = \dot{m}_2/\dot{m}_1 = \frac{h_1 - h_3}{h_2 - h_3} = 0.0579$$

$$\dot{m}_2 = x\dot{m}_1 = 0.579 \text{ kg/s} \qquad \dot{m}_3 = (1\text{-}x)\dot{m}_1 = 9.421 \text{ kg/s}$$

$$\dot{S}_{gen} = 0.579 \times 7.1271 + 9.421 \times 1.53 - 10 \times 1.8417 = 0.124 \text{ kW/K}$$

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

$\psi_1 = 632.18 - 104.87 - 298.15\,(1.8417 - 0.3673) = 87.72$ kJ/kg

$\psi_2 = 2706.63 - 104.87 - 298.15\,(7.1271 - 0.3673) = 586.33$ kJ/kg

$\psi_3 = 504.68 - 104.87 - 298.15\,(1.53 - 0.3673) = 53.15$ kJ/kg

$\dot{m}_1 \psi_1 =$ **877.2 kW** $\quad \dot{m}_2\psi_2 =$ **339.5 kW** $\quad \dot{m}_3\psi_3 =$ **500.7 kW**

$\dot{I} = \dot{m}_1 \psi_1 - \dot{m}_2 \psi_2 - \dot{m}_3\psi_3 =$ **37 kW**

10.54

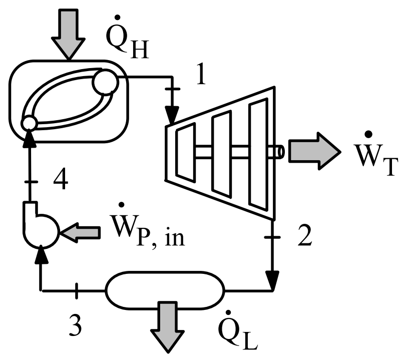
Find the availability at all 4 states in the power plant of Problem 9.42 with an ambient at 298 K.

Solution:

Flow availability from Eq.10.24 neglecting kinetic and potential energy is:

$$\psi = h - h_0 - T_0(s - s_0)$$

so we need (h,s) for all four states.



$P_1 = P_4 = 20$ MPa, $T_1 = 700$ °C

$h_1 = 3809.1$ kJ/kg,

$s_1 = 6.7993$ kJ/kg K

$P_2 = P_3 = 20$ kPa, $T_3 = 40$ °C

State 3: (P, T) Comp. liquid, take sat. liquid Table B.1.1

$h_3 = 167.5$ kJ/kg,

$v_3 = 0.001008$ m^3/kg

C.V. Turbine.

Entropy Eq.9.8: $s_2 = s_1 = 6.7993$ kJ/kg K

Table B.1.2 $s_2 = 0.8319 + x_2 \times 7.0766$ => $x_2 = 0.8433$

$h_2 = 251.4 + 0.8433\times 2358.33 = 2240.1$ kJ/kg

$w_T = h_1 - h_2 = 3809.1 - 2240.1 = 1569$ kJ/kg

CV. Pump, property relation in Eq.9.13 gives work from Eq.9.18 as

$w_P = - v_3(P_4 - P_3) = -0.001008(20000 – 20) = -20.1$ kJ/kg

$h_4 = h_3 - w_P = 167.5 + 20.1 = 187.6$ kJ/kg

Flow availability from Eq.10.24 and notice that since turbine work and pump work are reversible they represent also change in avalability.

$\psi_1 = h_1 - h_0 - T_0(s_1 - s_0) = 3809.1 – 104.87 - 298 (6.7993 – 0.3673)$

$= 1787.5$ kJ/kg

$\psi_2 = h_2 - h_0 - T_0(s_2 - s_0) = \psi_1 - w_T = 1787.5 - 1569 = 218.5$ kJ/kg

$\psi_3 = h_3 - h_0 - T_0(s_3 - s_0) = 167.5 - 104.87 - 298(0.5724 - 0.3673)$

$= 1.51$ kJ/kg

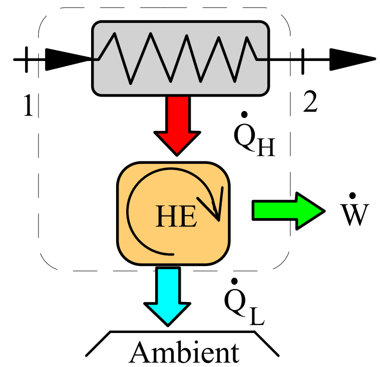
$\psi_4 = h_4 - h_0 - T_0(s_4 - s_0) = \psi_3 - w_P = 1.51 + 20.1 = 21.61$ kJ/kg

10.55

Air flows at 1500 K, 100 kPa through a constant pressure heat exchanger giving energy to a heat engine and comes out at 500 K. What is the constant temperature the same heat transfer should be delivered at to provide the same availability?

Solution:

C.V. Heat exchanger



Continuity eq.: $\dot{m}_1 = \dot{m}_2$;

Energy Eq.6.12: $\dot{m}_1 h_1 = \dot{m}_1 h_2 + \dot{Q}_H$

Table A.7.1: $h_1 = 1635.8$ kJ/kg,

$h_2 = 503.36$ kJ/kg, $s_1 = 8.61209$ kJ/kg K

$s_2 = 7.38692$ kJ/kg K

$q_{out} = h_1 - h_2 = 1635.8 - 503.36 = 1132.4$ kJ/kg

Availability from heat transfer at T: $\Delta\psi = (1 - \frac{T_o}{T_H})\, q_{out} = \psi_1 - \psi_2$

Eq.10.37: $\psi_1 - \psi_2 = h_1 - h_2 - T_o (s_1 - s_2)$

$= 1132.4 - 298.15\ (8.6121 - 7.38692)$

$= 1132.4 - 356.3 = 767.1$ kJ/kg

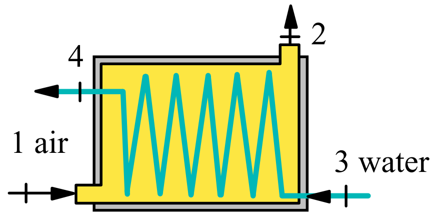
$$1 - \frac{T_o}{T_H} = (\psi_1 - \psi_2) / q_{out} = 767.1 / 1132.4 = 0.6774$$

$$\frac{T_o}{T_H} = 0.3226 \;\; => \;\; \mathbf{T_H = 924\ K}$$

10.56

Calculate the change in availability (kW) of the two flows in Problem 9.61.

Solution:



The two flows in the heat exchanger exchanges energy and thus also exergy (availability). Fist find state 4

Air A.7: $h_1 = 1046.22$, $h_2 = 401.3$ kJ/kg,

$s^o_{T1} = 8.1349$, $s^o_{T2} = 7.1593$ kJ/kg K

Water B.1.1: $h_3 = 83.94$ kJ/kg, $s_3 = 0.2966$ kJ/kg K

Energy Eq.6.10: $\dot{m}_{AIR}\Delta h_{AIR} = \dot{m}_{H2O}\Delta h_{H2O}$

$h_4 - h_3 = (\dot{m}_{AIR}/\dot{m}_{H2O})(h_1 - h_2) = (2/0.5)644.92 = 2579.68$ kJ/kg

$h_4 = h_3 + 2579.68 = 2663.62 < h_g$ at 200 kPa

$T_4 = T_{sat} = 120.23°C$,

$x_4 = (2663.62 – 504.68)/2201.96 = 0.9805$,

$s_4 = 1.53 + x_4\ 5.597 = 7.01786$ kJ/kg K

We consider each flow separately and for each flow availability is Eq.10.24, include mass flow rate as in Eq.10.36, use $T_o = 20$ C

For the air flow:

$\dot{m}_1(\psi_1 - \psi_2) = \dot{m}_1 [\ h_1 - h_2 - T_o\ (s_1 - s_2)\ ]$

$= 2\ [\ 1046.22 - 401.3 - 293.2(8.1349 - 7.1593 - 0.287 \ln\frac{125}{100})]$

$= 2\ (644.92 - 267.22\ ) =$ **755.4 kW**

For the water flow:

$\dot{m}_3(\psi_4 - \psi_3) = \dot{m}_3 [\ h_4 - h_3 - T_o\ (s_4 - s_3)\ ]$

$= 0.5\ [\ 2663.62 - 83.94 - 293.2(7.01786 - 0.2966)]$

$= 0.5[\ 2579.68 - 1970.7\ ] =$ **304.7 kW**

10.57

Nitrogen flows in a pipe with velocity 300 m/s at 500 kPa, 300°C. What is its availability with respect to an ambient at 100 kPa, 20°C?

Solution:

From the availability or exergy in Eq.10.24

$$\psi = h_1 - h_0 + (1/2)\mathbf{V}_1^2 - T_0(s_1 - s_0)$$

$$= C_p(T_1 - T_0) + (1/2)\mathbf{V}_1^2 - T_0\left[C_p \ln(\frac{T_1}{T_0}) - R \ln(\frac{P_1}{P_0})\right]$$

$$= 1.042(300 - 20) + \frac{300^2}{2000} - 293.15\left(1.042 \ln\left(\frac{573.15}{293.15}\right) - 0.2968 \ln\left(\frac{500}{100}\right)\right)$$

$$= \mathbf{272\ kJ/kg}$$

Notice that the high velocity does give a significant contribution.

10.58

A steady combustion of natural gas yields 0.15 kg/s of products (having approximately the same properties as air) at 1100°C, 100 kPa. The products are passed through a heat exchanger and exit at 550°C. What is the maximum theoretical power output from a cyclic heat engine operating on the heat rejected from the combustion products, assuming that the ambient temperature is 20°C?

Solution:

C.V. Heat exchanger

Continuity eq.: $\dot{m}_i = \dot{m}_e$;

Energy Eq.6.12: $\dot{m}_i h_i = \dot{m}_i h_e + \dot{Q}_H$

$$\dot{Q}_H = \dot{m}_i C_{P0}(T_i - T_e) = 0.15 \times 1.004(1100 - 550) = 82.83 \text{ kW}$$

We do not know the H.E efficiency, high T not constant.

C.V. Total heat exchanger plus heat engine, reversible process.

Entropy Eq.: $\dot{m}_i s_i + 0 = \dot{m}_i s_e + \dot{Q}_L/T_L$

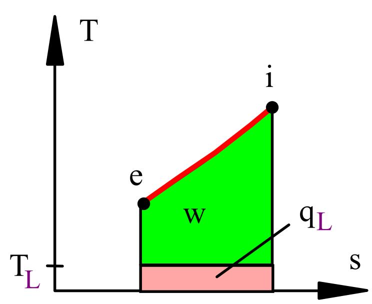
$$\dot{Q}_L = T_L \ \dot{m}_i (s_i - s_e) = T_L \dot{m}_i C_{P0} \ln\left(\frac{T_i}{T_e}\right)$$

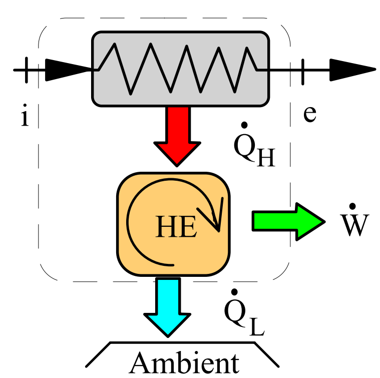
$$= 293.15 \times \ 0.15 \times 1.004 \ \ln\left(\frac{1373.15}{823.15}\right) = 22.57 \text{ kW}$$

her we used Eq.8.25 for the change in s of the air.

Energy Eq. heat engine:

$$\dot{W}_{NET} = \dot{Q}_H - \dot{Q}_L = 82.83 - 22.57 = \mathbf{60.26\ kW}$$





10.59

Find the change in availability from inlet to exit of the condenser in Problem 9.42.

Solution:

Condenser of Prob. 9.42 has inlet equal to turbine exit.

State 2: $P_2 = 20$ kPa; $s_2 = s_1 = 6.7993$ kJ/kg K

$\Rightarrow\ x_2 = (6.7993 - 0.8319)/7.0766 = 0.8433$

$h_2 = 2240.1$ kJ/kg

State 3: $P_2 = P_3$; $T_3 = 40°C$; Compressed liquid assume sat.liq. same T

Table B.1.1 $h_3 = 167.5$ kJ/kg; $s_3 = 0.5724$ kJ/kg K

From Eq.10.24 or 10.37

$$\psi_3 - \psi_2 = (h_3 - T_o s_3) - (h_2 - T_o s_2)$$

$$= (h_3 - h_2) - T_o(s_3 - s_2)$$

$$= (167.5 - 2240.1) - 298.2(0.5724 - 6.7993)$$

$$= -2072.6 + 1856.9 = \mathbf{-215.7\ kJ/kg}$$

10.60

Refrigerant R-12 at 30°C, 0.75 MPa enters a steady flow device and exits at 30°C, 100 kPa. Assume the process is isothermal and reversible. Find the change in availability of the refrigerant.

Solution:

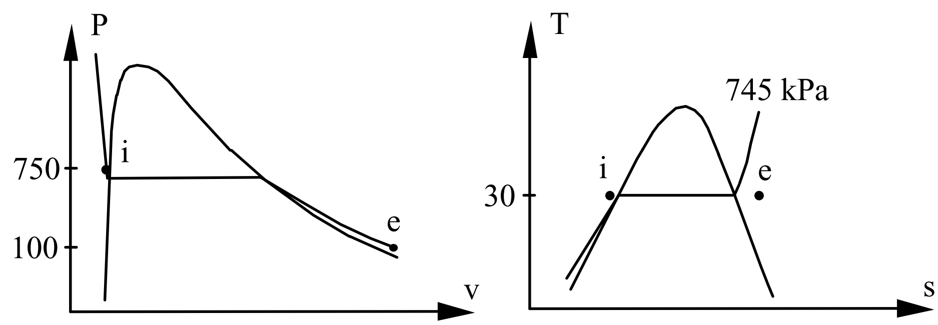
Table B.3.1: $h_i = 64.59$ kJ/kg, $s_i = 0.2399$ kJ/kg K, compr. liquid.

Table B.3.2: $h_e = 210.02$ kJ/kg, $s_e = 0.8488$ kJ/kg K, sup. vapor

From Eq. 10.24 or 10.37

$$\Delta\psi = h_e - h_i - T_0(s_e - s_i) = 210.02 - 64.59 - 298.15(0.8488 - 0.2399)$$

$$= \mathbf{-36.1\ kJ/kg}$$



Remark: Why did the availability drop? The exit state is much closer to the ambient dead state, so it lost its ability to expand and do work.

10.61

An air compressor is used to charge an initially empty 200-L tank with air up to 5 MPa. The air inlet to the compressor is at 100 kPa, 17°C and the compressor isentropic efficiency is 80%. Find the total compressor work and the change in availability of the air.

C.V. Tank + compressor Transient process with constant inlet conditions, no heat transfer.

Continuity: $m_2 - m_1 = m_{in}$ $(m_1 = 0)$ Energy: $m_2u_2 = m_{in}h_{in} - {}_1W_2$

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

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

State 1: $v_1 = RT_1/P_1 = 0.8323\ m^3/kg$,

State inlet, Table A.7.1: $h_{in} = 290.43$ kJ/kg, $s^o_{Tin} = 6.83521$ kJ/kg K

Eq.8.28: $s^o_{T2} = s^o_{Tin} + R \ln (\frac{P_2}{P_{in}}) = 6.83521 + 0.287 \ln (\frac{5000}{100}) = 7.95796$

Table A.7.1 $\Rightarrow$ $T_{2,s} = 854.6$ K, $u_{2,s} = 637.25$ kJ/kg

$\Rightarrow$ ${}_1w_{2,s} = h_{in} - u_{2,s} = 290.43 – 637.25 = -346.82$ kJ/kg

Actual compressor: ${}_1w_{2,AC} = {}_1w_{2,s}/\eta_c = -433.53$ kJ/kg

$u_{2,AC} = h_{in} - {}_1w_{2,AC} = 290.43 –(-433.53) = 723.96$ kJ/kg

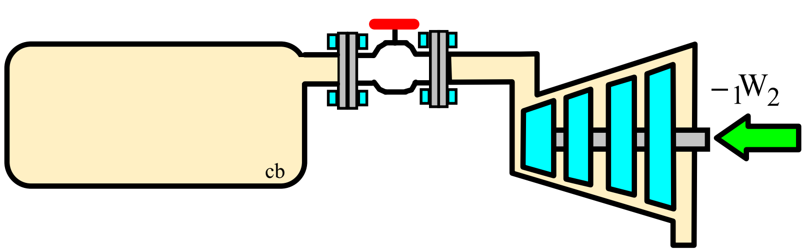
$\Rightarrow$ $T_{2,AC} = 958.5$ K, $s^o_{T2\ ac} = 8.08655$ kJ/kg K

State 2 $\boxed{u, P}$ $v_2 = RT_2/P_2 = 0.05502\ m^3/kg$ so $m_2 = V_2/v_2 = 3.635$ kg

$\Rightarrow$ ${}_1W_2 = m_2 ({}_1w_{2,AC}) =$ **-1575.9 kJ**

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

$= 3.635\ [723.96 - 207.19 + 100(0.05502 - 0.8323) - 290[8.08655 - 6.83521 - 0.287 \ln(5000/100)] =$ **1460.4 kJ**



10.62

Water as saturated liquid at 200 kPa goes through a constant pressure heat exchanger as shown in Fig. P10.62. The heat input is supplied from a reversible heat pump extracting heat from the surroundings at 17°C. The water flow rate is 2 kg/min and the whole process is reversible, that is, there is no overall net entropy change. If the heat pump receives 40 kW of work find the water exit state and the increase in availability of the water.

C.V. Heat exchanger + heat pump.

$\dot{m}_1 = \dot{m}_2 = 2$ kg/min, $\dot{m}_1 h_1 + \dot{Q}_0 + \dot{W}_{in} = \dot{m}_1 h_2$, $\dot{m}_1 s_1 + \dot{Q}_0/T_0 = \dot{m}_1 s_2$

Substitute $\dot{Q}_0$ into energy equation and divide by $\dot{m}_1$

$$h_1 - T_0 s_1 + w_{in} = h_2 - T_0 s_2$$

LHS = 504.7 - 290.15 × 1.5301 + 40×60/2 = 1260.7 kJ/kg

State 2: P_2, $h_2 - T_0 s_2 = 1260.7$ kJ/kg

At sat. vap. $h_g - T_0 s_g = 638.8$ so state 2 is superheated vapor at 200 kPa.

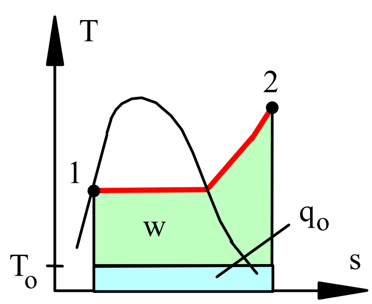
At 600°C: $h_2 - T_0 s_2 = 3703.96 - 290.15 \times 8.7769 = 1157.34$ kJ/kg

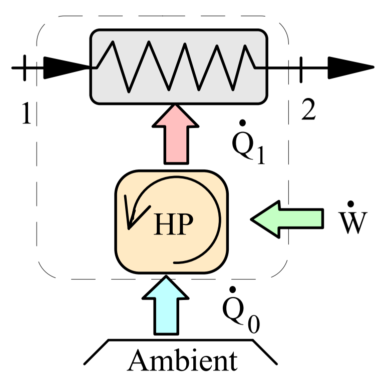
At 700°C: $h_2 - T_0 s_2 = 3927.66 - 290.15 \times 9.0194 = 1310.68$ kJ/kg

Linear interpolation ⇒ $\mathbf{T_2 = 667°C}$

$\Delta\psi = (h_2 - T_0 s_2) - (h_1 - T_0 s_1) = w_{in} =$ **1200 kJ/kg**

= 1260.7 - 504.7 + 290.15 × 1.5301 ≈ **1200 kJ/kg**





10.63

An electric stove has one heating element at 300°C getting 500 W of electric power. It transfers 90% of the power to 1 kg water in a kettle initially at 20°C, 100 kPa, 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}.

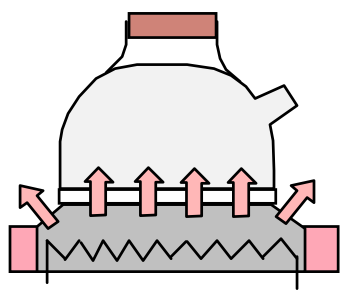
a) Work is availability $\dot{\Phi} = \dot{W} =$ **500 W**

b) Heat transfer at 300°C is only partly availability

$$\dot{\Phi} = \left(1 - \frac{T_o}{T_H}\right) \dot{Q} = \left(1 - \frac{293.15}{273.15 + 300}\right) 500 = \mathbf{244\ W}$$

c) Water receives heat transfer at 20°C as 90% of 500 W

$$\dot{\Phi} = \left(1 - \frac{T_o}{T_{water}}\right) \dot{Q} = \left(1 - \frac{293.15}{273.15 + 20}\right) 450 = \mathbf{0\ W}$$



500 W at 300°C

10.64

Calculate the availability of the water at the initial and final states of Problem 8.70, and the irreversibility of the process.

State properties

1: $u_1 = 83.94$ kJ/kg, $s_1 = 0.2966$ kJ/kg K, , $v_1 = 0.001$ m^3/kg

2: $u_2 = 3124.3$ kJ/kg, $s_2 = 7.7621$ kJ/kg K, $v_2 = 0.354$ m^3/kg

0: $u_o = 104.86$ kJ/kg, $s_o = 0.3673$ kJ/kg K, $v_o = 0.001003$ m^3/kg

Process transfers: ${}_1W_2^{ac} = 203$ kJ, ${}_1Q_2^{ac} = 3243.4$ kJ, $T_H = 873.15$ K

$\phi = (u - T_o s) - (u_o - T_o s_o) + P_o(v - v_o)$

$\phi_1 = (83.94 - 298.15\times0.2966) - (104.86 - 298.15\times0.3673)$

$+ 100\ (0.001002 - 0.001003) = 0.159$ kJ/kg

$\phi_2 = (3124.3 - 298.15\times7.7621) - (104.86 - 298.15\times0.3673)$

$+ 100\ (0.35411 - 0.001003) = 850$ kJ/kg

$${}_1I_2 = m(\phi_1 - \phi_2) + [1 - (T_0/T_H)]\,{}_1Q_2^{ac} - {}_1W_2^{ac} + P_o(V_2 - V_1)$$

$$= -849.84 + (1 - \frac{298.15}{873.15})\ 3243.4 - 203 + 100\ (0.3541 - 0.001)$$

$= -849.84 + 2135.9 - 203 + 35.31 =$ **1118. kJ**

[($S_{gen} = 3.75$ kJ/K $\quad T_o S_{gen} = 1118$ kJ so OK]

10.65

A 10-kg iron disk brake on a car is initially at 10°C. Suddenly the brake pad hangs up, increasing the brake temperature by friction to 110°C 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%.

Solution:

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

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

$${}_1Q_2 = 10 \times 0.45 \times (110 - 10) = 450 \text{ kJ}$$

Neglect the work to the surroundings at P_0, so change in availability is from Eq.10.27

$$\Delta\phi = m(u_2 - u_1) - T_0 m(s_2 - s_1)$$

Change in s for a solid, Eq.8.20

$$m(s_2\text{-}s_1) = mC \ln(T_2/T_1) = 10 \times 0.45 \times \ln\left(\frac{383.15}{283.15}\right) = 1.361 \text{ kJ/K}$$

$$\Delta\phi = 450 - 283.15 \times 1.361 = \mathbf{64.63\ kJ}$$

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

$$Q_{gas} = {}_1Q_2/\eta_{th} = 450/0.35 = \mathbf{1285.7\ kJ}$$

10.66

A 1 kg block of copper at 350°C is quenched in a 10 kg oil bath initially at ambient temperature of 20°C. Calculate the final uniform temperature (no heat transfer to/from ambient) and the change of availability of the system (copper and oil).

Solution:

C.V. Copper and oil. C_{co} = 0.42 kJ/kg K, C_{oil} = 1.8 kJ/kg K

$$m_2u_2 - m_1u_1 = {}_1Q_2 - {}_1W_2 = 0 = m_{co}C_{co}(T_2 - T_1)_{co} + (mC)_{oil}(T_2 - T_1)_{oil}$$

$$1 \times 0.42\ (T_2 - 350) + 10 \times 1.8\ (T_2 - 20) = 0$$

$$18.42\ T_2 = 507 \quad \Rightarrow \quad T = 27.5°\text{C} = 300.65\ \text{K}$$

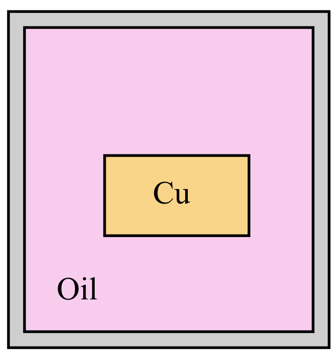
For each mass copper and oil, we neglect work term (v = C) so Eq.10.22 is

$$(\phi_2 - \phi_1) = u_2 - u_1 - T_o(s_2 - s_1) = mC\ [(T_2 - T_1) - T_o \ln (T_2 / T_1)]$$

$$m_{cv}(\phi_2 - \phi_1)_{cv} + m_{oil}\ (\phi_2 - \phi_1)_{oil} =$$

$$= 0.42 \times [(-322.5) - 293.15 \ln \frac{300.65}{623.15}] + 10 \times 1.8\ [7.5 - 293.15 \ln \frac{300.65}{293.15}]$$

$$= -45.713 + 1.698 = \mathbf{-44.0\ kJ}$$



10.67

Calculate the availability of the system (aluminum plus gas) at the initial and final states of Problem 8.137, and also the process irreversibility.

State 1: $T_1 = 200\ ^oC$, $v_1 = V_1/\ m = 0.05\ /\ 1.1186 = 0.0447\ m^3/kg$

State 2: $v_2 = v_1 \times (2\ /\ 1.5) \times (298.15\ /\ 473.15) = 0.03756\ m^3/kg$

The metal does not change volume, so the combined is using Eq.10.22 as

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

$$= m_{gas}[u_1\text{-}u_o\text{-}T_o(s_1 - s_o)]_{cv} + m_{gas}P_o(v_1\text{-}v_o) + m_{Al}[u_1\text{-}u_o - T_o(s_1\text{-}s_o)]_{Al}$$

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

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

$$\phi_1 = 1.1186\ [\ 0.653(200\text{-}25) - 298.15\ (0.842 \ln\frac{473.15}{298.15} - 0.18892 \ln\frac{2000}{100}\ )$$

$$+ 100\ (0.0447 - 0.5633\ )\ ] + 4 \times 0.90\ [\ 200 - 25 - 298.15 \ln\frac{473.15}{298.15}\ ]$$

$$= 128.88 + 134.3 = 263.2\ kJ$$

$$\phi_2 = 1.1186\ [\ 0.653(25 - 25) - 298.15\ (0.842 \ln\frac{298.15}{298.15} - 0.18892 \ln\frac{1500}{100}\ )$$

$$+ 100\ (0.03756 - 0.5633\ )\ ] + 4 \times 0.9\ [\ 25 - 25 - 298.15 \ln\frac{298.15}{298.15}\ ]$$

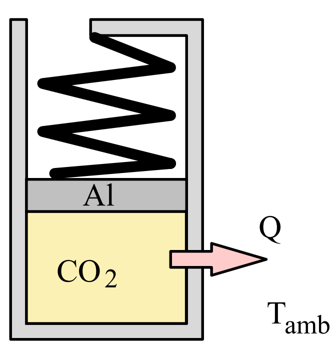
$$= 111.82 + 0 = 111.82\ kJ$$

The irreversibility is as in Eq.10.28

$$_1I_2 = \phi_1 - \phi_2 + [1 - (T_0/T_H)]\ _1Q_2 - {}_1W_2^{AC} + P_om(\ V_2 - V_1)$$

$$= 263.2 - 111.82 + 0 - (-14) + 100 \times 1.1186\ (0.03756 - 0.0447) = 164.58\ kJ$$

$[(S_{gen} = 0.552$ $\quad T_oS_{gen} = 164.58$ so OK]

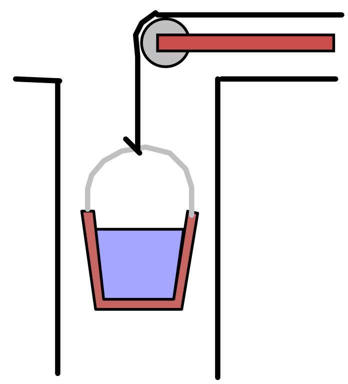


10.68

A wooden bucket (2 kg) with 10 kg hot liquid water, both at 85°C, is lowered 400 m down into a mineshaft. What is the availability of the bucket and water with respect to the surface ambient at 20°C?

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 A.3 for wood and table B.1.1 (sat. liq.) for water.
From Eq.10.27

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

$$= 2[1.26(85 - 20) - 293.15 \times 1.26 \ln\frac{273.15 + 85}{293.15}] + 10[\, 355.82 - 83.94$$

$$- 293(1.1342 - 0.2966)] + 12 \times 9.807 \times (-400) /1000$$

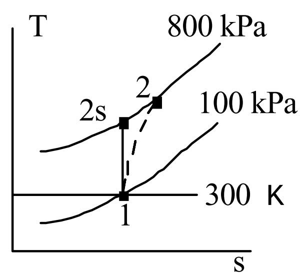
$$= 15.85 + 263.38 - 47.07 = \mathbf{232.2\ kJ}$$

Device Second-Law Efficiency

10.69

Air enters a compressor at ambient conditions, 100 kPa, 300 K, and exits at 800 kPa. If the isentropic compressor efficiency is 85%, what is the second-law efficiency of the compressor process?

Solution:



Ideal (isentropic, Eq.8.32)

$$T_{2s} = 300(8)^{0.286} = 543.8 \text{ K}$$

$$-w_s = 1.004(543.8 - 300) = 244.6 \text{ kJ/kg}$$

$$-w = \frac{-w_s}{\eta_s} = \frac{244.6}{0.85} = 287.8 \text{ kJ/kg K}$$

$$T_2 = T_1 + \frac{-w}{C_{P0}} = 300 + \frac{287.8}{1.004} = 586.8 \text{ K}$$

Eq.8.25: $s_2 - s_1 = 1.004 \ln(586.8/300) - 0.287 \ln 8 = 0.07645$

Availability, Eq.10.24

$$\psi_2 - \psi_1 = (h_2 - h_1) - T_0(s_2 - s_1) = 287.8 - 300(0.07645) = 264.9 \text{ kJ/kg}$$

2nd law efficiency, Eq.10.29 or 10.30 (but for a compressor):

$$\eta_{2nd\ Law} = \frac{\psi_2 - \psi_1}{-w} = \frac{264.9}{287.8} = \mathbf{0.92}$$

10.70

A compressor takes in saturated vapor R-134a at –20°C and delivers it at 30°C, 0.4 MPa. Assuming that the compression is adiabatic, find the isentropic efficiency and the second law efficiency.

Solution:

Table B.5 Inlet: $h_i = 386.08$ kJ/kg, $s_i = 1.7395$ kJ/kg K,

Actual exit: $h_{e,ac} = 423.22$ kJ/kg, $s_{e,ac} = 1.7895$ kJ/kg K

Ideal exit: P_e, $s_{e,s} = s_i \Rightarrow h_{e,s} = 408.51$ kJ/kg

Isentropic compressor $w_{c,s} = h_{e,s} - h_i = 22.43$ kJ/kg

Actual compressor $w_{c,ac} = h_{e,ac} - h_i = 37.14$ kJ/kg

Reversible between inlet and actual exit Eq.10.9

$-w_{c,rev} = h_i - h_{e,ac} - T_0(s_i - s_{e,ac}) = -37.14 - 298.15(1.7395 - 1.7895) = -22.23$

Eq.9.27: $\eta_s = (w_{c,s}/w_{c,ac}) = (22.43/37.14) = \mathbf{0.604}$

Second law efficiency for compressor, Eq.10.32 (modified)

$\eta_{II} = (w_{c,rev}/w_{c,ac}) = (22.23/37.14) = \mathbf{0.599}$

10.71

A steam turbine has inlet at 4 MPa, 500°C and actual exit of 100 kPa, x = 1.0. Find its first law (isentropic) and its 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 B.1.3 $h_i = 3445.2$ kJ/kg; $s_i = 7.0900$ kJ/kg K

Exit (actual) state: Table B.1.2 $h_e = 2675.5$; $s_e = 7.3593$ kJ/kg K

Actual turbine energy equation

$$w = h_i - h_e = 769.7 \text{ kJ/kg}$$

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

$$s_{es} = s_i = 70900 = 1.3025 + x_{es} \times 6.0568$$

$$x_{es} = 0.9555, \quad h_{es} = 417.4 + 0.9555 \times 2258.0 = 2575.0 \text{ kJ/kg}$$

The energy equation for the ideal gives

$$w_s = h_i - h_{es} = 870.2 \text{ kJ/kg}$$

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

$$\eta_s = w/w_s = \mathbf{0.885}$$

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

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

$$= 769.7 + 298.2(7.3593 - 7.0900)$$

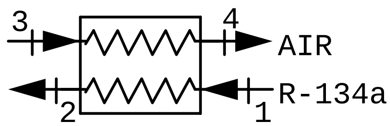
$$= 769.7 + 80.3 = 850.0 \text{ kJ/kg}$$

Second law efficiency Eq.10.29

$$\eta_{2^{nd}\text{ Law}} = w/w_{rev} = 769.7/850.0 = \mathbf{0.906}$$

10.72

The condenser in a refrigerator receives R-134a at 700 kPa, 50°C and it exits as saturated liquid at 25°C. The flowrate is 0.1 kg/s and the condenser has air flowing in at ambient 15°C and leaving at 35°C. Find the minimum flow rate of air and the heat exchanger second-law efficiency.



C.V. Total heat exchanger.
Energy Eq.6.10

$$\dot{m}_1 h_1 + \dot{m}_a h_3 = \dot{m}_1 h_2 + \dot{m}_a h_4$$

$$\Rightarrow \quad \dot{m}_a = \dot{m}_1 \times \frac{h_1 - h_2}{h_4 - h_3} = 0.1 \times \frac{436.89 - 234.59}{1.004(35 - 15)} = \mathbf{1.007\ kg/s}$$

Availability from Eq.10.24

$$\psi_1 - \psi_2 = h_1 - h_2 - T_0(s_1 - s_2) = 436.89 - 234.59$$

$$- 288.15(1.7919 - 1.1201) = 8.7208 \text{ kJ/kg}$$

$$\psi_4 - \psi_3 = h_4 - h_3 - T_0(s_4 - s_3)$$

$$= 1.004(35 - 15) - 288.15 \times 1.004 \times \ln \frac{308.15}{288.15} = +0.666 \text{ kJ/kg}$$

Efficiency from Eq.10.30

$$\eta_{II} = \dot{m}_a(\psi_4 - \psi_3)/\dot{m}_1(\psi_1 - \psi_2) = \frac{1.007(0.666)}{0.1(8.7208)} = \mathbf{0.77}$$

10.73

Steam enters a turbine at 25 MPa, 550°C and exits at 5 MPa, 325°C at a flow rate of 70 kg/s. Determine the total power output of the turbine, its isentropic efficiency and the second law efficiency.

Solution:

h_i = 3335.6 kJ/kg, s_i = 6.1765 kJ/kg K,

h_e = 2996.5 kJ/kg, s_e = 6.3289 kJ/kg K

Actual turbine: $w_{T,ac} = h_i - h_e = 339.1$ kJ/kg

Isentropic turbine: $s_{e,s} = s_i \Rightarrow h_{e,s} = 2906.6$ kJ/kg

$w_{T,s} = h_i - h_{e,s} = 429$ kJ/kg

Rev. turbine: $w_{rev} = w_{T,ac} + T_0(s_e - s_i) = 339.1 + 45.44 = 384.54$ kJ/kg

Eq.9.27: $\eta_T = w_{T,ac}/w_{T,s} = 339.1/429 = \mathbf{0.79}$

Eq.10.29: $\eta_{II} = w_{T,ac}/w_{rev} = 339.1/384.54 = \mathbf{0.88}$

10.74

A compressor is used to bring saturated water vapor at 1 MPa up to 17.5 MPa, where the actual exit temperature is 650°C. Find the irreversibility and the second-law efficiency.

Solution:

Inlet state: Table B.1.2 $h_i = 2778.1$ kJ/kg, $s_i = 6.5864$ kJ/kg K

Actual compressor Table B.1.3: $h_{e,ac} = 3693.9$ kJ/kg, $s_{e,ac} = 6.7356$ kJ/kg K

Energy Eq. Actual compressor: $-w_{c,ac} = h_{e,ac} - h_i = 915.8$ kJ/kg

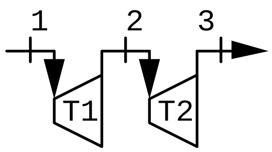
From Eq.10.11: $i = T_0(s_{e,ac} - s_i) = 298.15\ (6.7356 - 6.5864) =$ **44.48 kJ/kg**

From Eq.10.10: $w_{rev} = i + w_{c,ac} = -915.8 + 44.48 = -871.32$ kJ/kg

$\eta_{II} = -w_{rev}/w_{c,ac} = 871.32/915.8 =$ **0.951**

10.75

A flow of steam at 10 MPa, 550°C goes through a two-stage turbine. The pressure between the stages is 2 MPa and the second stage has an exit at 50 kPa. Assume both stages have an isentropic efficiency of 85%. Find the second law efficiencies for both stages of the turbine.



CV: T1, $h_1 = 3500.9$ kJ/kg, $s_1 = 6.7561$ kJ/kg K

Isentropic $s_{2s} = s_1 \Rightarrow h_{2s} = 3017.9$ kJ/kg

$w_{T1,s} = h_1 - h_{2s} = 483$ kJ/kg

Actual T1: $w_{T1,ac} = \eta_{T1}\, w_{T1,s} = 410.55 = h_1 - h_{2ac}$

$h_{2ac} = h_1 - w_{T1,ac} = 3090.35, \quad s_{2ac} = 6.8782$

CV: T2, $s_{3s} = s_{2ac} = 6.8782 \Rightarrow x_{3s} = (6.8782\text{-}1.091)/6.5029 = 0.8899,$

$h_{3s} = 340.47 + 0.8899 \times 2305.4 = 2392.2$ kJ/kg

$w_{T2,s} = h_{2ac} - h_{3s} = 698.15 \Rightarrow w_{T2,ac} = \eta_{T2}\, w_{T2,s} = 593.4$ kJ/kg

$\Rightarrow h_{3ac} = 2496.9, \quad x_{3ac} = (2496.9 - 340.47)/2305.4 = 0.9354,$

$s_{3ac} = 1.091 + 0.9354 \times 6.5029 = 7.1736$ kJ/kg K

Actual T1: $i_{T1,ac} = T_0(s_{2ac}\text{-}s_1) = 298.15(6.8782 - 6.7561) = 36.4$ kJ/kg

$\Rightarrow w^R_{T1} = w_{T1,ac} + i = 447$ kJ/kg, $\quad \eta_{II} = w_{T1,ac}/w^R_{T1} = \mathbf{0.918}$

Actual T2: $i_{T2,ac} = T_0(s_{3ac}\text{-}s_{2ac}) = 298.15(7.1736 - 6.8782) = 88.07$ kJ/kg

$\Rightarrow w^R_{T2} = w_{T2,ac} + i_{T2,ac} = 681.5, \quad \eta_{II} = w_{T2,ac}/w^R_{T2} = \mathbf{0.871}$

10.76

The simple steam power plant shown in Problem 6.99 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.

Solution:

interpolation or software: $h_5 = 3404.3$ kJ/kg, $s_5 = 6.8953$ kJ/kg K

Table B.1.2: $x_6 = 0.92$ so $h_6 = 2393.2$ kJ/kg, $s_6 = 7.5501$ kJ/kg K

Flow availability (exergy) from Eq.10.24

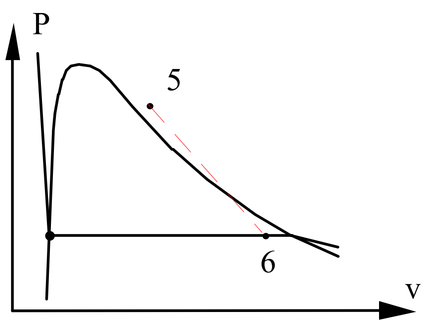
$\psi_6 = h_6 - h_0 - T_0(s_6 - s_0)$

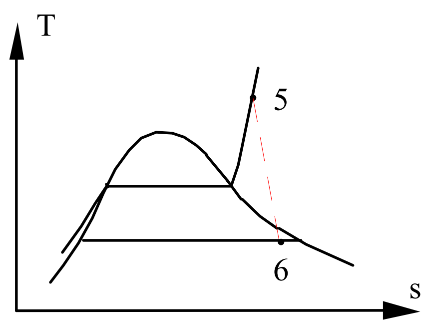
$= 2393.2 - 104.89 - 298.15(6.8953 - 0.3674) =$ **146.79 kJ/kg**

In the absence of heat transfer the work is form Eq.10.9 or 10.39

$w^{rev} = \psi_5 - \psi_6 = h_5 - h_6 - T_0(s_5 - s_6) = 1206.3$ kJ/kg

$w_{ac} = h_5 - h_6 = 1011.1$ kJ/kg; $\eta_{II} = w_{ac}/w^{rev} =$ **0.838**





10.77

A steam turbine inlet is at 1200 kPa, 500^{o}C. The actual exit is at 200 kPa, 300^{o}C. What are the isentropic efficiency and its second law efficiency?

Solution:

C.V. Turbine actual, steady state and adiabatic.

Inlet state: Table B.1.3: h_i = 3476.28 kJ/kg, s_i = 7.6758 kJ/kg K

Exit state: Table B.1.3: h_e = 3071.79 kJ/kg, s_e = 7.8926 kJ/kg K

Energy Eq.: $w_{Tac} = h_i - h_e = 3476.28 – 3071.79 = 404.49$ kJ/kg

C.V. Turbine isentropic, steady state, reversible and adiabatic.

Isentropic exit state: 200 kPa, $s = s_i$ => h_{es} = 2954.7 kJ/kg

Energy eq.: $w_{T\,s} = h_i - h_{es} = 3476.28 – 2954.7 = 521.58$ kJ/kg

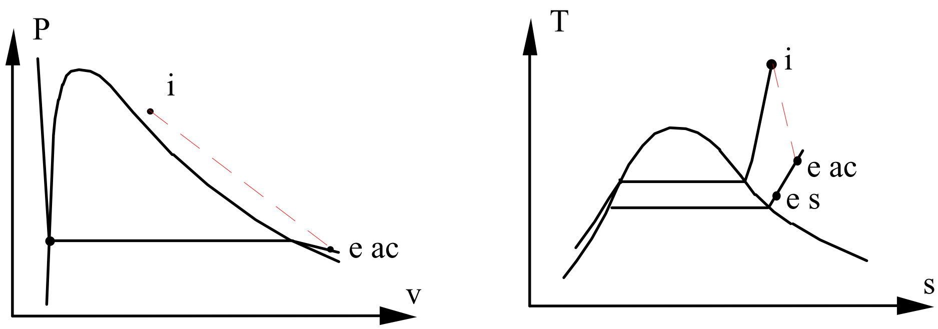
$$\eta_I = w_{Tac}/w_{T\,s} = \frac{404.49}{521.58} = \mathbf{0.776}$$

Reversible work for actual turbine is from Eq.10.9 or 10.39

$$w_T^{rev} = \psi_i - \psi_e = h_i - h_e - T_0(s_i - s_e) = w_{Tac} - T_0(s_i - s_e)$$
$$= 404.49 – 298.15(7.6758 – 7.8926) = 469.13 \text{ kJ/kg}$$

Then the second law efficiency is in Eq.10.29

$$\eta_{II} = w_{Tac}/w_T^{rev} = \frac{404.49}{469.13} = \mathbf{0.862}$$



10.78

Steam is supplied in a line at 3 MPa, 700°C. A turbine with an isentropic efficiency of 85% is connected to the line by a valve and it exhausts to the atmosphere at 100 kPa. If the steam is throttled down to 2 MPa 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.

Take C.V. as valve and a C.V. as the turbine.

Valve: $h_2 = h_1 = 3911.7$ kJ/kg, $s_2 > s_1 = 7.7571$ kJ/kg K,

$h_2, P_2 \Rightarrow s_2 = 7.9425$ kJ/kg K

$\psi_1 - \psi_2 = h_1 - h_2 - T_0(s_1 - s_2) = 0 - 298.15(7.7571 - 7.9425) =$ **55.3 kJ/kg**

So some potential work is lost in the throttling process.

Ideal turbine: $s_3 = s_2 \Rightarrow h_{3s} = 2929.13$ $\quad w_{T,s} = 982.57$ kJ/kg

$w_{T,ac} = h_2 - h_{3ac} = \eta w_{T,s} =$ **835.2 kJ/kg**

$h_{3ac} = 3911.7 - 835.2 = 3076.5 \Rightarrow s_{3ac} = 8.219$ kJ/kg K

$w^{rev} = h_2 - h_{3ac} - T_0(s_2 - s_{3ac}) = 835.2 - 298.15(7.9425 - 8.219)$

$= 917.63$ kJ/kg $\Rightarrow$ $\eta_{II} = 835.2/917.63 =$ **0.91**

10.79

Air flows into a heat engine at ambient conditions 100 kPa, 300 K, as shown in Fig. P10.79. Energy is supplied as 1200 kJ per kg air from a 1500 K source and in some part of the process a heat transfer loss of 300 kJ/kg air happens at 750 K. The air leaves the engine at 100 kPa, 800 K. Find the first and the second law efficiencies.

C.V. Engine out to reservoirs

$h_i + q_{1500} = q_{750} + h_e + w$

$w_{ac} = 300.47 + 1200 - 300 - 822.20 = 378.27$ kJ/kg

$\eta_{TH} = w/q_{1500} = 0.3152$

For second law efficiency also a q to/from ambient

$s_i + (q_{1500}/T_H) + (q_0/T_0) = (q_{750}/T_m) + s_e$

$q_0 = T_0(s_e - s_i) + (T_0/T_m)q_{750} - (T_0/T_H)q_{1500}$

$$= 300\left(7.88514 - 6.86925 - 0.287 \ln\frac{100}{100}\right) + \frac{300}{750}\,300$$

$$-(300/1500)\ 1200 = 184.764 \text{ kJ/kg}$$

$w_{rev} = h_i - h_e + q_{1500} - q_{750} + q_0 = w_{ac} + q_0 = 563.03$ kJ/kg

$\eta_{II} = w_{ac}/w_{rev} = 378.27/563.03 =$ **0.672**

10.80

Air enters a steady-flow turbine at 1600 K and exhausts to the atmosphere at 1000 K. The second law efficiency is 85%. What is the turbine inlet pressure?

C.V.: Turbine, exits to atmosphere so assume $P_e = 100$ kPa

Inlet: $T_i = 1600$ K, Table A.7: $h_i = 1757.3$ kJ/kg, $s^o_i = 8.1349$ kJ/kg K

Exit: $T_e = 1000$ K, $h_e = 1046.2$ kJ/kg, $s^o_e = 8.6905$ kJ/kg K

1st Law: $q + h_i = h_e + w;\ q = 0 \quad => \quad w = (h_i - h_e) = 711.1$ kJ/kg

2nd Law: $\psi_i - \psi_e = w/\eta_{2ndLaw} = 711.1/0.85 = 836.6$ kJ/kg

$\psi_i - \psi_e = (h_i - h_e) - T_o(s_i - s_e) = 836.6$ kJ/kg

$h_i - h_e = w = 711.1$ kJ/kg, assume $T_o = 25^oC \rightarrow s_i - s_e = 0.4209$ kJ/kg-K

$s_i - s_e = s^o_e - s^o_i - R \ln(P_i/P_e) = 0.4209$ kJ/kg K $\quad => \quad P_e/P_i = 30.03;$

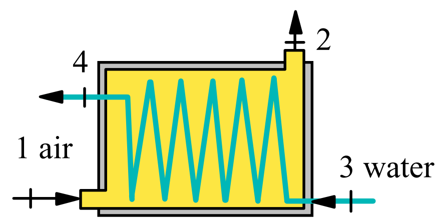
$P_i =$ **3003 kPa**

10.81

Calculate the second law efficiency of the counter flowing heat exchanger in Problem 9.61 with an ambient at 20°C.

Solution:

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.



Heat exchanger Prob 9.61 with T_o = 20°C solve first for state 4.

Energy Eq.6.10: $\dot{m}_{AIR}\Delta h_{AIR} = \dot{m}_{H2O}\Delta h_{H2O}$

From A.7: $h_1 - h_2 = 1046.22 – 401.3 = 644.92$ kJ/kg

From B.1.2 $h_3 = 83.94$ kJ/kg; $s_3 = 0.2966$ kJ/kg K

$h_4 - h_3 = (\dot{m}_{AIR}/\dot{m}_{H2O})(h_1 - h_2) = (2/0.5)644.92 = 2579.68$ kJ/kg

$h_4 = h_3 + 2579.68 = 2663.62 < h_g$ at 200 kPa

$T_4 = T_{sat} = 120.23$°C,

$x_4 = (2663.62 – 504.68)/2201.96 = 0.9805$,

$s_4 = 1.53 + x_4\ 5.597 = 7.01786$ kJ/kg K

We need the change in availability for each flow from Eq.10.24

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

$= (1046.2 – 401.3) + 293.2(7.1593 – 8.1349 – 0.287 \ln(100/125))$

$= 644.9 + 293.2(-0.91156) = 377.6$ kJ/kg

$(\psi_4 - \psi_3) = (h_4 - h_3) + T_o(s_4 - s_3)$

$= (2663.6 – 83.9) – 293.2(7.0179 – 0.2966)$

$= 2579.9 – 1970.7 = 609.0$

Efficiency from Eq.10.30

$\eta_{2^{nd}\ Law} = [\dot{m}_w(\psi_4 - \psi_3)]/[\dot{m}_A(\psi_1 - \psi_2)]$

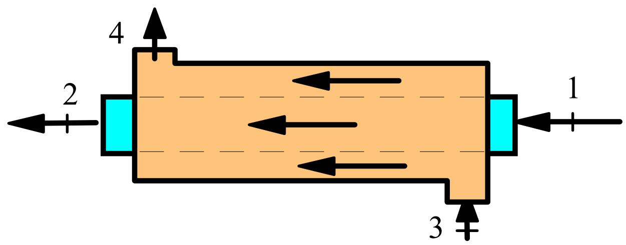
$= (0.5 \times 609.0)/(2 \times 377.6) =$ **0.403**

10.82

Calculate the second law efficiency of the coflowing heat exchanger in Problem 9.62 with an ambient at 17°C.

Solution:

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



First solve for the exit temperature in Problem 9.62

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 A.5

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

$$T_2 = \frac{0.25 \times 0.922 \times 290 + 0.6 \times 1.042 \times 500}{0.25 \times 0.922 + 0.6 \times 1.042} = \frac{379.45}{0.8557}$$

$$= \mathbf{443.4\ K}$$

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. We thus have to find the change of availability in both flows.

For each flow availability is Eq.10.24 include mass flow rate as in Eq.10.36

For the oxygen flow:

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

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

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

$$= 0.25 \times 0.922 [\ 443.4 - 290 - 290 \ln(443.4/290)\ ]$$

$$= 6.977 \text{ kW}$$

For the nitrogen flow

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

$$= 0.6 \times 1.042 [\ 500 - 443.4 - 290 \ln(500/443.4)\ ]$$

$$= 13.6 \text{ kW}$$

From Eq.10.30

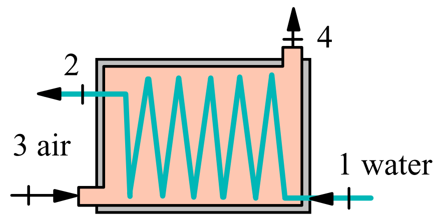
$$\eta_{2^{nd}\ Law} = \frac{\dot{m}_{O2}(\psi_1 - \psi_2)}{\dot{m}_{N2}(\psi_3 - \psi_4)} = \frac{6.977}{13.6} = \mathbf{0.513}$$

10.83

A heat exchanger brings 10 kg/s water from 100°C to 500°C at 2000 kPa using air coming in at 1400 K and leaving at 460 K. What is the second law efficiency?

Solution:

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. We need to find the air mass flow rate.



Energy Eq.: $\dot{m}_{H2O}(h_2 - h_1) = \dot{m}_{air}(h_3 - h_4)$

$$\dot{m}_{air} = \dot{m}_{H2O} \frac{h_2 - h_1}{h_3 - h_4} = 10 \frac{3467.55 - 420.45}{1515.27 - 462.34} = 28.939 \text{ kg/s}$$

Availability increase of the water flow

$$\dot{m}_{H2O}(\psi_2 - \psi_1) = \dot{m}_{H2O}[h_2 - h_1 - T_o(s_2 - s_1)]$$
$$= 10 \, [\, 3467.55 – 420.45 – 298.15(7.4316 – 1.3053)]$$
$$= 10 \, [\, 3047.1 – 1826.56 \,] = 12\,205 \text{ kW}$$

Availability decrease of the air flow

$$\dot{m}_{air}(\psi_3 - \psi_4) = \dot{m}_{air}[h_3 - h_4 – T_o(s_3 - s_4)]$$
$$= 28.939 \, [1515.27 – 462.34 – 298.15(8.52891 – 7.30142)]$$
$$= 19\,880 \text{ kW}$$

$$\eta_{2^{nd}\text{ Law}} = \frac{\dot{m}_{H2O}(\psi_2 - \psi_1)}{\dot{m}_{air}(\psi_3 - \psi_4)} = \frac{12\,205}{19\,880} = \mathbf{0.614}$$

Exergy Balance Equation

10.84

Find the specific flow exergy in and out of the steam turbine in Example 9.1 assuming an ambient at 293 K. Use the exergy balance equation to find the reversible specific work. Does this calculation of specific work depend on T_o?

Solution:

The specific flow exergy is from Eq. 10.37

$$\psi_i = h_i + \frac{1}{2}\mathbf{V}_i^2 - T_o s_i - (h_o - T_o s_o)$$

Reference state: $h_o = 83.94$ kJ/kg, $s_o = 0.2966$ kJ/kg K,

$$h_o - T_o s_o = -2.9638 \text{ kJ/kg}$$

The properties are listed in Example 9.1 so the specific flow exergies are

$$\psi_i = 3051.2 + 1.25 - 293 \times 7.1228 - (-2.9638) = \mathbf{968.43\ kJ/kg}$$

$$\psi_e = 2655.0 + 20 - 293 \times 7.1228 - (-2.9638) = \mathbf{590.98\ kJ/kg}$$

The reversible work is from Eq.10.39, with $q = 0$ and $s_{gen} = 0$, so

$$w = \psi_i - \psi_e = 968.43 - 590.98 = \mathbf{377.45\ kJ/kg}$$

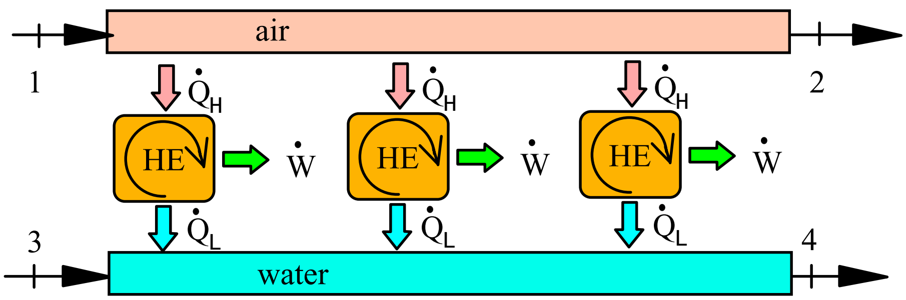
The offset T_o terms drop out as we take the difference and also ($s_i = s_e$)

$$\psi_i - \psi_e = h_i - h_e - T_o(s_i - s_e) = h_i - h_e$$

Notice since the turbine is reversible we get the same as in Example 9.1

10.85

A counterflowing heat exchanger cools air at 600 K, 400 kPa to 320 K using a supply of water at 20°C, 200 kPa. The water flow rate is 0.1 kg/s and the air flow rate is 1 kg/s. Assume this can be done in a reversible process by the use of heat engines and neglect kinetic energy changes. Find the water exit temperature and the power out of the heat engine(s).



C.V. Total

Energy eq.: $\dot{m}_a h_1 + \dot{m}_{H_2O} h_3 = \dot{m}_a h_2 + \dot{m}_{H_2O} h_4 + \dot{W}$

Entropy Eq,: $\dot{m}_a s_1 + \dot{m}_{H_2O} s_3 = \dot{m}_a s_2 + \dot{m}_{H_2O} s_4$ $(s_{gen} = 0)$

Table A.7: $h_1 = 607.316$ kJ/kg, $s^o_{T1} = 7.57638$ kJ/kg K

Table A.7: $h_2 = 320.576$ kJ/kg, $s^o_{T2} = 6.93413$ kJ/kg K,

Table B.1.1: $h_3 = 83.96$ kJ/kg, $s_3 = 0.2966$ kJ/kg K

From the entropy equation we first find state 4

$$s_4 = (\dot{m}_a/\dot{m}_{H_2O})(s_1 - s_2) + s_3 = (1/0.1)(7.57638 - 6.93413) + 0.2966 = 6.7191$$

4: $P_4 = P_3$, s_4 $\Rightarrow$ Table B.1.2: $x_4 = (6.7191-1.530)/5.597 = 0.9271$,

$$h_4 = 504.68 + 0.9271 \times 2201.96 = 2546.1 \text{ kJ/kg}, \quad T_4 = 120.20°C$$

From the energy equation

$$\dot{W} = \dot{m}_a(h_1 - h_2) + \dot{m}_{H_2O}(h_3 - h_4)$$

$$= 1(607.32 - 320.58) + 0.1(83.96 - 2546.1) = \mathbf{40.53\ kW}$$

10.86

Evaluate the steady state exergy fluxes due to a heat transfer of 250 W through a wall with 600 K on one side and 400 K on the other side. What is the exergy destruction in the wall.

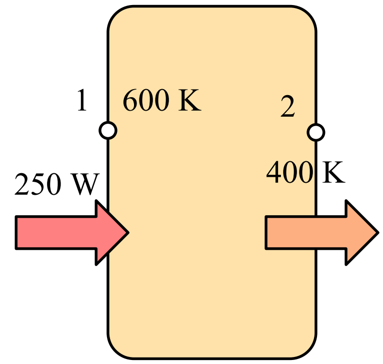
Solution:

Exergy flux due to a $\dot{Q}$ term Eq.10.36:

$$\dot{\Phi}_Q = (1 - \frac{T_o}{T})\,\dot{Q}$$

$$\dot{\Phi}_1 = (1 - \frac{T_o}{T_1})\,\dot{Q} = (1 - \frac{298}{600})\,250 = 125.8 \text{ W}$$

$$\dot{\Phi}_2 = (1 - \frac{T_o}{T_2})\,\dot{Q} = (1 - \frac{298}{400})\,250 = 63.8 \text{ W}$$



Steady state state so no storage and Eq.10.36 is

$$0 = \dot{\Phi}_1 - \dot{\Phi}_2 - \dot{\Phi}_{destr.}$$

$$\dot{\Phi}_{destr.} = \dot{\Phi}_1 - \dot{\Phi}_2 = 125.8 - 63.8 = \mathbf{62\ W}$$

10.87

A heat engine operating with an evironment at 298 K produces 5 kW of power output with a first law efficiency of 50%. It has a second law efficiency of 80% and T_L = 310 K. Find all the energy and exergy transfers in and out.

Solution:

From the definition of the first law efficiency

$$\dot{Q}_H = \dot{W} / \eta = \frac{5}{0.5} = \mathbf{10\ kW}$$

Energy Eq.: $\dot{Q}_L = \dot{Q}_H - \dot{W} = 10 – 5 = \mathbf{5\ kW}$

$$\dot{\Phi}_W = \dot{W} = \mathbf{5\ kW}$$

From the definition of the second law efficiency $\eta = \dot{W}/\dot{\Phi}_H$, this requires that we assume the availability delivered at 310 K is lost and not counted otherwise the efficiency should be $\eta = \dot{W}/(\dot{\Phi}_H - \dot{\Phi}_L)$.

$$\dot{\Phi}_H = (1 - \frac{T_o}{T_H})\ \dot{Q}_H = \frac{5}{0.8} = \mathbf{6.25\ kW}$$

$$\dot{\Phi}_L = (1 - \frac{T_o}{T_L})\ \dot{Q}_L = (1 - \frac{298}{310})\ 5 = \mathbf{0.194\ kW}$$

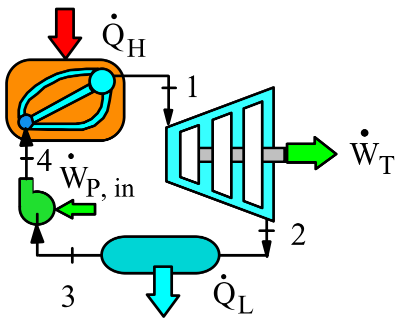
Notice from the $\dot{\Phi}_H$ form we could find the single characteristic T_H as

$$(1 - \frac{T_o}{T_H}) = 6.25\ \text{kW} / \dot{Q}_H = 0.625 \quad => \quad T_H = 795\ \text{K}$$

10.88

Consider the condenser in Problem 9.42. Find the specific energy and exergy that are given out, assuming an ambient at 20^{o}C. Find also the specific exergy destruction in the process.

Solution:



Condenser from state 2 to state 3

$P_2 = P_3 = 20$ kPa

$T_3 = 40$ °C

State 1: (P, T) Table B.1.3

$h_1 = 3809.1$ kJ/kg, $s_1 = 6.7993$ kJ/kg K

C.V. Turbine.

Entropy Eq.9.8: $s_2 = s_1 = 6.7993$ kJ/kg K

Table B.1.2 $s_2 = 0.8319 + x_2 \times 7.0766$ => $x_2 = 0.8433$

$h_2 = 251.4 + 0.8433\times 2358.33 = 2240.1$ kJ/kg

State 3: (P, T) Compressed liquid, take sat. liq. Table B.1.1

$h_3 = 167.54$ kJ/kg, $s_3 = 0.5724$ kJ/kg K

C.V. Condenser

Energy Eq.: $q_L = h_2 - h_3 = 2240.1 - 167.54 =$ **2072.56 kJ/kg**

Exergy Eq.: $\Delta\psi = \psi_2 - \psi_3 = h_2 - h_3 - T_o(s_2 - s_3)$

$= 2072.56 - 293.15(6.7993 - 0.5724)$

$=$ **247.1 kJ/kg** going out

Since all the exergy that goes out ends up at the ambient where it has zero exergy, the destruction equals the outgoing exergy.

$\psi_{destr} = \Delta\psi =$ **247.1 kJ/kg**

Notice the condenser gives out a large amount of energy byt little exergy.

10.89

The condenser in a power plant cools 10 kg/s water at 10 kPa, quality 90% so it comes out as saturated liquid at 10 kPa. The cooling is done by ocean-water coming in at ambient $15^{o}C$ and returned to the ocean at $20^{o}C$. 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.: $\dot{Q}_{out} = \dot{m}\,(h_1 - h_2) = 10(2345.35 - 191.81) =$ **21 535 kW**

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

Energy Eq.: $q = h_4 - h_3 = 83.94 - 62.98 = 20.96$ kJ/kg

$\dot{m}_{ocean} = \dot{Q}_{out} / q = 21\,535 / 20.96 = 1027.4$ kg/s

Exergy out of the water follows Eq.10.37

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

$= 10\,[\,2345.35 - 191.81 - 288.15(7.4001 - 0.6492)]$

= **2082.3 kW**

Exergy into the ocean water

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

$= 1027.4\,[\,20.96 - 288.15(0.2966 - 0.2245)]$

= **189.4 kW**

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

10.90

Use the exergy equation to analyze the compressor in Example 6.10 to find its second law efficiency assuming an ambient at 20^{o}C.

C.V. The R-134a compressor. Steady flow. We need to find the reversible work and compare that to the actual work.

Exergy eq.: 10.36: $0 = \dot{m}(\psi_1 - \dot{m}\psi_2) + (-\dot{W}^{rev}_{comp}) + 0$

$$-\dot{W}^{rev}_{comp} = \dot{m} [h_2 - h_1 - T_o (s_2 - s_1)]$$

$$= -\dot{W}^{ac}_{comp} - \dot{m}T_o (s_2 - s_1)$$

$$= 5 \text{ kW} – 0.1 \text{ kg/s} \times 293.15 \text{ K} \times (1.7768 – 1.7665) \frac{\text{kJ}}{\text{kg K}}$$

$$= 4.7 \text{ kW}$$

$$\eta_{II} = -\dot{W}^{rev}_{comp} / -\dot{W}^{ac}_{comp} = \frac{4.7}{5} = \mathbf{0.94}$$

For a real device this is a little high.

10.91

Consider the car engine in Example 7.1 and assume the fuel energy is delivered at a constant 1500 K. The 70% of the energy that is lost is 40% exhaust flow at 900 K and the remainder 30% heat transfer to the walls at 450 K goes on to the coolant fluid at 370 K, finally ending up in atmospheric air at ambient 20°C. Find all the energy and exergy flows for this heat engine. Find also the exergy destruction and where that is done.

From the example in the text we get: $\dot{Q}_L = 0.7\ \dot{Q}_H = 233$ kW

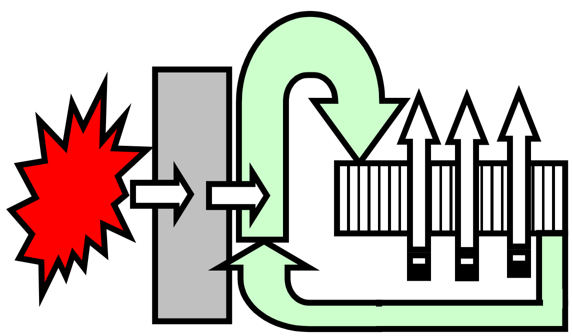
This is separated into two fluxes:

$\dot{Q}_{L1} = 0.4\ \dot{Q}_H = 133$ kW @900 K

$\dot{Q}_{L2} = 0.3\ \dot{Q}_H = 100$ kW @450 K

$= \dot{Q}_{L3} = 100$ kW @370 K

$= \dot{Q}_{L4} = 100$ kW @293 K



Assume all the fuel energy is delivered at 1500 K then that has an exergy of

$$\dot{\Phi}_{QH} = (1 - \frac{T_o}{T_H})\ \dot{Q}_H = (1 - \frac{293}{1500})\ 333 = 267.9 \text{ kW}$$

10.92

Estimate some reasonable temperatures to use and find all the fluxes of exergy in the refrigerator given in Example 7.2

We will assume the following temperatures:

Ambient: $T = 20^oC$ usually it is the kitchen air.

Low T: $T = 5^oC$ (refrigerator) $T = -10^oC$ (freezer)

$$\dot{\Phi}_W = \dot{W} = \mathbf{150\ W}$$

$$\dot{\Phi}_H = \left(1 - \frac{T_o}{T_H}\right) \dot{Q}_H = \left(1 - \frac{T_{amb}}{T_{amb}}\right) \dot{Q}_H = \mathbf{0}$$

$$\dot{\Phi}_L = \left(1 - \frac{T_o}{T_L}\right) \dot{Q}_L = \left(1 - \frac{293}{278}\right) 250 = \mathbf{-13.5\ W}$$

I.e. the flux goes into the cold space! Why? As you cool it $T < T_o$ and you increase its availability (exergy), it is further away from the ambient.

10.93

Use the exergy equation to evaluate the exergy destruction for Problem 10.44. A 2-kg piece of iron is heated from room temperature 25°C to 400°C by a heat source at 600°C. What is the irreversibility in the process?

Solution:

C.V. Iron out to 600°C source, which is a control mass.

Exergy Eq.10.42: $\Phi_2 - \Phi_1 = (1 - \frac{T_o}{T_H})\,{}_1Q_2 - {}_1W_2 + P_o(V_2 - V_1) - {}_1\Phi_{2\ \text{destr.}}$

To evaluate it we need the heat transfer and the change in exergy Eq.10.43

$$\Phi_2 - \Phi_1 = m_{Fe}(u_2 - u_1) + P_o(V_2 - V_1) - m_{Fe}T_o(s_2 - s_1)$$

Energy Eq.5.11: $m_{Fe}(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

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

$$\Rightarrow\ {}_1Q_2 = m_{Fe}(h_2 - h_1) = m_{Fe}C(T_2 - T_1) = 2 \times 0.42 \times (400 - 25) = 315 \text{ kJ}$$

$$\begin{aligned}{}_1\Phi_{2\ \text{destr.}} &= (1 - \frac{T_o}{T_H})\,{}_1Q_2 - {}_1W_2 - m_{Fe}(u_2 - u_1) + m_{Fe}T_o(s_2 - s_1)\\ &= (1 - \frac{T_o}{T_H})\,{}_1Q_2 - {}_1Q_2 + m_{Fe}T_o(s_2 - s_1)\\ &= (1 - \frac{298}{873})\ 315 - 315 + 2 \times 0.42 \times 298 \ln \frac{673}{298} = \mathbf{96.4\ kJ}\end{aligned}$$

Notice the destruction is equal to ${}_1I_2 = T_o\, S_{gen}$

10.94

Use the exergy balance equation to solve for the work in Problem 10.33.
A piston/cylinder has forces on the piston so it keeps constant pressure. It contains 2 kg of ammonia at 1 MPa, 40°C and is now heated to 100°C by a reversible heat engine that receives heat from a 200°C source. Find the work out of the heat engine.

Solution:

To evaluate it we need the change in exergy Eq.10.43

$$\Phi_2 - \Phi_1 = m_{am}(u_2 - u_1) + P_o(V_2 - V_1) - m_{am}T_o(s_2 - s_1)$$

The work in Eq.10.44 ($W = W_{H.E.} + {}_1W_{2,pist}$) is from the exergy Eq.10.42

$$W = P_o(V_2 - V_1) + (1 - \frac{T_o}{T_H})_1Q_2 - (\Phi_2 - \Phi_1) - 0$$

$$= (1 - \frac{T_o}{T_H})_1Q_2 - m_{am}(u_2 - u_1) + m_{am}T_o(s_2 - s_1)$$

Now we must evaluate the three terms on the RHS and the work ${}_1W_{2,pist}$.

State 1: $u_1 = 1369.8$ kJ/kg, $v_1 = 0.13868$ m^3/kg, $s_1 = 5.1778$ kJ/kg K

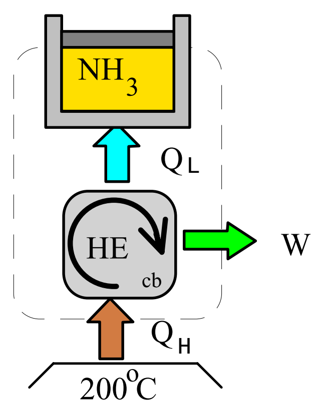
State 2: $u_2 = 1490.5$ kJ/kg, $v_2 = 0.17389$ m^3/kg, $s_2 = 5.6342$ kJ/kg K

$${}_1W_{2,pist} = m_{am}P(v_2 - v_1) = 2 \times 1000\ (0.17389 - 0.13868) = 70.42 \text{ kJ}$$

C.V. Heat engine and ammnia (otherwise we involve another Q)

Entropy: $m_{am}(s_2 - s_1) = {}_1Q_2/T_H + 0$

$$\Rightarrow \quad {}_1Q_2 = T_H\, m_{am}(s_2 - s_1)$$
$$= 473.15 \times 2\ (5.6342 - 5.1778)$$
$$= 431.89 \text{ kJ}$$



Substitute this heat transfer into the work term

$$W = (1 - \frac{298.15}{473.15})\ 431.89 - 2(1490.5 - 1369.8) + 2 \times 298.15(5.6342 - 5.1778)$$

$$= 159.74 - 241.4 + 272.15 = 190.49 \text{ kJ}$$

$$W_{H.E.} = W - {}_1W_{2,pist} = 190.49 - 70.42 = \mathbf{120.0\ kJ}$$

Review Problems

10.95

A small air gun has 1 cm^3 air at 250 kPa, 27^oC. The piston is a bullet of mass 20 g. What is the potential highest velocity with which the bullet can leave?

Solution:
The availability of the air can give the bullet kinetic energy expressed in the exergy balance Eq.10.42 (no heat transfer and reversible),

$$\Phi_2 - \Phi_1 = m(u_2 - u_1) + P_o(V_2 – V_1) - mT_o(s_2 - s_1) = -{}_1W_2 + P_o(V_2 – V_1)$$

Ideal gas so: $\quad m = PV/RT = \frac{250 \times 1 \times 10^{-6}}{0.287 \times 300} = 2.9 \times 10^{-6}$ kg

The second state with the lowest exergy to give maximum velocity is the dead state and we take $T_o = 20^oC$. Now solve for the work term

$$_1W_2 = -m(u_2 - u_1) + mT_o(s_2 - s_1)$$

$$= mC_v(T_1 – T_2) + mT_o \,[\, C_p \ln(\frac{T_2}{T_1}) – R \ln(\frac{P_2}{P_1}) \,]$$

$$= 2.9 \times 10^{-6} \,[\, 0.717(27 – 20) + 293.15 \,(1.004 \ln\frac{293}{300} – 0.287 \ln\frac{100}{250})]$$

$$= 0.0002180 \text{ kJ} = 0.218 \text{ J} = \frac{1}{2}\, m_{bullet}\mathbf{V}^2_{ex}$$

$$\mathbf{V}^2_{ex} = \sqrt{2 \times 0.218/0.020} = \mathbf{4.67\ m/s}$$

Comment: Notice that an isentropic expansion from 250 kPa to 100 kPa will give the final air temperature as 230.9 K but less work out. The above process is not adiabatic but Q is transferred from ambient at T_o.

10.96

Calculate the reversible work and irreversibility for the process described in Problem 5.134, assuming that the heat transfer is with the surroundings at 20°C.

C.V.: A + B. This is a control mass.

Continuity equation: $m_2 - (m_{A1} + m_{B1}) = 0$;

Energy: $m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} = {}_1Q_2 - {}_1W_2$

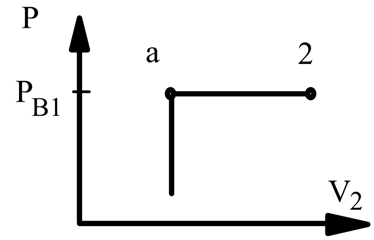
System: if $V_B \geq 0$ piston floats $\Rightarrow$ $P_B = P_{B1} =$ const.

if $V_B = 0$ then $P_2 < P_{B1}$ and $v = V_A/m_{tot}$ see P-V diagram

State A1: Table B.1.1, x = 1

$v_{A1} = 1.694\ m^3/kg,\ u_{A1} = 2506.1$ kJ/kg

$m_{A1} = V_A/v_{A1} =$ **0.5903 kg**



State B1: Table B.1.2 sup. vapor

$v_{B1} = 1.0315\ m^3/kg,\ u_{B1} = 2965.5$ kJ/kg

$m_{B1} = V_{B1}/v_{B1} =$ **0.9695 kg** => $m_2 = m_{TOT} = 1.56$ kg

At (T_2, P_{B1}) $v_2 = 0.7163 > v_a = V_A/m_{tot} = 0.641$ so $V_{B2} > 0$

so now state 2: $P_2 = P_{B1} = 300$ kPa, $T_2 = 200$ °C

=> $u_2 = 2650.7$ kJ/kg and $V_2 = m_2 v_2 = 1.56 \times 0.7163 = 1.117\ m^3$

(we could also have checked T_a at: 300 kPa, 0.641 m^3/kg => T = 155 °C)

$${}_1W_2^{ac} = \int P_B dV_B = P_{B1}(V_2 - V_1)_B = P_{B1}(V_2 - V_1)_{tot} = \mathbf{-264.82\ kJ}$$

$${}_1Q_2 = m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} + {}_1W_2 = \mathbf{-484.7\ kJ}$$

From the results above we have :

$s_{A1} = 7.3593$ kJ/kg K, $s_{B1} = 8.0329$ kJ/kg K, $s_2 = 7.3115$ kJ/kg K

$$\begin{aligned}{}_1W_2^{rev} &= T_o(S_2 - S_1) - (U_2 - U_1) + {}_1Q_2(1 - T_o/T_H) \\ &= T_o(m_2s_2 - m_{A1}s_{A1} - m_{B1}s_{B1}) + {}_1W_2^{ac} - {}_1Q_2T_o/T_H \\ &= 293.15\ (1.5598 \times 7.3115 - 0.5903 \times 7.3593 - 0.9695 \times 8.0329) \\ &\quad + (-264.82) - (-484.7) \times 293.15 / 293.15 \\ &= -213.3 - 264.82 + 484.7 = 6.6\ \text{kJ}\end{aligned}$$

$${}_1I_2 = {}_1W_2^{rev} - {}_1W_2^{ac} = 6.6 - (-264.82) = \mathbf{271.4\ kJ}$$

10.97

A piston/cylinder arrangement has a load on the piston so it maintains constant pressure. It contains 1 kg of steam at 500 kPa, 50% quality. Heat from a reservoir at 700°C brings the steam to 600°C. 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.

Solution:

1: Table B.1.2 $P_1, x_1 \Rightarrow v_1 = 0.001093 + 0.5 \times 0.3738 = 0.188 \text{ m}^3\text{/kg}$,

$h_1 = 640.21 + 0.5 \times 2108.47 = 1694.5$ kJ/kg,

$s_1 = 1.8606 + 0.5 \times 4.9606 = 4.341$ kJ/kg K

2: $P_2 = P_1, T_2 \Rightarrow v_2 = 0.8041, \quad h_2 = 3701.7$ kJ/kg, $\quad s_2 = 8.3521$ kJ/kg K

Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = {}_1Q_2 - P(V_2 - V_1)$

${}_1Q_2 = m(u_2 - u_1) + Pm(v_2 - v_1) = m(h_2 - h_1) = 2007.2$ kJ

${}_1W_2 = Pm(v_2 - v_1) = 308.05$ kJ

${}_1W_{2\text{ to atm}} = P_0 m(v_2 - v_1) = 61.61$ kJ

Useful work out $= {}_1W_2 - {}_1W_{2\text{ to atm}} = 246.44$ kJ

$$\Delta\phi_{reservoir} = (1 - T_0/T_{res})\,{}_1Q_2 = \left(1 - \frac{298.15}{973.15}\right) 2007.2 = 1392.2 \text{ kJ}$$

$\eta_{II} = W_{net}/\Delta\phi =$ **0.177**

10.98

Consider the high-pressure closed feedwater heater in the nuclear power plant described in Problem 6.102. Determine its second-law efficiency.

For this case with no work the second law efficiency is from Eq. 10.25:

$$\eta_{II} = \dot{m}_{16}(\psi_{18} - \psi_{16})/\dot{m}_{17}(\psi_{17} - \psi_{15})$$

Properties (taken from computer software):

h [kJ/kg]	$h_{15} = 585$	$h_{16} = 565$	$h_{17} = 2593$	$h_{18} = 688$
s [kJ/kgK]	$s_{15} = 1.728$	$s_{16} = 1.6603$	$s_{17} = 6.1918$	$s_{18} = 1.954$

The change in specific flow availability becomes

$$\psi_{18} - \psi_{16} = h_{18} - h_{16} - T_0(s_{18} - s_{16}) = 35.433 \text{ kJ/kg}$$

$$\psi_{17} - \psi_{15} = h_{17} - h_{15} - T_0(s_{17} - s_{15}) = 677.12 \text{ kJ/kg}$$

$$\eta_{II} = (75.6 \times 35.433)/(4.662 \times 677.12) = \mathbf{0.85}$$

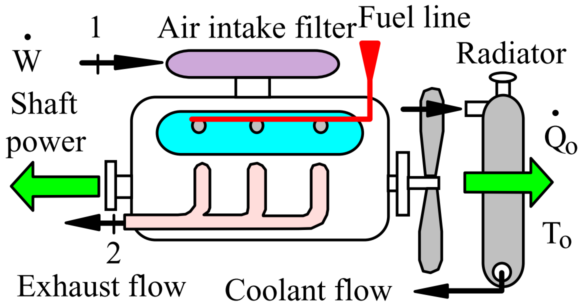
10.99

Consider a gasoline engine for a car as a steady device where air and fuel enters at the surrounding conditions 25°C, 100 kPa and leaves the engine exhaust manifold at 1000 K, 100 kPa as products assumed to be air. The engine cooling system removes 750 kJ/kg air through the engine to the ambient. For the analysis take the fuel as air where the extra energy of 2200 kJ/kg of air released in the combustion process, is added as heat transfer from a 1800 K reservoir. Find the work out of the engine, the irreversibility per kilogram 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 A.7

	kJ/kg		kJ/kg K
	$h_1 = 298.61$		$s^o_{T1} = 6.8631$
	$h_2 = 1046.22$		$s^o_{T1} = 8.1349$

$w_{ac} = \dot{W}/\dot{m}_a = h_1 - h_2 + q_H - q_{out} = 298.6 - 1046.22 + 2200 - 750 = 702.4$ kJ/kg

$\eta_{TH} = w/q_H = 702.4/2200 = \mathbf{0.319}$

$$s_{gen} = s_2 - s_1 + \frac{q_{out}}{T_0} - \frac{q_H}{T_H} = 8.1349 - 6.8631 + \frac{750}{298.15} - \frac{2200}{1800} = 2.565 \text{ kJ/kg K}$$

$i_{tot} = (T_0)s_{gen} = \mathbf{764.8\ kJ/kg}$

For reversible case have $s_{gen} = 0$ and q^R_0 from T_0, no q_{out}

$q^R_{0,in} = T_0(s_2 - s_1) - (T_0/T_H)q_H = 14.78$ kJ/kg

$w^{rev} = h_1 - h_2 + q_H + q^R_{0,in} = w_{ac} + i_{tot} = 1467.2$ kJ/kg

$\eta_{II} = w_{ac}/w^{rev} = \mathbf{0.479}$

10.100

Consider the nozzle in Problem 9.112. What is the second law efficiency for the nozzle?

A nozzle in a high pressure liquid water sprayer has an area of 0.5 cm^2. It receives water at 250 kPa, 20°C and the exit pressure is 100 kPa. Neglect the inlet kinetic energy and assume a nozzle isentropic efficiency of 85%. Find the ideal nozzle exit velocity and the actual nozzle mass flow rate.

Solution:

C.V. Nozzle. Liquid water is incompressible v ≈ constant, no work, no heat transfer => Bernoulli Eq.9.17

$$\frac{1}{2}\mathbf{V}_{ex}^2 - 0 = v(P_i - P_e) = 0.001002\ (250 - 100) = 0.1503 \text{ kJ/kg}$$

$$\mathbf{V}_{ex} = \sqrt{2 \times 0.1503 \times 1000 \text{ J/kg}} = \mathbf{17.34\ m\ s^{-1}}$$

This was the ideal nozzle now we can do the actual nozzle, Eq. 9.30

$$\frac{1}{2}\mathbf{V}_{ex\ ac}^2 = \eta\ \frac{1}{2}\mathbf{V}_{ex}^2 = 0.85 \times 0.1503 = 0.12776 \text{ kJ/kg}$$

$$\mathbf{V}_{ex\ ac} = \sqrt{2 \times 0.12776 \times 1000 \text{ J/kg}} = 15.99 \text{ m s}^{-1}$$

The second law efficiency is the actual nozzle compare to a reversible process between the inlet and actual exit states. However here there is no work so the actual exit state then must have the reversible possible kinetic energy.

Energy actual nozzle: $h_i + 0 = h_e + \frac{1}{2}\mathbf{V}_{ex\ ac}^2$ same Z, no q and no w.

The reversible process has zero change in exergies from Eq.10.36 as

$$0 = 0 - 0 + 0 + \psi_i - \psi_e - 0$$

$$\psi_i = \psi_e = h_i + 0 - T_o\, s_i = h_e + \frac{1}{2}\mathbf{V}_{ex\ rev}^2 - T_o s_e$$

$$\frac{1}{2}\mathbf{V}_{ex\ rev}^2 = h_i - h_e + T_o\,(s_e - s_i) = \frac{1}{2}\mathbf{V}_{ex\ ac}^2 + T_o\, s_{gen}$$

We can not get properties for these states accurately enough by interpolation to carry out the calculations. With the computer program we can get:

Inlet: $h_i = 84.173$ kJ/kg, $s_i = 0.29652$ kJ/kg K

Exit,s: $h_{e\ s} = 84.023$ kJ/kg, $T_{e\ s} = 19.998$°C, $\frac{1}{2}\mathbf{V}_{ex}^2 = 0.15$ kJ/kg

Exit,ac: $\frac{1}{2}\mathbf{V}_{ex\ ac}^2 = 0.1275$ kJ/kg, $h_e = 84.173 - 0.1275 = 84.0455$ kJ/kg

(P, h) => $s_e = 0.29659$ kJ/kg K, T = 20.003°C

$$\frac{1}{2}\mathbf{V}_{ex\ rev}^2 = \frac{1}{2}\mathbf{V}_{ex\ ac}^2 + T_o\, s_{gen} = 0.1275 + 293.15(0.29659 - 0.29652)$$

$$= 0.148 \text{ kJ/kg}$$

$$\eta_{II} = 0.1275/0.148 = \mathbf{0.86}$$

10.101

Air in a piston/cylinder arrangement is at 110 kPa, 25°C, with a volume of 50 L. It goes through a reversible polytropic process to a final state of 700 kPa, 500 K, and exchanges heat with the ambient at 25°C through a reversible device. Find the total work (including the external device) and the heat transfer from the ambient.

C.V. Total out to ambient

$$m_a(u_2 - u_1) = {}_1Q_2 - {}_1W_{2,tot}\ , \quad m_a(s_2 - s_1) = {}_1Q_2/T_0$$

$$m_a = 110 \times 0.05/0.287 \times 298.15 = 0.0643\ \text{kg}$$

$${}_1Q_2 = T_0 m_a(s_2 - s_1) = 298.15 \times 0.0643\Big[7.3869 - 6.8631 - 0.287\ \ln\,(700/110)\Big] = -0.14\ \text{kJ}$$

$${}_1W_{2,tot} = {}_1Q_2 - m_a(u_2 - u_1)$$

$$= -0.14 - 0.0643 \times (359.844 - 213.037) = \mathbf{-9.58\ kJ}$$

10.102

Consider the irreversible process in Problem 8.128. Assume that the process could be done reversibly by adding heat engines/pumps between tanks A and B and the cylinder. The total system is insulated, so there is no heat transfer to or from the ambient. Find the final state, the work given out to the piston and the total work to or from the heat engines/pumps.

C.V. Water $m_A + m_B$ + heat engines. No Qexternal, only ${}_1W_{2,cyl} + W_{HE}$

$m_2 = m_{A1} + m_{B1} = 6$ kg, $m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} = -{}_1W_{2,cyl} - W_{HE}$

$m_2s_2 - m_{A1}s_{A1} - m_{B1}s_{B1} = \emptyset + \emptyset$

$v_{A1} = 0.06283$ $u_{A1} = 3448.5$ $s_{A1} = 7.3476$ $V_A = 0.2513$ m^3

$v_{B1} = 0.09053$ $u_{B1} = 2843.7$ $s_{B1} = 6.7428$ $V_B = 0.1811$ m^3

$m_2s_2 = 4\times7.3476 + 2\times6.7428 = 42.876 \Rightarrow s_2 = 7.146$ kJ/kg K

If $P_2 < P_{lift} = 1.4$ MPa then

$V_{2'} = V_A + V_B = 0.4324$ m^3 , $v_{2'} = 0.07207$ m^3/kg

$(P_{lift}, s_2) \Rightarrow v_2 = 0.20135 \Rightarrow V_2 = 1.208$ m$^3 > V_{2'}$ OK

$\Rightarrow P_2 = P_{lift} =$ **1.4 MPa** $u_2 = 2874.2$ kJ/kg

${}_1W_{2,cyl} = P_{lift}(V_2 - V_A - V_B) = 1400\times(1.208 - 0.4324) =$ **1085.84 kJ**

$W_{HE} = m_{A1}u_{A1} + m_{B1}u_{B1} - m_2u_2 - {}_1W_{2,cyl}$

$= 4 \times 3447.8 + 2 \times 2843.7 - 6 \times 2874.2 - 1085.84 =$ **1147.6 kJ**

10.103

Consider the heat engine in Problem 10.79. The exit temperature was given as 800 K, but what are the theoretical limits for this temperature? Find the lowest and the highest, assuming the heat transfers are as given. For each case give the first and second law efficiency.

The **lowest exhaust temperature** will occur when the maximum amount of work is delivered which is a reversible process. Assume no other heat transfers then

2nd law: $s_i + q_H/T_H + \emptyset = s_e + q_m/T_m$

$$s_e - s_i = q_H/T_H - q_m/T_m = s^\circ_{Te} - s^\circ_{Ti} - R\ln(P_e/P_i)$$

$$s^\circ_{Te} = s^\circ_{Ti} + R\ln(P_e/P_i) + q_H/T_H - q_m/T_m$$

$$= 6.86926 + 0.287\ln(100/100) + 1200/1500 - 300/750$$

$$= 7.26926 \text{ kJ/kg K}$$

Table A.7.1 $\Rightarrow$ $T_{e,min}$ = **446 K**, $h_e = 447.9$ kJ/kg

$$h_i + q_{1500} = q_{750} + h_e + w$$

$$w_{rev} = h_i + q_{1500} - q_{750} - h_e = 300.47 + 1200 - 300 - 447.9$$

$$= 752.57 \text{ kJ/kg}$$

$$\eta_I = \eta_{TH} = \frac{w_{rev}}{q_{1500}} = \frac{752.57}{1200} = \mathbf{0.627}$$

The second law efficiency measures the work relative to the source of availability and not q_{1500}. So

$$\eta_{II} = \frac{w_{rev}}{(1 - T_o/T_H)q_{1500}} = \frac{752.57}{(1 - 300/1500)1200} = \frac{752.57}{960} = \mathbf{0.784}$$

The **maximum exhaust temperature** occurs with no work out

$$h_i + q_H = q_m + h_e \Rightarrow h_e = 300.473 + 1200 - 300 = 1200.5 \text{ kJ/kg}$$

Table A.7.1 $\Rightarrow$ $T_{e,max}$ = **1134 K**

Now : $w_{ac} = 0$ so $\eta_I = \eta_{II} = \mathbf{0}$

10.104

Air in a piston/cylinder arrangement, shown in Fig. P10.104, is at 200 kPa, 300 K with a volume of 0.5 m^3. If the piston is at the stops, the volume is 1 m^3 and a pressure of 400 kPa is required. The air is then heated from the initial state to 1500 K by a 1900 K reservoir. Find the total irreversibility in the process assuming surroundings are at 20°C.

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

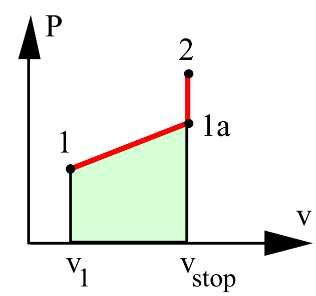
Eq. of state ⇒ $T_{stop} = T_1P_{stop}V_{stop}/P_1V_1 = 1200 < T_2$

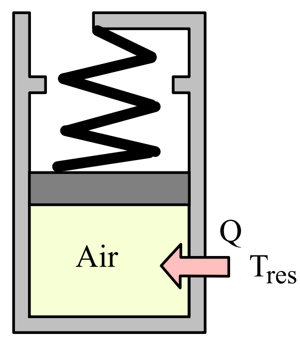
So the piston will hit the stops => $V_2 = V_{stop}$

$$P_2 = (T_2/T_{stop})\ P_{stop} = (1500/1200)\ 400 = 500 \text{ kPa} = 2.5\ P_1$$

State 1:

$$m_2 = m_1 = \frac{P_1V_1}{RT_1} = \frac{200 \times 0.5}{0.287 \times 300} = 1.161 \text{ kg}$$





$${}_1W_2 = \tfrac{1}{2}(P_1 + P_{stop})(V_{stop} - V_1) = \tfrac{1}{2}(200 + 400)(1 - 0.5) = 150 \text{ kJ}$$

$${}_1Q_2 = M(u_2 - u_1) + {}_1W_2 = 1.161(1205.25 - 214.36) + 150 = 1301 \text{ kJ}$$

$$s_2 - s_1 = s^o_{T2} - s^o_{T1} - R \ln(P_2/P_1) = 8.6121 - 6.8693 - 0.287 \ln 2.5 = 1.48 \text{ kJ/kg K}$$

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

$${}_1S_{2\ gen\ tot} = m(s_2 - s_2) - {}_1Q_2/T_{RES} = 1.034 \text{ kJ/K}$$

$${}_1I_2 = T_0\left({}_1S_{2\ gen}\right) = 293.15 \times 1.034 = \mathbf{303\ kJ}$$

10.105

A jet of air at 200 m/s flows at 25°C, 100 kPa towards a wall where the jet flow stagnates and leaves at very low velocity. Consider the process to be adiabatic and reversible. Use the exergy equation and the second law to find the stagnation temperature and pressure.

Solution:

C.V. From free flow to stagnation point. Reversible adiabatic steady flow.

Exergy Eq.10.36: $0 = \dot{m}\psi_i - \dot{m}\psi_e - \dot{\Phi}_{destr.}$

Entropy Eq.: $0 = \dot{m}s_i - \dot{m}s_e + \int \dot{m}dq/T + \dot{m}s_{gen} = \dot{m}s_i - \dot{m}s_e + 0 + 0$

Process: Reversible $\dot{\Phi}_{destr.} = 0$, $s_{gen} = 0$, adiabatic $q = 0$

From exergy Eq.: $\psi_e - \psi_i = 0 = h_e - T_o s_e - h_i + T_o s_i - \frac{1}{2}\mathbf{V}_i^2$

From entropy Eq.: $s_e = s_i$, so entropy terms drop out

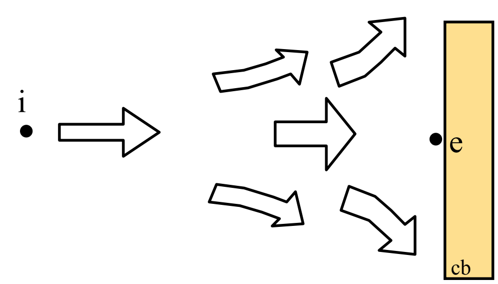
Exergy eq. now leads to: $h_e = h_i + \frac{1}{2}\mathbf{V}_i^2$ => $T_e = T_i + \frac{1}{2}\mathbf{V}_i^2 /C_p$

$$T_e = 25 + \frac{1}{2}\frac{200^2 \text{ J/kg}}{1004 \text{ J/kg K}} = \mathbf{44.92^oC}$$

Eq.8.32: $P_e = P_i\,(T_e/T_e)^{\frac{k}{k-1}} = 100\left(\frac{273 + 44.92}{273 + 25}\right)^{1.4/0.4} = \mathbf{125.4\ kPa}$

State i is the free stream state.

State e is the stagnation state.



10.106

Consider the light bulb in Problem 8.123. What are the fluxes of exergy at the various locations mentioned? What are the exergy destruction in the filament, the entire bulb including the glass and the entire room including the bulb? The light does not affect the gas or the glass in the bulb but it gets absorbed on the room walls.

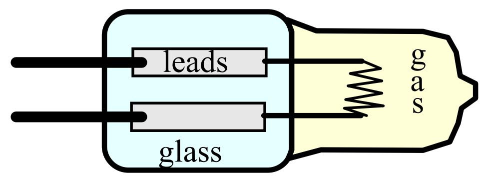
A small halogen light bulb receives an electrical power of 50 W. The small filament is at 1000 K and gives out 20% of the power as light and the rest as heat transfer to the gas, which is at 500 K; the glass is at 400 K. All the power is absorbed by the room walls at 25°C. Find the rate of generation of entropy in the filament, in the total bulb including glass and the total room including bulb.

Solution:

$\dot{W}_{el} = 50$ W

$\dot{Q}_{RAD} = 10$ W

$\dot{Q}_{COND} = 40$ W



We will assume steady state and no storage in the bulb, air or room walls.

C.V. Filament steady-state

Energy Eq.5.31: $dE_{c.v.}/dt = 0 = \dot{W}_{el} - \dot{Q}_{RAD} - \dot{Q}_{COND}$

Entropy Eq.8.43: $dS_{c.v.}/dt = 0 = -\dfrac{\dot{Q}_{RAD}}{T_{FILA}} - \dfrac{\dot{Q}_{COND}}{T_{FILA}} + \dot{S}_{gen}$

$$\dot{S}_{gen} = (\dot{Q}_{RAD} + \dot{Q}_{COND})/T_{FILA} = \dot{W}_{el}/T_{FILA} = \frac{50}{1000} = \mathbf{0.05\ W/K}$$

C.V. Bulb including glass

$\dot{Q}_{RAD}$ leaves at 1000 K $\qquad$ $\dot{Q}_{COND}$ leaves at 400 K

$\dot{S}_{gen} = \int d\dot{Q}/T = -(-10/1000) - (-40/400) = \mathbf{0.11\ W/K}$

C.V. Total room. All energy leaves at 25°C

Eq.5.31: $dE_{c.v.}/dt = 0 = \dot{W}_{el} - \dot{Q}_{RAD} - \dot{Q}_{COND}$

Eq.8.43: $dS_{c.v.}/dt = 0 = -\dfrac{\dot{Q}_{TOT}}{T_{WALL}} + \dot{S}_{gen}$

$$\dot{S}_{gen} = \frac{\dot{Q}_{TOT}}{T_{WALL}} = 50/(25+273) = \mathbf{0.168\ W/K}$$

Problems Solved Using Pr and vr Functions

10.31

An air compressor receives atmospheric air at T_0 = 17°C, 100 kPa, and compresses it up to 1400 kPa. The compressor has an isentropic efficiency of 88% and it loses energy by heat transfer to the atmosphere as 10% of the isentropic work. Find the actual exit temperature and the reversible work.

C.V. Compressor

Isentropic: $w_{c,in,s} = h_{e,s} - h_i$; $s_{e,s} = s_i$

Table A.7: $P_{r,e,s} = P_{r,i} \times (P_e/P_i) = 0.9917 \times 14 = 13.884$

$\Rightarrow h_{e,s} = 617.51$ kJ/kg

$w_{c,in,s} = 617.51 - 290.58 = 326.93$ kJ/kg

Actual: $w_{c,in,ac} = w_{c,in,s}/\eta_c = 371.51$; $q_{loss} = 32.693$ kJ/kg

$w_{c,in,ac} + h_i = h_{e,ac} + q_{loss}$

=> $h_{e,ac} = 290.58 + 371.51 - 32.693 = 629.4$ kJ/kg

=> $T_{e,ac} = 621$ K

Reversible: $w^{rev} = h_i - h_{e,ac} + T_0(s_{e,ac} - s_i)$

$= 290.58 - 629.4 + 290.15 \times (7.6121 - 6.8357)$

$= -338.82 + 225.42 =$ **-113.4 kJ/kg**

Since q_{loss} is also to the atmosphere it is not included as it will not be reversible.

10.61

An air compressor is used to charge an initially empty 200-L tank with air up to 5 MPa. The air inlet to the compressor is at 100 kPa, 17°C and the compressor isentropic efficiency is 80%. Find the total compressor work and the change in availability of the air.

Solution:

C.V. Tank + compressor Transient process with constant inlet conditions, no heat transfer.

Continuity: $m_2 - m_1 = m_{in}$ ($m_1 = 0$) Energy: $m_2u_2 = m_{in}h_{in} - {}_1W_2$

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

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

State 1: $v_1 = RT_1/P_1 = 0.8323\ m^3/kg$,

State inlet, Table A.7.1: $h_{in} = 290.43$ kJ/kg, $s^o_{Tin} = 6.8352$ kJ/kg K

Table A.7.2 $P_{rin} = 0.9899$ used for constant s process

Table A.7.2 $\Rightarrow$ $P_{r2} = P_{rin}(P_2/P_{in}) = 0.9899 \times (5000/100) = 49.495$

$\Rightarrow$ $T_{2,s} = 855$ K, $u_{2,s} = 637.2$ kJ/kg

$\Rightarrow$ ${}_1w_{2,s} = h_{in} - u_{2,s} = 290.43 - 637.2 = -346.77$ kJ/kg

Actual compressor: ${}_1w_{2,AC} = {}_1w_{2,s}/\eta_c = -433.46$ kJ/kg

$u_{2,AC} = h_{in} - {}_1w_{2,AC} = 290.43 - (-433.46) = 723.89$ kJ/kg

Backinterpolate in Table A.7.1 $\Rightarrow$ $T_{2,AC} = 958$ K, $s^o_{T2,AC} = 8.0867$ kJ/kg K

$\Rightarrow$ $v_2 = RT_2/P_2 = 0.055\ m^3/kg$

State 2 $\boxed{u, P}$ $m_2 = V_2/v_2 = 3.636$ kg $\Rightarrow$ ${}_1W_2 = m_2({}_1w_{2,AC}) =$ **-1576 kJ**

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

$= 3.636\ [723.89 - 207.19 + 100(0.055 - 0.8323) - 290[8.0867 - 6.8352 - 0.287 \ln(5000/100)] =$ **1460.3 kJ**

Here we used Eq.8.28 for the change in entropy.