

**SOLUTION MANUAL  
SI UNIT PROBLEMS  
CHAPTER 8**

SONNTAG • BORGNAKKE • VAN WYLEN



FUNDAMENTALS  
*of*  
Thermodynamics  
*Sixth Edition*

**CONTENT**

<b>SUBSECTION</b>	<b>PROB NO.</b>
Correspondence table	
Concept-Study Guide problems	1-20
Inequality of Clausius	21-25
Entropy of a pure substance	26-30
Reversible processes	31-60
Entropy generation	61-74
Entropy of a liquid or solid	75-86
Entropy of ideal gases	87-105
Polytropic processes	106-119
Rates or fluxes of entropy	120-125
Review problems	126-139
Problem solution repeated, but using the Pr and vr functions in Table A.7.2:	
88, 95, 107, 112	

## Correspondence table

**CHAPTER 8**      **6<sup>th</sup> edition**      **Sonntag/Borgnakke/Wylen**

The correspondence between this problem set and the 5th edition chapter 8 problem set.

The study guide problems 8.1-8.20 are all new

<b>New</b>	<b>Old</b>	<b>New</b>	<b>Old</b>	<b>New</b>	<b>Old</b>	<b>New</b>	<b>Old</b>
21	new	51	22 mod	81	42	111	64
22	new	52	new	82	43	112	new
23	new	53	new	83	new	113	62
24	new	54	new	84	new	114	new
25	new	55	new	85	new	115	69
26	new	56	new	86	44	116	70
27	2	57	17	87	45	117	new
28	new	58	new	88	new	118	71
29	new	59	19	89	47	119	66
30	new	60	24	90	51	120	new
31	3	61	new	91	new	121	26 mod
32	4mod	62	new	92	new	122	new
33	5	63	29	93	49	123	new
34	6	64	new	94	50	124	new
35	7	65	27	95	53	125	new
36	8	66	28	96	54	126	25
37	new	67	new	97	new	127	18
38	new	68	30	98	52	128	34
39	9	69	new	99	48	129	23
40	10	70	32	100	new	130	33
41	11	71	new	101	56	131	14
42	12	72	36	102	57	132	35
43	13	73	37	103	new	133	39
44	new	74	new	104	59	134	new
45	15 mod	75	new	105	60	135	58
46	new	76	41	106	61	136	68
47	16	77	31	107	46	137	74
48	new	78	40	108	67	138	78
49	18 mod	79	new	109	63	139	82
50	20	80	new	110	65		

## Concept-Study Guide Problems

## 8.1

Does Clausius say anything about the sign for  $\oint dQ$  ?

No.

The total (net) heat transfer can be coming in like in a heat engine ( $W_{\text{out}} = Q_H - Q_L$ ) in which case it is positive. It can also be net going out like in a refrigerator or heat pump ( $W_{\text{in}} = Q_H - Q_L$ ) in which case the sign is negative. Finally if you look at a transmission gearbox there could be no heat transfer (first approximation) in which case the integral is zero.

## 8.2

When a substance has completed a cycle  $v$ ,  $u$ ,  $h$  and  $s$  are unchanged. Did anything happen? Explain.

Yes.

During various parts of the cycle work and heat transfer may be transferred. That happens at different  $P$  and  $T$ . The net work out equals the net heat transfer in (energy conservation) so dependent upon the sign it is a heat engine or a heat pump (refrigerator). The net effect is thus a conversion of energy from one storage location to another and it may also change nature (some  $Q$  got changed to  $W$  or the opposite)

## 8.3

Assume a heat engine with a given  $Q_H$ . Can you say anything about  $Q_L$  if the engine is reversible? If it is irreversible?

For a reversible heat engine it must be that:

$$\oint \frac{dQ}{T} = 0 = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \quad \text{or integrals if } T \text{ not constant}$$

So as  $T_L$  is lower than  $T_H$  then  $Q_L$  must be correspondingly lower than  $Q_H$  to obtain the net zero integral.

For an irreversible heat engine we have

$$\oint \frac{dQ}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} < 0$$

This means that  $Q_L$  is larger than before (given  $Q_H$  and the  $T$ 's). The irreversible heat engine rejects more energy and thus gives less out as work.

**8.4**

How can you change  $s$  of a substance going through a reversible process?

From the definition of entropy

$$ds = \frac{dq}{T}$$

for a reversible process. Thus only heat transfer gives a change in  $s$ , expansion/compression involving work does not give such a contribution.

**8.5**

Does the statement of Clausius require a constant  $T$  for the heat transfer as in a Carnot cycle?

No.

The statement for a cycle involves an integral of  $dQ/T$  so  $T$  can vary, which it does during most processes in actual devices. This just means that you cannot that easily get a closed expression for the integral.

**8.6**

A reversible process adds heat to a substance. If  $T$  is varying does that influence the change in  $s$ ?

Yes.

$$\text{Reversible: } ds = \frac{dq}{T}$$

So if  $T$  goes up it means that  $s$  changes less per unit of  $dq$ , and the opposite if  $T$  decreases then  $s$  changes more per unit of  $dq$ .

**8.7**

Water at 100 kPa, 150°C receives 75 kJ/kg in a reversible process by heat transfer. Which process changes  $s$  the most: constant  $T$ , constant  $v$  or constant  $P$ ?

$$ds = \frac{dq}{T}$$

Look at the constant property lines in a  $T$ - $s$  diagram, Fig. 8.5. The constant  $v$  line has a higher slope than the constant  $P$  line also at positive slope. Thus both the constant  $P$  and  $v$  processes have an increase in  $T$ . As  $T$  goes up the change in  $s$  is smaller.

The constant  $T$  (isothermal) process therefore changes  $s$  the most.

**8.8**

A substance has heat transfer out. Can you say anything about changes in  $s$  if the process is reversible? If it is irreversible?

Reversible:  $ds = \frac{dq}{T} < 0$  since  $dq < 0$

Irreversible:  $ds = \frac{dq}{T} + ds_{\text{gen}} = ?$   $dq < 0$  but  $ds_{\text{gen}} > 0$

You cannot say,  $ds$  depends on the magnitude of  $dq/T$  versus  $ds_{\text{gen}}$

**8.9**

A substance is compressed adiabatically so P and T go up. Does that change s?

If the process is reversible then s is constant,  $ds = \frac{dq}{T} = 0$

If the process is irreversible then s goes up,  $ds = \frac{dq}{T} + ds_{\text{gen}} = ds_{\text{gen}} > 0$

**8.10**

Saturated water vapor at 200 kPa is compressed to 600 kPa in a reversible adiabatic process. Find the new v and T.

Process adiabatic:  $dq = 0$

Process reversible:  $ds_{\text{gen}} = 0$

Change in s:  $ds = dq/T + ds_{\text{gen}} = 0 + 0 = 0$  thus s is constant

Table B.1.3:  $T_1 = 120.23^\circ\text{C}$ ,  $v_1 = 0.88573 \text{ m}^3/\text{kg}$ ,  $s_1 = 7.1271 \text{ kJ/kg-K}$

Table B.1.3 at 600 kPa and  $s = s_1 = 7.1271 \text{ kJ/kg-K}$

$$T = 200 + 50 \frac{7.1271 - 6.9665}{7.1816 - 6.9665} = 200 + 50 \times 0.74663 = \mathbf{237.3^\circ\text{C}}$$

$$v = 0.35202 + (0.39383 - 0.35202) \times 0.74663 = \mathbf{0.38324 \text{ m}^3/\text{kg}}$$

## 8.11

A computer chip dissipates 2 kJ of electric work over time and rejects that as heat transfer from its 50°C surface to 25°C air. How much entropy is generated in the chip? How much if any is generated outside the chip?

C.V.1 Chip with surface at 50°C, we assume chip state is constant.

$$\text{Energy: } U_2 - U_1 = 0 = {}_1Q_2 - {}_1W_2 = W_{\text{electrical in}} - Q_{\text{out 1}}$$

$$\text{Entropy: } S_2 - S_1 = 0 = -\frac{Q_{\text{out 1}}}{T_{\text{surf}}} + {}_1S_2_{\text{gen1}}$$

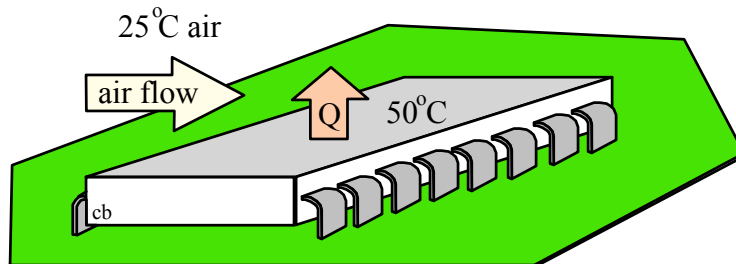
$${}_1S_2_{\text{gen1}} = \frac{Q_{\text{out 1}}}{T_{\text{surf}}} = \frac{W_{\text{electrical in}}}{T_{\text{surf}}} = \frac{2 \text{ kJ}}{323.15 \text{ K}} = \mathbf{6.19 \text{ J/K}}$$

C.V.2 From chip surface at 50°C to air at 25°C, assume constant state.

$$\text{Energy: } U_2 - U_1 = 0 = {}_1Q_2 - {}_1W_2 = Q_{\text{out 1}} - Q_{\text{out 2}}$$

$$\text{Entropy: } S_2 - S_1 = 0 = \frac{Q_{\text{out 1}}}{T_{\text{surf}}} - \frac{Q_{\text{out 2}}}{T_{\text{air}}} + {}_1S_2_{\text{gen2}}$$

$${}_1S_2_{\text{gen2}} = \frac{Q_{\text{out 2}}}{T_{\text{air}}} - \frac{Q_{\text{out 1}}}{T_{\text{surf}}} = \frac{2 \text{ kJ}}{298.15 \text{ K}} - \frac{2 \text{ kJ}}{323.15 \text{ K}} = \mathbf{0.519 \text{ J/K}}$$





**8.12**

A car uses an average power of 25 hp for a one hour round trip. With a thermal efficiency of 35% how much fuel energy was used? What happened to all the energy? What change in entropy took place if we assume ambient at 20°C?

Since it is a round trip, there are no changes in storage of energy for the car after it has cooled down again. All the energy is given out to the ambient in the form of exhaust flow (hot air) and heat transfer from the radiator and underhood air flow.

$$E = \int \dot{W} dt = 25 \text{ hp} \times 0.7457 \text{ (kW/hp)} \times 3600 \text{ s} = 67\,113 \text{ kJ} = \eta Q$$

$$Q = E / \eta = 67\,113 / 0.35 = \mathbf{191\,751 \text{ kJ}}$$

$$\Delta S = Q / T = 191\,751 / 293.15 = \mathbf{654.1 \text{ kJ/K}}$$

All the energy ends up in the ambient at the ambient temperature.

**8.13**

A liquid is compressed in a reversible adiabatic process. What is the change in T?

If the process is reversible then  $s$  is constant,  $ds = \frac{dq}{T} = 0$

Change in  $s$  for a liquid (an incompressible substance) is

$$\text{Eq. 8.19} \quad ds = \frac{C}{T} dT$$

From this it follows that if  $ds = 0$  then **T is constant.**

## 8.14

Two 5 kg blocks of steel, one at 250°C the other at 25°C, come in thermal contact. Find the final temperature and the total entropy generation in the process?

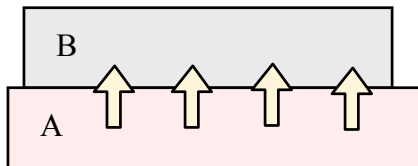
C.V. Both blocks, no external heat transfer, C from Table A.3.

$$\begin{aligned}\text{Energy Eq.: } U_2 - U_1 &= m_A(u_2 - u_1)_A + m_B(u_2 - u_1)_B = 0 - 0 \\ &= m_A C(T_2 - T_{A1}) + m_B C(T_2 - T_{B1})\end{aligned}$$

$$T_2 = \frac{m_A T_{A1} + m_B T_{B1}}{m_A + m_B} = \frac{1}{2} T_{A1} + \frac{1}{2} T_{B1} = \mathbf{137.5^\circ\text{C}}$$

$$\text{Entropy Eq.: } S_2 - S_1 = m_A(s_2 - s_1)_A + m_B(s_2 - s_1)_B = {}_1S_2 \text{ gen}$$

$$\begin{aligned}{}_1S_2 \text{ gen} &= m_A C \ln \frac{T_2}{T_{A1}} + m_B C \ln \frac{T_2}{T_{B1}} \\ &= 5 \times 0.46 \ln \frac{137.5 + 273.15}{250 + 273.15} + 5 \times 0.46 \ln \frac{137.5 + 273.15}{298.15} \\ &= -0.5569 + 0.7363 = \mathbf{0.1794 \text{ kJ/K}}\end{aligned}$$



Heat transfer over a finite temperature difference is an irreversible process

## 8.15

One kg of air at 300 K is mixed with one kg air at 400 K in a process at a constant 100 kPa and  $Q = 0$ . Find the final  $T$  and the entropy generation in the process.

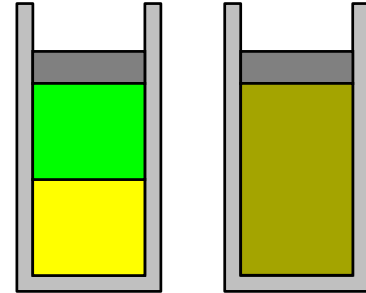
C.V. All the air.

$$\text{Energy Eq.: } U_2 - U_1 = 0 - W$$

$$\text{Entropy Eq.: } S_2 - S_1 = 0 + {}_1S_2 \text{ gen}$$

$$\text{Process Eq.: } P = C; \quad W = P(V_2 - V_1)$$

Substitute  $W$  into energy Eq.



$$U_2 - U_1 + W = U_2 - U_1 + P(V_2 - V_1) = H_2 - H_1 = 0$$

Due to the low  $T$  let us use constant specific heat

$$\begin{aligned} H_2 - H_1 &= m_A(h_2 - h_1)_A + m_B(h_2 - h_1)_B \\ &= m_A C_p (T_2 - T_{A1}) + m_B C_p (T_2 - T_{B1}) = 0 \end{aligned}$$

$$T_2 = \frac{m_A T_{A1} + m_B T_{B1}}{m_A + m_B} = \frac{1}{2} T_{A1} + \frac{1}{2} T_{B1} = \mathbf{350 \text{ K}}$$

Entropy change is from Eq. 8.25 with no change in  $P$

$$\begin{aligned} {}_1S_2 \text{ gen} &= S_2 - S_1 = m_A C_p \ln \frac{T_2}{T_{A1}} + m_B C_p \ln \frac{T_2}{T_{B1}} \\ &= 1 \times 1.004 \ln \frac{350}{300} + 1 \times 1.004 \ln \frac{350}{400} \\ &= 0.15477 - 0.13407 = \mathbf{0.0207 \text{ kJ/K}} \end{aligned}$$

Remark: If you check, the volume does not change and there is no work.

## 8.16

One kg of air at 100 kPa is mixed with one kg air at 200 kPa, both at 300 K, in a rigid insulated tank. Find the final state (P, T) and the entropy generation in the process.

C.V. All the air.

$$\text{Energy Eq.: } U_2 - U_1 = 0 - 0$$

$$\text{Entropy Eq.: } S_2 - S_1 = 0 + {}_1S_{2 \text{ gen}}$$

$$\text{Process Eqs.: } V = C; \quad W = 0, \quad Q = 0$$

$$\text{States A1, B1: } u_{A1} = u_{B1}$$

$$V_A = m_A RT_1 / P_{A1}; \quad V_B = m_B RT_1 / P_{B1}$$

$$U_2 - U_1 = m_2 u_2 - m_A u_{A1} - m_B u_{B1} = 0 \Rightarrow u_2 = (u_{A1} + u_{B1}) / 2 = u_{A1}$$

$$\text{State 2: } T_2 = T_1 = \mathbf{300 \text{ K}} \text{ (from } u_2); \quad m_2 = m_A + m_B = 2 \text{ kg};$$

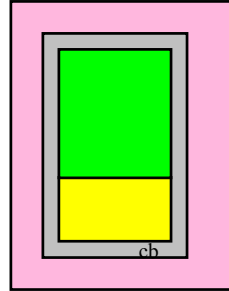
$$V_2 = m_2 RT_1 / P_2 = V_A + V_B = m_A RT_1 / P_{A1} + m_B RT_1 / P_{B1}$$

Divide with  $m_A RT_1$  and get

$$2/P_2 = 1/P_{A1} + 1/P_{B1} = \frac{1}{100} + \frac{1}{200} = 0.015 \text{ kPa}^{-1} \Rightarrow P_2 = \mathbf{133.3 \text{ kPa}}$$

Entropy change from Eq. 8.25 with the same T, so only P changes

$$\begin{aligned} {}_1S_{2 \text{ gen}} &= S_2 - S_1 = -m_A R \ln \frac{P_2}{P_{A1}} - m_B R \ln \frac{P_2}{P_{B1}} \\ &= -1 \times 0.287 \left[ \ln \frac{133.3}{100} + \ln \frac{133.3}{200} \right] \\ &= -0.287 (0.2874 - 0.4057) = \mathbf{0.034 \text{ kJ/K}} \end{aligned}$$



**8.17**

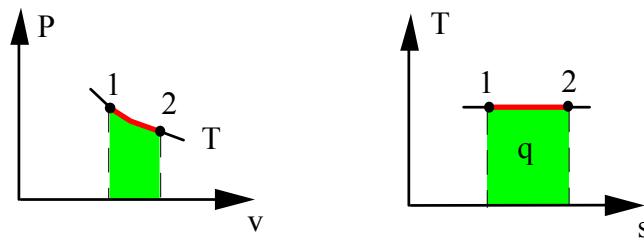
An ideal gas goes through a constant  $T$  reversible heat addition process. How do the properties ( $v$ ,  $u$ ,  $h$ ,  $s$ ,  $P$ ) change (up, down or constant)?

Ideal gas:  $u(T)$ ,  $h(T)$  so they are both constant

Eq. 8.11 gives:  $ds = dq/T + ds_{\text{gen}} = dq/T + 0 > 0$  so  $s$  goes up by  $q/T$

Eq. 8.21 gives:  $ds = (R/v) dv$  so  $v$  increases

Eq. 8.23 gives:  $ds = -(R/P) dP$  so  $P$  decreases

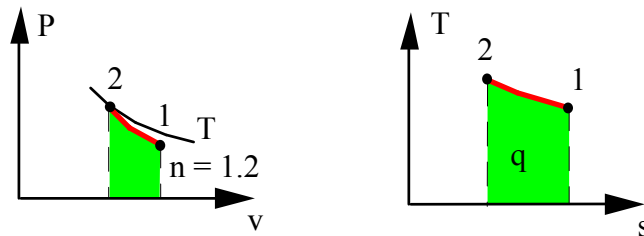


**8.18**

Carbon dioxide is compressed to a smaller volume in a polytropic process with  $n = 1.2$ . How do the properties ( $u$ ,  $h$ ,  $s$ ,  $P$ ,  $T$ ) change (up, down or constant)?

For carbon dioxide Table A.5  $k = 1.4$  so we have  $n < k$  and the process curve can be recognized in Figure 8.18. From this we see a smaller volume means moving to the left in the  $P$ - $v$  diagram and thus also up.

$P$  up,  $T$  up and  $s$  down. As  $T$  is up so is  $h$  and  $u$ .



**8.19**

Hot combustion air at 1500 K expands in a polytropic process to a volume 6 times as large with  $n = 1.5$ . Find the specific boundary work and the specific heat transfer.

$$\text{Energy Eq.: } u_2 - u_1 = {}_1q_2 - {}_1w_2$$

$$\text{Reversible work Eq. 8.38: } {}_1w_2 = \frac{1}{1-n} (P_2v_2 - P_1v_1) = \frac{R}{1-n} (T_2 - T_1)$$

$$\text{Process Eq: } Pv^n = C; \quad T_2 = T_1 (v_1/v_2)^{n-1} = 1500 \left(\frac{1}{6}\right)^{0.5} = 612.4 \text{ K}$$

Properties from Table A.7.1:  $u_1 = 444.6 \text{ kJ/kg}$ ,  $u_2 = 1205.25 \text{ kJ/kg}$

$${}_1w_2 = \frac{0.287}{1 - 1.5} (612.4 - 1500) = \mathbf{509.5 \text{ kJ/kg}}$$

$${}_1q_2 = u_2 - u_1 + {}_1w_2 = 1205.25 - 444.6 + 509.5 = \mathbf{1270 \text{ kJ/kg}}$$

## 8.20

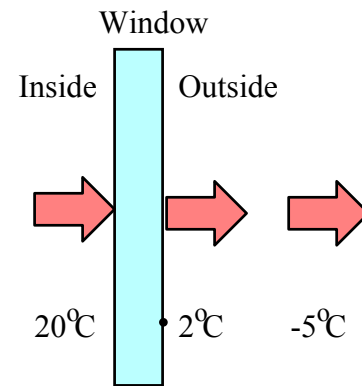
A window receives 200 W of heat transfer at the inside surface of 20°C and transmits the 200 W from its outside surface at 2°C continuing to ambient air at –5°C. Find the flux of entropy at all three surfaces and the window's rate of entropy generation.

$$\text{Flux of entropy: } \dot{S} = \frac{\dot{Q}}{T}$$

$$\dot{S}_{\text{inside}} = \frac{200 \text{ W}}{293.15 \text{ K}} = 0.682 \text{ W/K}$$

$$\dot{S}_{\text{win}} = \frac{200 \text{ W}}{275.15 \text{ K}} = 0.727 \text{ W/K}$$

$$\dot{S}_{\text{amb}} = \frac{200 \text{ W}}{268.15 \text{ K}} = 0.746 \text{ W/K}$$



$$\text{Window only: } \dot{S}_{\text{gen win}} = \dot{S}_{\text{win}} - \dot{S}_{\text{inside}} = 0.727 - 0.682 = \mathbf{0.045 \text{ W/K}}$$

If you want to include the generation in the outside air boundary layer where T changes from 2°C to the ambient –5°C then it is

$$\dot{S}_{\text{gen tot}} = \dot{S}_{\text{amb}} - \dot{S}_{\text{inside}} = 0.746 - 0.682 = 0.064 \text{ W/K}$$



## Inequality of Clausius

## 8.21

Consider the steam power plant in Example 6.9 and assume an average  $T$  in the line between 1 and 2. Show that this cycle satisfies the inequality of Clausius.

Solution:

Show Clausius: 
$$\int \frac{dQ}{T} \leq 0$$

For this problem we have three heat transfer terms:

$$q_b = 2831 \text{ kJ/kg}, \quad q_{\text{loss}} = 21 \text{ kJ/kg}, \quad q_c = 2173.3 \text{ kJ/kg}$$

$$\begin{aligned} \int \frac{dq}{T} &= \frac{q_b}{T_b} - \frac{q_{\text{loss}}}{T_{\text{avg } 1-2}} - \frac{q_c}{T_c} \\ &= \frac{2831}{573} - \frac{21}{568} - \frac{2173.3}{318} \\ &= -1.93 \text{ kJ/kg K} < 0 \quad \mathbf{OK} \end{aligned}$$

## 8.22

Assume the heat engine in Problem 7.25 has a high temperature of 1200 K and a low temperature of 400 K. What does the inequality of Clausius say about each of the four cases?

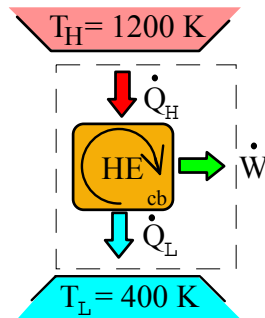
Solution:

$$\text{Cases a) } \int \frac{d\dot{Q}}{T} = \frac{6}{1200} - \frac{4}{400} = -0.005 \text{ kW/K} < 0 \quad \mathbf{OK}$$

$$\text{b) } \int \frac{d\dot{Q}}{T} = \frac{6}{1200} - \frac{0}{400} = 0.005 \text{ kW/K} > 0 \quad \mathbf{Impossible}$$

$$\text{c) } \int \frac{d\dot{Q}}{T} = \frac{6}{1200} - \frac{2}{400} = 0 \text{ kW/K} \quad \mathbf{Possible if reversible}$$

$$\text{d) } \int \frac{d\dot{Q}}{T} = \frac{6}{1200} - \frac{6}{400} = -0.001 \text{ kW/K} < 0 \quad \mathbf{OK}$$



## 8.23

Let the steam power plant in Problem 7.26 have  $700^{\circ}\text{C}$  in the boiler and  $40^{\circ}\text{C}$  during the heat rejection in the condenser. Does that satisfy the inequality of Clausius? Repeat the question for the cycle operated in reverse as a refrigerator.

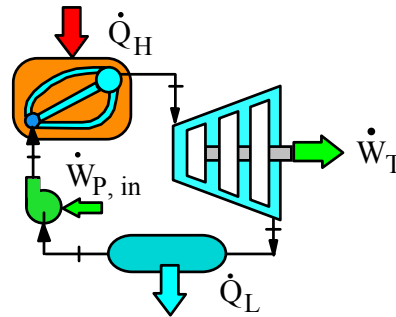
Solution:

$$\dot{Q}_H = 1 \text{ MW} \quad \dot{Q}_L = 0.58 \text{ MW}$$

$$\int \frac{d\dot{Q}}{T} = \frac{1000}{973} - \frac{580}{313} = -0.82 \text{ kW/K} < 0 \quad \text{OK}$$

Refrigerator

$$\int \frac{d\dot{Q}}{T} = \frac{580}{313} - \frac{1000}{973} = 0.82 > 0 \quad \text{Cannot be possible}$$



## 8.24

A heat engine receives 6 kW from a 250°C source and rejects heat at 30°C. Examine each of three cases with respect to the inequality of Clausius.

- a.  $\dot{W} = 6 \text{ kW}$       b.  $\dot{W} = 0 \text{ kW}$       c. Carnot cycle

Solution:

$$T_H = 250 + 273 = 523 \text{ K}; \quad T_L = 30 + 273 = 303 \text{ K}$$

$$\text{Case a) } \int \frac{d\dot{Q}}{T} = \frac{6000}{523} - \frac{0}{303} = 11.47 \text{ kW/K} > 0 \quad \textbf{Impossible}$$

$$\text{b) } \int \frac{d\dot{Q}}{T} = \frac{6000}{523} - \frac{6000}{303} = -8.33 \text{ kW/K} < 0 \quad \textbf{OK}$$

$$\text{c) } \int \frac{d\dot{Q}}{T} = 0 = \frac{6000}{523} - \frac{\dot{Q}_L}{303} \quad \Rightarrow$$

$$\dot{Q}_L = \frac{303}{523} \times 6 = 3.476 \text{ kW}$$

$$\dot{W} = \dot{Q}_H - \dot{Q}_L = 2.529 \text{ kW}$$

## 8.25

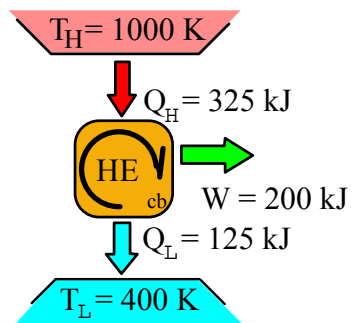
Examine the heat engine given in Problem 7.50 to see if it satisfies the inequality of Clausius.

Solution:

$$Q_H = 325 \text{ kJ} \quad \text{at} \quad T_H = 1000 \text{ K}$$

$$Q_L = 125 \text{ kJ} \quad \text{at} \quad T_L = 400 \text{ K}$$

$$\int \frac{dQ}{T} = \frac{325}{1000} - \frac{125}{400} = 0.0125 \text{ kJ/K} > 0 \quad \textbf{Impossible}$$



## Entropy of a pure substance

## 8.26

Find the entropy for the following water states and indicate each state on a T-s diagram relative to the two-phase region.

- 250°C,  $v = 0.02 \text{ m}^3/\text{kg}$
- 250°C, 2000 kPa
- 2°C, 100 kPa
- 20°C, 100 kPa
- 20°C, 10 000 kPa

Solution:

a) Table B.1.1:  $x = \frac{0.02 - 0.001251}{0.04887} = 0.38365$

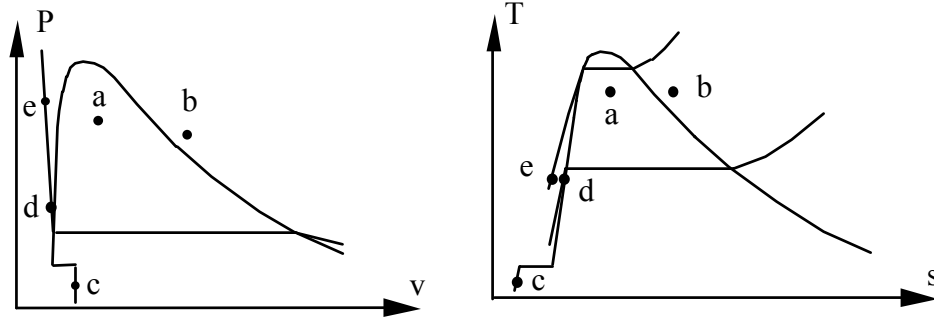
$$s = s_f + x s_{fg} = 2.7927 + 0.38365 \times 3.2802 = \mathbf{4.05 \text{ kJ/kg K}}$$

b) Table B.1.3:  $s = \mathbf{6.5452 \text{ kJ/kg K}}$

c) Table B.1.5:  $s = \mathbf{-1.2369 \text{ kJ/kg K}}$

d) Table B.1.1:  $s = \mathbf{0.2966 \text{ kJ/kg K}}$

e) Table B.1.4  $s = \mathbf{0.2945 \text{ kJ/kg K}}$



## 8.27

Find the missing properties and give the phase of the substance

- a.  $\text{H}_2\text{O}$   $s = 7.70 \text{ kJ/kg K}$ ,  $P = 25 \text{ kPa}$   $h = ?$   $T = ?$   $x = ?$   
 b.  $\text{H}_2\text{O}$   $u = 3400 \text{ kJ/kg}$ ,  $P = 10 \text{ MPa}$   $T = ?$   $x = ?$   $s = ?$   
 c.  $\text{R-12}$   $T = 0^\circ\text{C}$ ,  $P = 200 \text{ kPa}$   $s = ?$   $x = ?$   
 d.  $\text{R-134a}$   $T = -10^\circ\text{C}$ ,  $x = 0.45$   $v = ?$   $s = ?$   
 e.  $\text{NH}_3$   $T = 20^\circ\text{C}$ ,  $s = 5.50 \text{ kJ/kg K}$   $u = ?$   $x = ?$

Solution:

a) Table B.1.1  $T = T_{\text{sat}}(P) = 64.97^\circ\text{C}$

$$x = (s - s_f)/s_{fg} = \frac{7.70 - 0.893}{6.9383} = 0.981$$

$$h = 271.9 + 0.981 \times 2346.3 = 2573.8 \text{ kJ/kg}$$

b) Table B.1.2  $u > u_g \Rightarrow$  Sup.vap Table B.1.3,  $x = \text{undefined}$

$$T \cong 682^\circ\text{C}, \quad s \cong 7.1223 \text{ kJ/kg K}$$

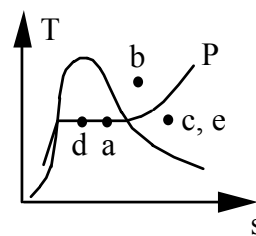
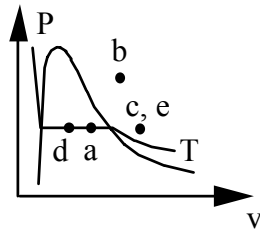
c) Table B.3.2, superheated vapor,  $x = \text{undefined}$ ,  $s = 0.7325 \text{ kJ/kg K}$

d) Table B.5.1  $v = v_f + xv_{fg} = 0.000755 + 0.45 \times 0.098454 = 0.04506 \text{ m}^3/\text{kg}$

$$s = s_f + xs_{fg} = 0.9507 + 0.45 \times 0.7812 = 1.3022 \text{ kJ/kg K}$$

e) Table B.2.1,  $s > s_g \Rightarrow$  Sup.vap. Table B.2.2,  $x = \text{undefined}$

$$u = h - Pv = 1492.8 - 439.18 \times 0.3100 = 1356.7 \text{ kJ/kg}$$



8.28

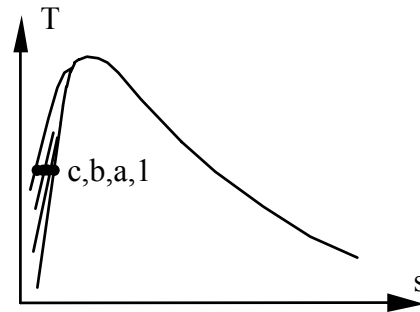
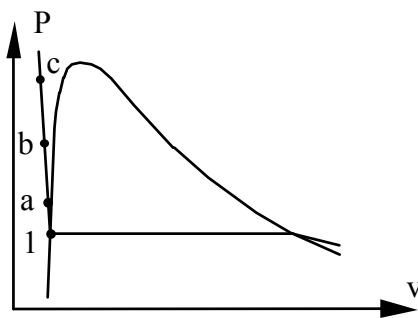
Saturated liquid water at 20°C is compressed to a higher pressure with constant temperature. Find the changes in  $u$  and  $s$  when the final pressure is is

- a. 500 kPa    b. 2000 kPa    c. 20 000 kPa

Solution:

	kJ/kg	kJ/kg K		
B.1.1:	$u_1 = 83.94$	$s_1 = 0.2966$		
B.1.4:	$u_a = 83.91$	$s_a = 0.2965$	$\Delta u = -0.03$	$\Delta s = -0.0001$
B.1.4:	$u_b = 83.82$	$s_b = 0.2962$	$\Delta u = -0.12$	$\Delta s = -0.0004$
B.1.4:	$u_c = 82.75$	$s_c = 0.2922$	$\Delta u = -1.19$	$\Delta s = -0.0044$

**Nearly constant  $u$  and  $s$ , incompressible media**





8.29

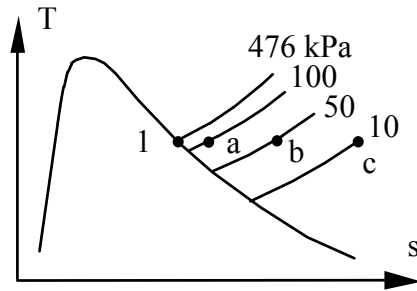
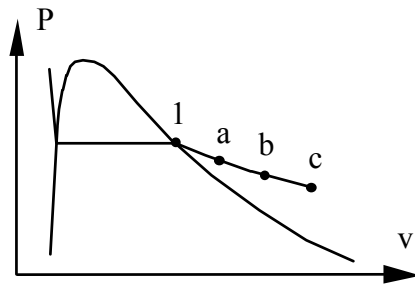
Saturated vapor water at 150°C is expanded to a lower pressure with constant temperature. Find the changes in  $u$  and  $s$  when the final pressure is is

- a. 100 kPa    b. 50 kPa    c. 10 kPa

Solution:

Table B.1.1 for the first state then B.1.3 for the a, b and c states.

	kJ/kg	kJ/kg K		
$u_1 =$	2559.54	$s_1 =$	6.8378	
$u_a =$	2582.75	$s_a =$	7.6133	$\Delta u = 23.21$ $\Delta s = 0.7755$
$u_b =$	2585.61	$s_b =$	7.94	$\Delta u = 26.07$ $\Delta s = 1.1022$
$u_c =$	2587.86	$s_c =$	8.6881	$\Delta u = 28.32$ $\Delta s = 1.8503$



8.30

Determine the missing property among  $P$ ,  $T$ ,  $s$ ,  $x$  for the following states:

- a. Ammonia  $25^\circ\text{C}$ ,  $v = 0.10 \text{ m}^3/\text{kg}$
- b. Ammonia  $1000 \text{ kPa}$ ,  $s = 5.2 \text{ kJ/kg K}$
- c. R-134a  $5^\circ\text{C}$ ,  $s = 1.7 \text{ kJ/kg K}$
- d. R-134a  $50^\circ\text{C}$ ,  $s = 1.9 \text{ kJ/kg K}$
- e. R-22  $100 \text{ kPa}$ ,  $v = 0.3 \text{ m}^3/\text{kg}$

Solution:

	Table	P kPa	T °C	s kJ/kg K	x
a)	B2.1	1003	25	4.1601	0.7776
b)	B2.2	1000	42.53	5.2	----
c)	B5.1	350.9	5	1.7	0.96598
d)	B5.2	232.3	50	1.9	----
e)	B4.2	100	42.6	1.1975	----

a)  $x = (0.1 - 0.001658)/0.12647 = \mathbf{0.7776}$

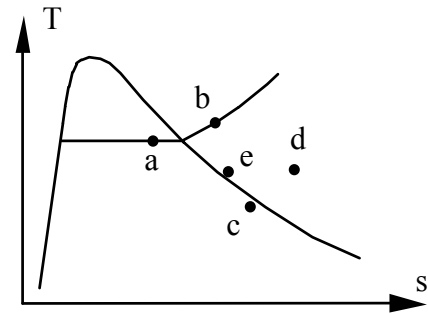
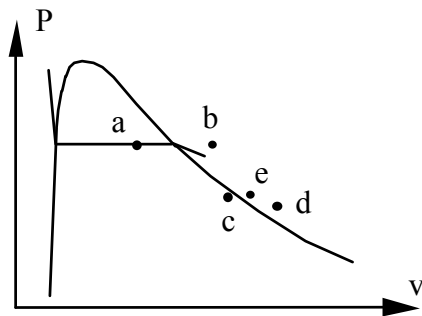
$s = s_f + x s_{fg} = 1.121 + x \times 3.9083 = \mathbf{4.1601 \text{ kJ/kg K}}$

b)  $T = 40 + 10 \times (5.2 - 5.1778)/(5.2654 - 5.1778) = \mathbf{42.53^\circ\text{C}}$   
 superheated vapor so  $x$  is undefined

c)  $x = (1.7 - 1.0243)/0.6995 = \mathbf{0.96598}$   
 $P = P_{\text{sat}} = \mathbf{350.9 \text{ kPa}}$

d) superheated vapor between 200 and 300 kPa  
 $P = 200 + 100 \times (1.9 - 1.9117)/(1.8755 - 1.9117) = \mathbf{232.3 \text{ kPa}}$

e)  $T = 40 + 10 \times (0.3 - 0.29739)/(0.30729 - 0.29739) = \mathbf{42.636^\circ\text{C}}$   
 $s = 1.1919 + 0.2636 \times (1.2132 - 1.1919) = \mathbf{1.1975 \text{ kJ/kg K}}$



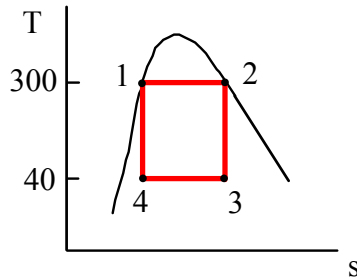
## Reversible processes

## 8.31

Consider a Carnot-cycle heat engine with water as the working fluid. The heat transfer to the water occurs at 300°C, during which process the water changes from saturated liquid to saturated vapor. The heat is rejected from the water at 40°C. Show the cycle on a  $T$ - $s$  diagram and find the quality of the water at the beginning and end of the heat rejection process. Determine the net work output per kilogram of water and the cycle thermal efficiency.

Solution:

From the definition of the Carnot cycle, two constant  $s$  and two constant  $T$  processes.



From table B.1.1

State 2 is saturated vapor so

$$s_3 = s_2 = 5.7044 \text{ kJ/kg K} \\ = 0.5724 + x_3(7.6845)$$

$$x_3 = \mathbf{0.6678}$$

State 1 is saturated liquid so

$$s_4 = s_1 = 3.2533 \text{ kJ/kg K} = 0.5724 + x_4(7.6845)$$

$$x_4 = \mathbf{0.3489}$$

$$\eta_{\text{TH}} = \frac{w_{\text{NET}}}{q_{\text{H}}} = \frac{T_{\text{H}} - T_{\text{L}}}{T_{\text{H}}} = \frac{260}{573.2} = \mathbf{0.4536}$$

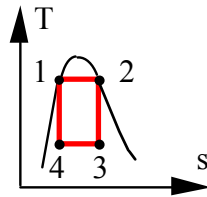
$$q_{\text{H}} = T_{\text{H}}(s_2 - s_1) = 573.2 \text{ K} (5.7044 - 3.2533) \text{ kJ/kg K} = 1405.0 \text{ kJ/kg}$$

$$w_{\text{NET}} = \eta_{\text{TH}} \times q_{\text{H}} = \mathbf{637.3 \text{ kJ/kg}}$$

## 8.32

In a Carnot engine with ammonia as the working fluid, the high temperature is  $60^\circ\text{C}$  and as  $Q_H$  is received, the ammonia changes from saturated liquid to saturated vapor. The ammonia pressure at the low temperature is  $190\text{ kPa}$ . Find  $T_L$ , the cycle thermal efficiency, the heat added per kilogram, and the entropy,  $s$ , at the beginning of the heat rejection process.

Solution:



Constant  $T \Rightarrow$  constant  $P$  from 1 to 2, Table B.2.1

$$\begin{aligned} q_H &= \int T ds = T (s_2 - s_1) = T s_{fg} \\ &= h_2 - h_1 = h_{fg} = \mathbf{997.0\text{ kJ/kg}} \end{aligned}$$

States 3 & 4 are two-phase, Table B.2.1

$$\Rightarrow T_L = T_3 = T_4 = T_{\text{sat}}(P) = \mathbf{-20^\circ\text{C}}$$

$$\eta_{\text{cycle}} = 1 - \frac{T_L}{T_H} = 1 - \frac{253.2}{333.2} = \mathbf{0.24}$$

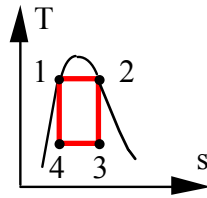
Table B.2.1:  $s_3 = s_2 = s_g(60^\circ\text{C}) = \mathbf{4.6577\text{ kJ/kg K}}$

## 8.33

Water is used as the working fluid in a Carnot cycle heat engine, where it changes from saturated liquid to saturated vapor at  $200^\circ\text{C}$  as heat is added. Heat is rejected in a constant pressure process (also constant  $T$ ) at  $20\text{ kPa}$ . The heat engine powers a Carnot cycle refrigerator that operates between  $-15^\circ\text{C}$  and  $+20^\circ\text{C}$ . Find the heat added to the water per kg water. How much heat should be added to the water in the heat engine so the refrigerator can remove  $1\text{ kJ}$  from the cold space?

Solution:

Carnot cycle heat engine:



Constant  $T \Rightarrow$  constant  $P$  from 1 to 2, Table B.2.1

$$q_H = \int T ds = T (s_2 - s_1) = T s_{fg} = h_{fg}$$

$$= 473.15 (4.1014) = \mathbf{1940\text{ kJ/kg}}$$

States 3 & 4 are two-phase, Table B.2.1

$$\Rightarrow T_L = T_3 = T_4 = T_{\text{sat}}(P) = 60.06^\circ\text{C}$$

Carnot cycle refrigerator ( $T_L$  and  $T_H$  are different from above):

$$\beta_{\text{ref}} = \frac{Q_L}{W} = \frac{T_L}{T_H - T_L} = \frac{273 - 15}{20 - (-15)} = \frac{258}{35} = 7.37$$

$$W = \frac{Q_L}{\beta} = \frac{1}{7.37} = 0.136\text{ kJ}$$

The needed work comes from the heat engine

$$W = \eta_{\text{HE}} Q_{H\text{H}_2\text{O}} ; \quad \eta_{\text{HE}} = 1 - \frac{T_L}{T_H} = 1 - \frac{333}{473} = 0.296$$

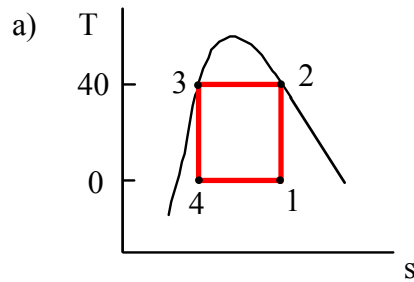
$$Q_{H\text{H}_2\text{O}} = \frac{W}{\eta_{\text{HE}}} = \frac{0.136}{0.296} = \mathbf{0.46\text{ kJ}}$$

## 8.34

Consider a Carnot-cycle heat pump with R-22 as the working fluid. Heat is rejected from the R-22 at 40°C, during which process the R-22 changes from saturated vapor to saturated liquid. The heat is transferred to the R-22 at 0°C.

- Show the cycle on a  $T$ - $s$  diagram.
- Find the quality of the R-22 at the beginning and end of the isothermal heat addition process at 0°C.
- Determine the coefficient of performance for the cycle.

Solution:



- b) From Table B.4.1, state 3 is saturated liquid

$$\begin{aligned}
 s_4 = s_3 &= 0.3417 \text{ kJ/kg K} \\
 &= 0.1751 + x_4(0.7518) \\
 \Rightarrow x_4 &= \mathbf{0.2216}
 \end{aligned}$$

State 2 is saturated vapor so from Table B.4.1

$$\begin{aligned}
 s_1 = s_2 &= 0.8746 \text{ kJ/kg K} = 0.1751 + x_1(0.7518) \\
 \Rightarrow x_1 &= \mathbf{0.9304}
 \end{aligned}$$

c)

$$\beta' = \frac{q_H}{w_{IN}} = \frac{T_H}{T_H - T_L} = \frac{313.2}{40} = \mathbf{7.83}$$

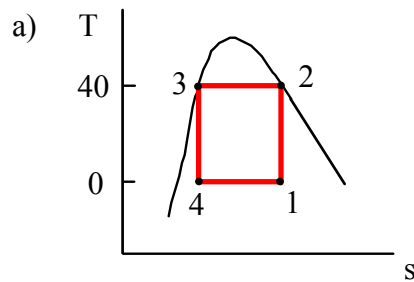
## 8.35

Do Problem 8.34 using refrigerant R-134a instead of R-22.

Consider a Carnot-cycle heat pump with R-22 as the working fluid. Heat is rejected from the R-22 at 40°C, during which process the R-22 changes from saturated vapor to saturated liquid. The heat is transferred to the R-22 at 0°C.

- Show the cycle on a  $T$ - $s$  diagram.
- Find the quality of the R-22 at the beginning and end of the isothermal heat addition process at 0°C.
- Determine the coefficient of performance for the cycle.

Solution:



- b) From Table B.5.1, state 3 is saturated liquid

$$s_4 = s_3 = 1.1909 \text{ kJ/kg K} \\ = 1.00 + x_4(0.7262)$$

$$\Rightarrow x_4 = \mathbf{0.2629}$$

State 2 is saturated vapor so from Table B.5.1

$$s_1 = s_2 = 1.7123 \text{ kJ/kg K} = 1.00 + x_1(0.7262)$$

$$\Rightarrow x_1 = \mathbf{0.9809}$$

c)

$$\beta' = \frac{q_H}{w_{IN}} = \frac{T_H}{T_H - T_L} = \frac{313.2}{40} = \mathbf{7.83}$$

## 8.36

Water at 200 kPa,  $x = 1.0$  is compressed in a piston/cylinder to 1 MPa, 250°C in a reversible process. Find the sign for the work and the sign for the heat transfer.

Solution:

State 1: Table B.1.1:

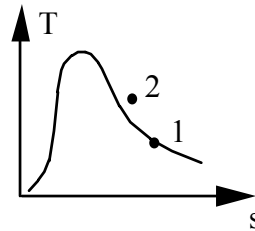
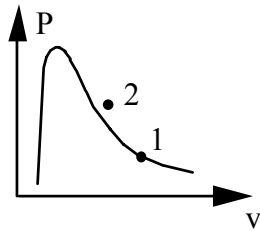
$$v_1 = 0.8857 \text{ m}^3/\text{kg}; \quad u_1 = 2529.5 \text{ kJ/kg}; \quad s_1 = 7.1271 \text{ kJ/kg K}$$

State 2: Table B.1.3:

$$v_2 = 0.23268 \text{ m}^3/\text{kg}; \quad u_2 = 2709.9 \text{ kJ/kg}; \quad s_2 = 6.9246 \text{ kJ/kg K}$$

$$v_2 < v_1 \quad \Rightarrow \quad {}_1w_2 = \int P \, dv < 0$$

$$s_2 < s_1 \quad \Rightarrow \quad {}_1q_2 = \int T \, ds < 0$$





## 8.37

Water at 200 kPa,  $x = 1.0$  is compressed in a piston/cylinder to 1 MPa, 350°C in a reversible process. Find the sign for the work and the sign for the heat transfer.

Solution:

$${}_1w_2 = \int P \, dv$$

so sign  $dv$

$${}_1q_2 = \int T \, ds$$

so sign  $ds$

B1.2  $v_1 = 0.88573 \text{ m}^3/\text{kg}$

$s_1 = 7.1271 \text{ kJ/kg K}$

B1.3  $v_2 = 0.28247 \text{ m}^3/\text{kg}$

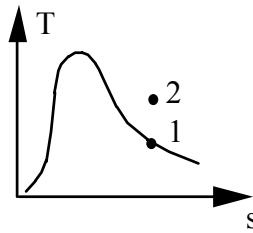
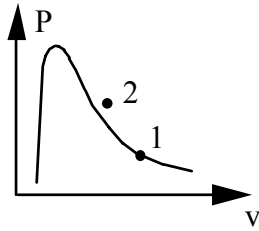
$s_2 = 7.301 \text{ kJ/kg K}$

$dv < 0 \quad \Rightarrow$

**w is negative**

$ds > 0 \quad \Rightarrow$

**q is positive**



## 8.38

Ammonia at 1 MPa, 50°C is expanded in a piston/cylinder to 500 kPa, 20°C in a reversible process. Find the sign for both the work and the heat transfer.

Solution:

$${}_1w_2 = \int P \, dv \quad \text{so sign } dv$$

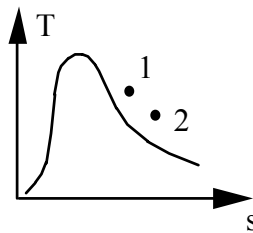
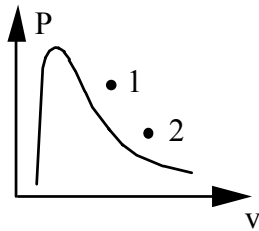
$${}_1q_2 = \int T \, ds \quad \text{so sign } ds$$

$$\text{B.2.2 } v_1 = 0.14499 \, \text{m}^3/\text{kg} \quad s_1 = 5.2654 \, \text{kJ/kg K}$$

$$\text{B.2.2 } v_2 = 0.26949 \, \text{m}^3/\text{kg} \quad s_2 = 5.4244 \, \text{kJ/kg K}$$

$$dv > 0 \quad \Rightarrow \quad \mathbf{w \text{ is positive}}$$

$$ds > 0 \quad \Rightarrow \quad \mathbf{q \text{ is positive}}$$



## 8.39

One kilogram of ammonia in a piston/cylinder at 50°C, 1000 kPa is expanded in a reversible isothermal process to 100 kPa. Find the work and heat transfer for this process.

Solution:

C.V.: NH<sub>3</sub> This is a control mass  $m_2 = m_1$  with a reversible process

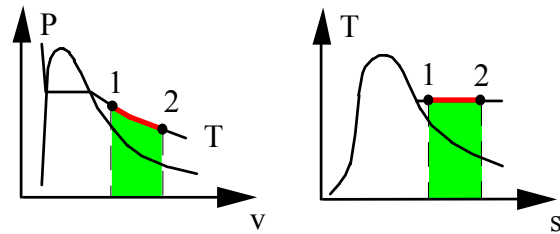
$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.3: } m(s_2 - s_1) = \int (1/T) dQ = {}_1Q_2/T \quad (= \text{since reversible})$$

$$\text{Rev.: } {}_1W_2 = \int PdV$$

$${}_1Q_2 = \int Tm ds = mT(s_2 - s_1)$$

From Table B.2.2



$$\text{State 1: } u_1 = 1391.3 \text{ kJ/kg; } s_1 = 5.265 \text{ kJ/kg K}$$

$$\text{State 2: } u_2 = 1424.7 \text{ kJ/kg; } s_2 = 6.494 \text{ kJ/kg K; } v_2 = 1.5658 \text{ m}^3/\text{kg;}$$

$$h_2 = 1581.2 \text{ kJ/kg}$$

$${}_1Q_2 = 1 \text{ kg } (273 + 50) \text{ K } (6.494 - 5.265) \text{ kJ/kg K} = \mathbf{396.967 \text{ kJ}}$$

$${}_1W_2 = {}_1Q_2 - m(u_2 - u_1) = \mathbf{363.75 \text{ kJ}}$$

## 8.40

One kilogram of ammonia in a piston/cylinder at 50°C, 1000 kPa is expanded in a reversible isobaric process to 140°C. Find the work and heat transfer for this process.

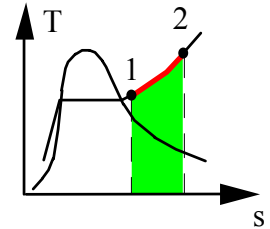
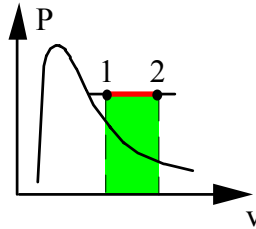
Solution:

Control mass.

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

Process:  $P = \text{constant}$

$$\Rightarrow {}_1W_2 = mP(v_2 - v_1)$$



State 1: Table B.2.2  $v_1 = 0.145 \text{ m}^3/\text{kg}$ ,  $u_1 = 1391.3 \text{ kJ/kg}$

State 2: Table B.2.2  $v_2 = 0.1955 \text{ m}^3/\text{kg}$ ,  $u_2 = 1566.7 \text{ kJ/kg}$

$${}_1W_2 = 1 \times 1000(0.1955 - 0.145) = \mathbf{50.5 \text{ kJ}}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1 \times (1566.7 - 1391.3) + 50.5 = \mathbf{225.9 \text{ kJ}}$$

## 8.41

One kilogram of ammonia in a piston/cylinder at 50°C, 1000 kPa is expanded in a reversible adiabatic process to 100 kPa. Find the work and heat transfer for this process.

Solution:

Control mass: Energy Eq.5.11:  $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.8.3:  $m(s_2 - s_1) = \int dQ/T$  (= since reversible)

Process:  ${}_1Q_2 = 0 \Rightarrow s_2 = s_1$

State 1: (P, T) Table B.2.2,  $u_1 = 1391.3$  kJ/kg,  $s_1 = 5.2654$  kJ/kg K

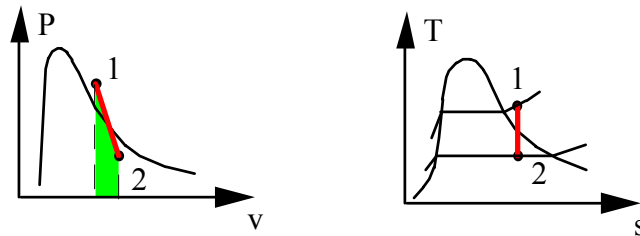
State 2:  $P_2, s_2 \Rightarrow$  2 phase Table B.2.1

Interpolate:  $s_{g2} = 5.8404$  kJ/kg K,  $s_f = 0.1192$  kJ/kg K

$$x_2 = \frac{s - s_f}{s_{fg}} = \frac{5.2654 - 0.1192}{5.7212} = 0.90,$$

$$u_2 = u_f + x_2 u_{fg} = 27.66 + 0.9 \times 1257.0 = 1158.9 \text{ kJ/kg}$$

$${}_1W_2 = 1 \times (1391.3 - 1158.9) = \mathbf{232.4 \text{ kJ}}$$



## 8.42

A cylinder fitted with a piston contains ammonia at 50°C, 20% quality with a volume of 1 L. The ammonia expands slowly, and during this process heat is transferred to maintain a constant temperature. The process continues until all the liquid is gone. Determine the work and heat transfer for this process.

Solution:

C.V. Ammonia in the cylinder.

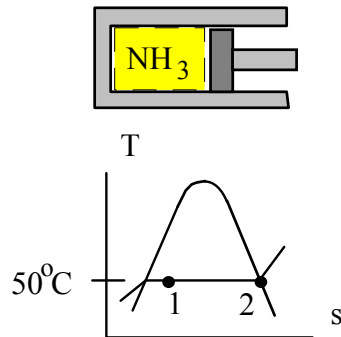


Table B.2.1:  $T_1 = 50^\circ\text{C}$ ,  $x_1 = 0.20$ ,  $V_1 = 1 \text{ L}$

$$v_1 = 0.001777 + 0.2 \times 0.06159 = 0.014095 \text{ m}^3/\text{kg}$$

$$s_1 = 1.5121 + 0.2 \times 3.2493 = 2.1620 \text{ kJ/kg K}$$

$$m = V_1/v_1 = 0.001/0.014095 = 0.071 \text{ kg}$$

$$v_2 = v_g = 0.06336 \text{ m}^3/\text{kg},$$

$$s_2 = s_g = 4.7613 \text{ kJ/kg K}$$

Process:  $T = \text{constant to } x_2 = 1.0$ ,  $P = \text{constant} = 2.033 \text{ MPa}$

From the constant pressure process

$${}_1W_2 = \int PdV = Pm(v_2 - v_1) = 2033 \times 0.071 \times (0.06336 - 0.014095) = \mathbf{7.11 \text{ kJ}}$$

From the second law Eq.8.3 with constant T

$${}_1Q_2 = \int TdS = Tm(s_2 - s_1) = 323.2 \times 0.071(4.7613 - 2.1620) = \mathbf{59.65 \text{ kJ}}$$

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

$$h_1 = 421.48 + 0.2 \times 1050.01 = 631.48 \text{ kJ/kg}, \quad h_2 = 1471.49 \text{ kJ/kg}$$

$${}_1Q_2 = 0.071(1471.49 - 631.48) = \mathbf{59.65 \text{ kJ}}$$

8.43

An insulated cylinder fitted with a piston contains 0.1 kg of water at 100°C, 90% quality. The piston is moved, compressing the water until it reaches a pressure of 1.2 MPa. How much work is required in the process?

Solution:

C.V. Water in cylinder.

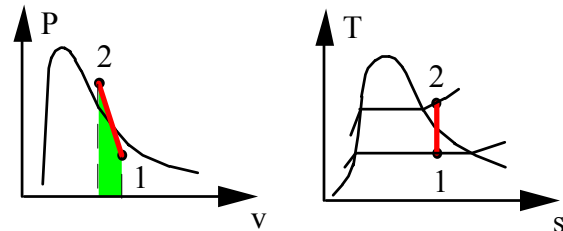
$$\text{Energy Eq.5.11: } {}_1Q_2 = 0 = m(u_2 - u_1) + {}_1W_2$$

$$\text{Entropy Eq.8.3: } m(s_2 - s_1) = \int dQ/T = 0 \quad (\text{assume reversible})$$

State 1: 100°C,  $x_1 = 0.90$ :

Table B.1.1,

$$s_1 = 1.3068 + 0.90 \times 6.048 \\ = 6.7500 \text{ kJ/kg K}$$



$$u_1 = 418.91 + 0.9 \times 2087.58 = 2297.7 \text{ kJ/kg}$$

$$\text{State 2: Given by (P, s) B.1.3 } \left. \begin{array}{l} s_2 = s_1 = 6.7500 \\ P_2 = 1.2 \text{ MPa} \end{array} \right\} \Rightarrow \left\{ \begin{array}{l} T_2 = 232.3^\circ\text{C} \\ u_2 = 2672.9 \end{array} \right.$$

$${}_1W_2 = -m(u_2 - u_1) = -0.1(2672.9 - 2297.7) = \mathbf{-37.5 \text{ kJ}}$$

## 8.44

Compression and heat transfer brings R-134a in a piston/cylinder from 500 kPa, 50°C to saturated vapor in an isothermal process. Find the specific heat transfer and the specific work.

Solution:

$m = \text{constant}$

Energy Eq.5.11:  $u_2 - u_1 = {}_1q_2 - {}_1w_2$

Entropy Eq.8.3:  $s_2 - s_1 = \int dq/T = {}_1q_2/T$

Process:  $T = C$  and assume reversible  $\Rightarrow {}_1q_2 = T(s_2 - s_1)$

State 1: Table B.5.2:

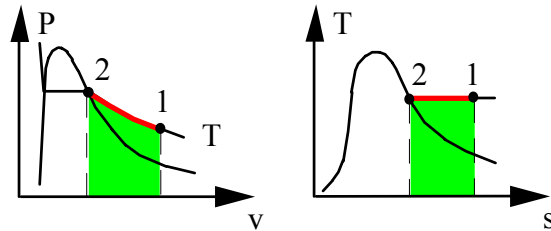
$$u_1 = 415.91 \text{ kJ/kg,}$$

$$s_1 = 1.827 \text{ kJ/kg K}$$

State 2: Table B.5.1

$$u_2 = 403.98 \text{ kJ/kg,}$$

$$s_2 = 1.7088 \text{ kJ/kg K}$$



$${}_1q_2 = (273 + 50) \times (1.7088 - 1.827) = \mathbf{-38.18 \text{ kJ/kg}}$$

$${}_1w_2 = {}_1q_2 + u_1 - u_2 = -38.18 + 415.91 - 403.98$$

$$= \mathbf{-26.25 \text{ kJ/kg}}$$



## 8.45

One kilogram of water at 300°C expands against a piston in a cylinder until it reaches ambient pressure, 100 kPa, at which point the water has a quality of 90.2%. It may be assumed that the expansion is reversible and adiabatic. What was the initial pressure in the cylinder and how much work is done by the water?

Solution:

C.V. Water. Process: Rev.,  $Q = 0$

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = -{}_1W_2$$

$$\text{Entropy Eq.8.3: } m(s_2 - s_1) = \int dQ/T$$

Process: Adiabatic  $Q = 0$  and reversible  $\Rightarrow s_2 = s_1$

State 2:  $P_2 = 100 \text{ kPa}$ ,  $x_2 = 0.902$  from Table B.1.2

$$s_2 = 1.3026 + 0.902 \times 6.0568 = 6.7658 \text{ kJ/kg K}$$

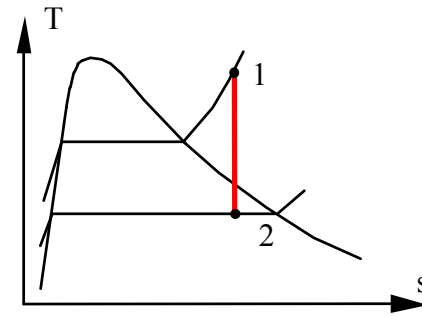
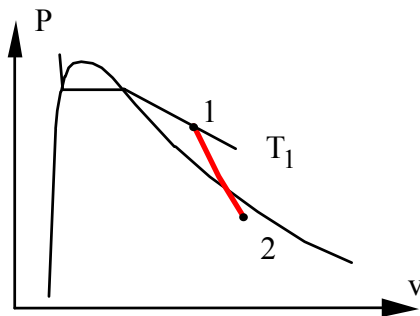
$$u_2 = 417.36 + 0.902 \times 2088.7 = 2301.4 \text{ kJ/kg}$$

State 1 At  $T_1 = 300^\circ\text{C}$ ,  $s_1 = 6.7658$  Find it in Table B.1.3

$$\Rightarrow P_1 = \mathbf{2000 \text{ kPa}}, \quad u_1 = 2772.6 \text{ kJ/kg}$$

From the energy equation

$${}_1W_2 = m(u_1 - u_2) = 1(2772.6 - 2301.4) = \mathbf{471.2 \text{ kJ}}$$



## 8.46

Water in a piston/cylinder at  $400^\circ\text{C}$ ,  $2000\text{ kPa}$  is expanded in a reversible adiabatic process. The specific work is measured to be  $415.72\text{ kJ/kg}$  out. Find the final  $P$  and  $T$  and show the  $P$ - $v$  and the  $T$ - $s$  diagram for the process.

Solution:

C.V. Water, which is a control mass. Adiabatic so:  ${}_1q_2 = 0$

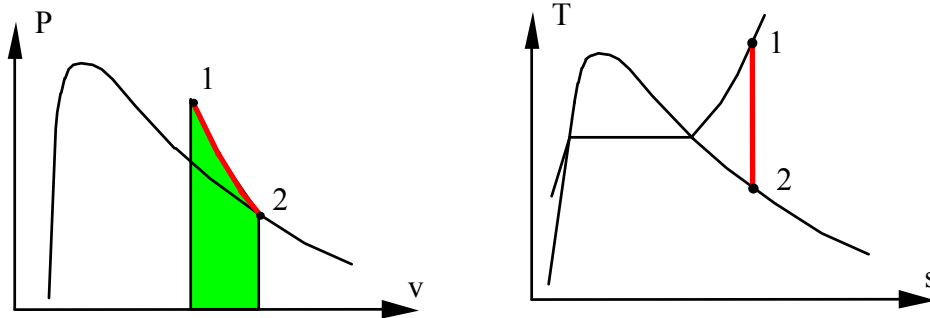
Energy Eq.5.11:  $u_2 - u_1 = {}_1q_2 - {}_1w_2 = -{}_1w_2$

Entropy Eq.8.3:  $s_2 - s_1 = \int dq/T = 0$  (= since reversible)

State 1: Table B.1.3  $u_1 = 2945.21\text{ kJ/kg}$ ;  $s_1 = 7.127\text{ kJ/kg K}$

State 2: (s, u):  $u_2 = u_1 - {}_1w_2 = 2945.21 - 415.72 = 2529.49\text{ kJ/kg}$

$\Rightarrow$  **sat. vapor  $200\text{ kPa}$ ,  $T = 120.23^\circ\text{C}$**



## 8.47

A piston/cylinder has 2 kg ammonia at 50°C, 100 kPa which is compressed to 1000 kPa. The process happens so slowly that the temperature is constant. Find the heat transfer and work for the process assuming it to be reversible.

Solution:

CV : NH<sub>3</sub> Control Mass

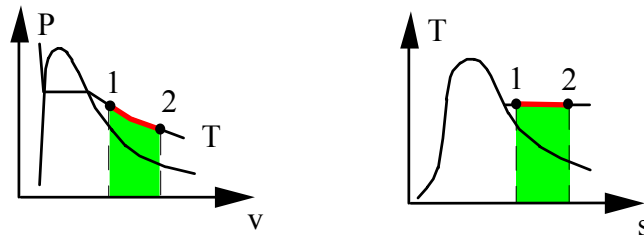
Energy Eq.5.11:  $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$  ;

Entropy Eq.8.3:  $m(s_2 - s_1) = \int dQ/T$

Process:  $T = \text{constant}$  and assume reversible process

1: (T,P), Table B.2.2:  $v_1 = 1.5658 \text{ m}^3/\text{kg}$ ,  $u_1 = 1424.7 \text{ kJ/kg}$ ,  
 $s_1 = 6.4943 \text{ kJ/kg K}$

2: (T,P), Table B.2.2:  $v_2 = 0.1450 \text{ m}^3/\text{kg}$ ,  $u_2 = 1391.3 \text{ kJ/kg}$ ,  
 $s_2 = 5.2654 \text{ kJ/kg K}$



From the entropy equation (2nd law)

$${}_1Q_2 = mT(s_2 - s_1) = 2 \times 323.15 (5.2654 - 6.4943) = \mathbf{-794.2 \text{ kJ}}$$

From the energy equation

$${}_1W_2 = {}_1Q_2 - m(u_2 - u_1) = -794.24 - 2(1391.3 - 1424.62) = \mathbf{-727.6 \text{ kJ}}$$

## 8.48

A piston cylinder has R-134a at  $-20^{\circ}\text{C}$ , 100 kPa which is compressed to 500 kPa in a reversible adiabatic process. Find the final temperature and the specific work.

Solution:

C.V. R-134a, Control mass of unknown size, adiabatic  ${}_1q_2 = 0$

Energy Eq.5.11:  $u_2 - u_1 = {}_1q_2 - {}_1w_2 = -{}_1w_2$

Entropy Eq.8.3:  $s_2 - s_1 = \int dq/T$

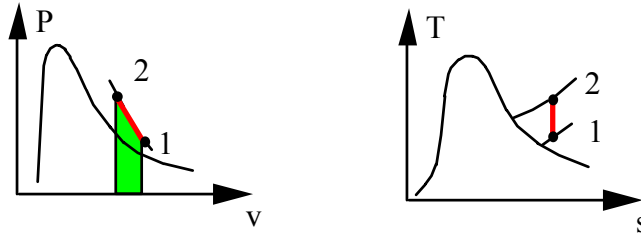
Process: Adiabatic and reversible  $\Rightarrow s_2 = s_1$

State 1: (T, P) B.5.2  $u_1 = 367.36 \text{ kJ/kg}$ ,  $s_1 = 1.7665 \text{ kJ/kg K}$

State 2: (P, s) B.5.2  $P_2 = 500 \text{ kPa}$ ,  $s_2 = s_1 = 1.7665 \text{ kJ/kg K}$

very close at  $30^{\circ}\text{C}$   $u_2 = 398.99 \text{ kJ/kg}$

$${}_1w_2 = u_2 - u_1 = 367.36 - 398.99 = \mathbf{-31.63 \text{ kJ/kg}}$$



## 8.49

A closed tank,  $V = 10$  L, containing 5 kg of water initially at  $25^\circ\text{C}$ , is heated to  $175^\circ\text{C}$  by a heat pump that is receiving heat from the surroundings at  $25^\circ\text{C}$ . Assume that this process is reversible. Find the heat transfer to the water and the change in entropy.

Solution:

C.V.: Water from state 1 to state 2.

$$\text{Energy Eq. 5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq. 8.3: } m(s_2 - s_1) = \int dQ/T$$

Process: constant volume (reversible isometric) so  ${}_1W_2 = 0$

State 1:  $v_1 = V/m = 0.002$  from Table B.1.1

$$x_1 = (0.002 - 0.001003)/43.358 = 0.000023$$

$$u_1 = 104.86 + 0.000023 \times 2304.9 = 104.93 \text{ kJ/kg}$$

$$s_1 = 0.3673 + 0.000023 \times 8.1905 = 0.36759 \text{ kJ/kg K}$$

Continuity eq. (same mass) and  $V = C$  fixes  $v_2$

State 2:  $T_2, v_2 = v_1$  so from Table B.1.1

$$x_2 = (0.002 - 0.001121)/0.21568 = 0.004075$$

$$u_2 = 740.16 + 0.004075 \times 1840.03 = 747.67 \text{ kJ/kg}$$

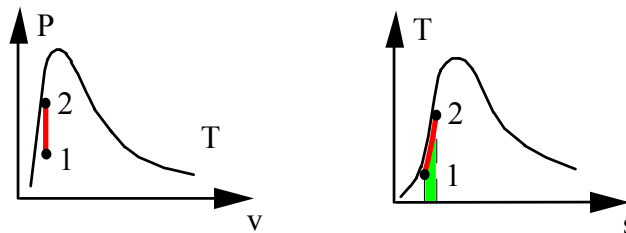
$$s_2 = 2.0909 + 0.004075 \times 4.5347 = 2.1094 \text{ kJ/kg K}$$

Energy eq. has  $W = 0$ , thus provides heat transfer as

$${}_1Q_2 = m(u_2 - u_1) = 3213.7 \text{ kJ}$$

The entropy change becomes

$$m(s_2 - s_1) = 5(2.1094 - 0.36759) = \mathbf{8.709 \text{ kJ/K}}$$



Notice we do not perform the integration  $\int dQ/T$  to find change in  $s$  as the equation for the  $dQ$  as a function of  $T$  is not known.

## 8.50

A cylinder containing R-134a at 10°C, 150 kPa, has an initial volume of 20 L. A piston compresses the R-134a in a reversible, isothermal process until it reaches the saturated vapor state. Calculate the required work and heat transfer to accomplish this process.

Solution:

C.V. R-134a.

Cont.Eq.:  $m_2 = m_1 = m$  ;

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

Entropy Eq.8.3:  $m(s_2 - s_1) = \int dQ/T$

Process:  $T = \text{constant}$ , reversible

State 1: (T, P) Table B.5.2  $u_1 = 388.36 \text{ kJ/kg}$ ,  $s_1 = 1.822 \text{ kJ/kg K}$

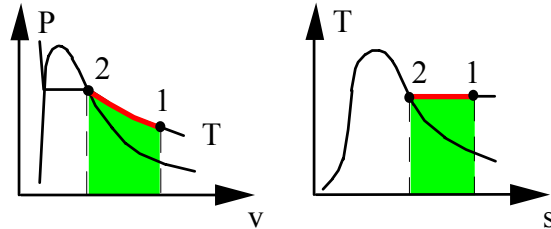
$$m = V/v_1 = 0.02/0.148283 = 0.1349 \text{ kg}$$

State 2: (10°C, sat. vapor)

Table B.5.1

$$u_2 = 383.67 \text{ kJ/kg},$$

$$s_2 = 1.7218 \text{ kJ/kg K}$$



As  $T$  is constant we can find  $Q$  by integration as

$${}_1Q_2 = \int T ds = mT(s_2 - s_1) = 0.1349 \times 283.15 \times (1.7218 - 1.822) = \mathbf{-3.83 \text{ kJ}}$$

The work is then from the energy equation

$${}_1W_2 = m(u_1 - u_2) + {}_1Q_2 = 0.1349 \times (388.36 - 383.67) - 3.83 = \mathbf{-3.197 \text{ kJ}}$$

## 8.51

A heavily-insulated cylinder fitted with a frictionless piston, as shown in Fig. P8.51 contains ammonia at 5°C, 92.9% quality, at which point the volume is 200 L. The external force on the piston is now increased slowly, compressing the ammonia until its temperature reaches 50°C. How much work is done by the ammonia during this process?

Solution:

C.V. ammonia in cylinder, insulated so assume adiabatic  $Q = 0$ .

Cont.Eq.:  $m_2 = m_1 = m$  ;

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

Entropy Eq.8.3:  $m(s_2 - s_1) = \int dQ/T$

State 1:  $T_1 = 5^\circ\text{C}$ ,  $x_1 = 0.929$ ,  $V_1 = 200 \text{ L} = 0.2 \text{ m}^3$

Table B.2.1 saturated vapor,  $P_1 = P_g = 515.9 \text{ kPa}$

$$v_1 = v_f + x_1 v_{fg} = 0.001583 + 0.929 \times 0.2414 = 0.2258 \text{ m}^3/\text{kg},$$

$$u_1 = u_f + x_1 u_{fg} = 202.8 + 0.929 \times 1119.2 = 1242.5 \text{ kJ/kg}$$

$$s_1 = s_f + x_1 s_{fg} = 0.7951 + 0.929 \times 4.44715 = 4.9491 \text{ kJ/kg K},$$

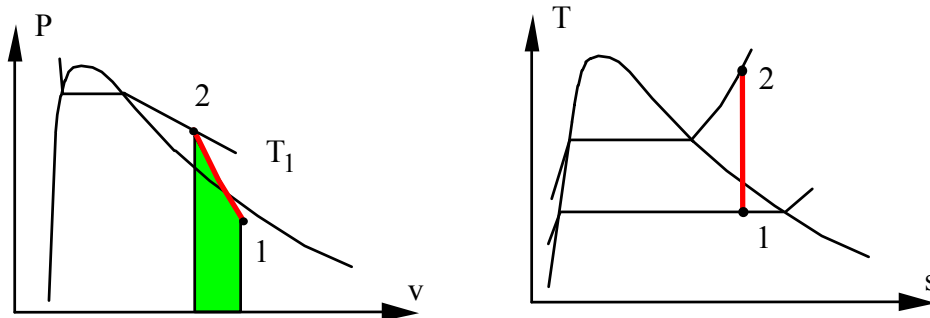
$$m_1 = V_1/v_1 = 0.2 / 0.2258 = 0.886 \text{ kg}$$

Process:  $1 \rightarrow 2$  Adiabatic  ${}_1Q_2 = 0$  & Reversible  $\Rightarrow s_1 = s_2$

State 2:  $T_2 = 50^\circ\text{C}$ ,  $s_2 = s_1 = 4.9491 \text{ kJ/kg K}$

superheated vapor, interpolate in Table B.2.2  $\Rightarrow$

$$P_2 = 1600 \text{ kPa}, \quad u_2 = 1364.9 \text{ kJ/kg}$$



Energy equation gives the work as

$${}_1W_2 = m(u_1 - u_2) = 0.886 (1242.5 - 1364.9) = -108.4 \text{ kJ}$$

## 8.52

A piston/cylinder has 2 kg water at 1000 kPa, 250°C which is now cooled with a constant loading on the piston. This isobaric process ends when the water has reached a state of saturated liquid. Find the work and heat transfer and sketch the process in both a P-v and a T-s diagram.

Solution:

C.V. H<sub>2</sub>O

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.3: } m(s_2 - s_1) = \int dQ/T$$

$$\text{Process: } P = C \Rightarrow W = \int P dV = P(V_2 - V_1)$$

$$\text{State 1: B.1.3 } v_1 = 0.23268 \text{ m}^3/\text{kg}, s_1 = 6.9246 \text{ kJ/kg K}, u_1 = 2709.91 \text{ kJ/kg}$$

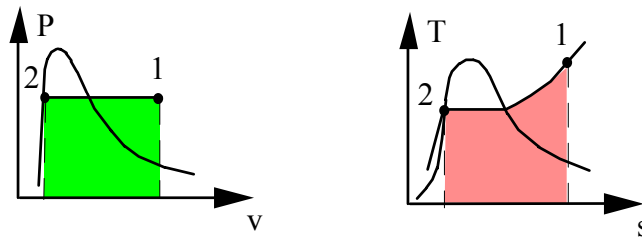
$$\text{State 2: B.1.2 } v_2 = 0.001127 \text{ m}^3/\text{kg}, s_2 = 2.1386 \text{ kJ/kg K}, u_2 = 761.67 \text{ kJ/kg}$$

From the process equation

$${}_1W_2 = m P (v_2 - v_1) = 2 \times 1000 (0.001127 - 0.23268) = \mathbf{-463.1 \text{ kJ}}$$

From the energy equation we get

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 2 (761.67 - 2709.91) - 463.1 = \mathbf{-4359.6 \text{ kJ}}$$





## 8.53

Water at 1000 kPa, 250°C is brought to saturated vapor in a piston/cylinder with an isothermal process. Find the specific work and heat transfer. Estimate the specific work from the area in the P-v diagram and compare it to the correct value.

Solution:

$$\text{Continuity Eq.: } m_2 = m_1 = m ;$$

$$\text{Energy Eq.:5.11 } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.3: } m(s_2 - s_1) = \int dQ/T$$

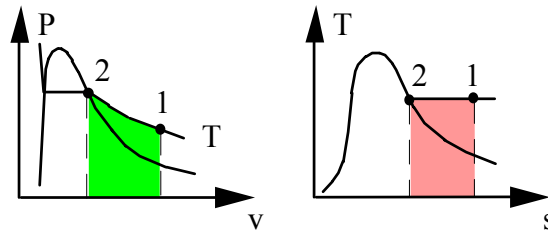
Process:  $T = \text{constant}$ , reversible

State 1: Table B.1.3:

$$v_1 = 0.23268 \text{ m}^3/\text{kg}; \quad u_1 = 2709.91 \text{ kJ/kg}; \quad s_1 = 6.9246 \text{ kJ/kg K}$$

State 2: (T, x) Table B.1.1  $P_2 = 3973 \text{ kPa}$

$$v_2 = 0.05013 \text{ m}^3/\text{kg}, \quad u_2 = 2602.37 \text{ kJ/kg}, \quad s_2 = 6.0729 \text{ kJ/kg K}$$



From the entropy equation

$${}_1q_2 = \int T ds = T(s_2 - s_1) = (250 + 273)(6.0729 - 6.9246) = \mathbf{-445.6 \text{ kJ/kg}}$$

From the energy equation

$${}_1w_2 = {}_1q_2 + u_1 - u_2 = -445.6 + 2709.91 - 2602.37 = \mathbf{-338 \text{ kJ/kg}}$$

Estimation of the work term from the area in the P-v diagram

$$\begin{aligned} {}_1w_2 \text{ area} &\cong \frac{1}{2} (P_1 + P_2)(v_2 - v_1) = \frac{1}{2}(1000 + 3973)(0.05013 - 0.23268) \\ &= \mathbf{-454 \text{ kJ/kg}} \end{aligned}$$

Not extremely accurate estimate; P-v curve not linear more like  $Pv = \text{constant}$  as curve has positive curvature the linear variation over-estimates area.

## 8.54

Water at 1000 kPa, 250°C is brought to saturated vapor in a rigid container, shown in Fig. P8.54. Find the final T and the specific heat transfer in this isometric process.

Solution:

$$\text{Energy Eq.5.11: } u_2 - u_1 = {}_1q_2 - {}_1w_2$$

$$\text{Entropy Eq.8.3: } s_2 - s_1 = \int dq/T$$

$$\text{Process: } v = \text{constant} \Rightarrow {}_1w_2 = 0$$

$$\text{State 1: (T, P) Table B.1.3 } u_1 = 2709.91 \text{ kJ/kg, } v_1 = 0.23268 \text{ m}^3/\text{kg}$$

$$\text{State 2: } x = 1 \text{ and } v_2 = v_1 \text{ so from Table B.1.1 we see } P_2 \cong 800 \text{ kPa}$$

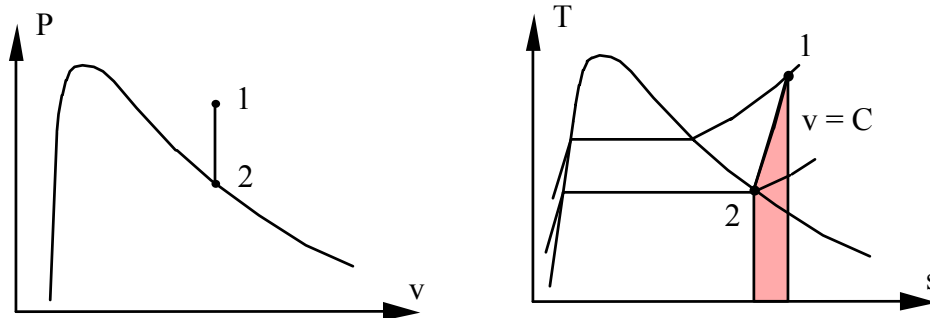
$$T_2 = 170 + 5 \times (0.23268 - 0.24283)/(0.2168 - 0.24283)$$

$$= 170 + 5 \times 0.38993 = \mathbf{171.95^\circ\text{C}}$$

$$u_2 = 2576.46 + 0.38993 \times (2580.19 - 2576.46) = 2577.9 \text{ kJ/kg}$$

From the energy equation

$${}_1q_2 = u_2 - u_1 = 2577.9 - 2709.91 = \mathbf{-132 \text{ kJ/kg}}$$



Notice to get  ${}_1q_2 = \int T ds$  we must know the function  $T(s)$  which we do not readily have for this process.

**8.55**

Estimate the specific heat transfer from the area in the T-s diagram and compare it to the correct value for the states and process in Problem 8.54.

Solution:

$$\text{Energy Eq.5.11: } u_2 - u_1 = {}_1q_2 - {}_1w_2$$

$$\text{Entropy Eq.8.3: } s_2 - s_1 = \int dq/T$$

$$\text{Process: } v = \text{constant} \Rightarrow {}_1w_2 = 0$$

$$\text{State 1: (T, P) Table B.1.3 } u_1 = 2709.91 \text{ kJ/kg, } v_1 = 0.23268 \text{ m}^3/\text{kg}, \\ s_1 = 6.9246 \text{ kJ/kg K}$$

$$\text{State 2: } x = 1 \text{ and } v_2 = v_1 \text{ so from Table B.1.1 we see } P_2 \cong 800 \text{ kPa}$$

$$T_2 = 170 + 5 \times (0.23268 - 0.24283)/(0.2168 - 0.24283)$$

$$= 170 + 5 \times 0.38993 = \mathbf{171.95^\circ\text{C}}$$

$$u_2 = 2576.46 + 0.38993 \times (2580.19 - 2576.46) = 2577.9 \text{ kJ/kg}$$

$$s_2 = 6.6663 + 0.38993 (6.6256 - 6.6663) = 6.6504 \text{ kJ/kg K}$$

From the energy equation

$${}_1q_2 \text{ actual} = u_2 - u_1 = 2577.9 - 2709.91 = \mathbf{-132 \text{ kJ/kg}}$$

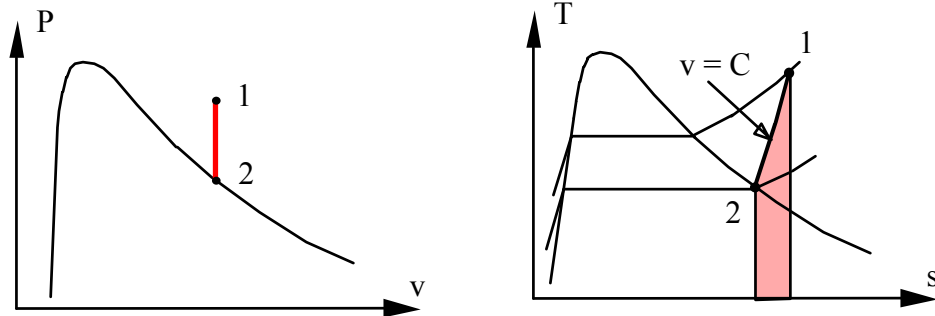
Assume a linear variation of T versus s.

$${}_1q_2 = \int T ds = \text{area} \cong \frac{1}{2} (T_1 + T_2)(s_2 - s_1)$$

$$= \frac{1}{2} (171.95 + (2 \times 273.15) + 250)(6.6504 - 6.9246)$$

$$= \mathbf{-132.74 \text{ kJ/kg}}$$

very close i.e. the  $v = C$  curve is close to a straight line in the T-s diagram. Look at the constant  $v$  curves in Fig. E.1. In the two-phase region they curve slightly and more so in the region above the critical point.



## 8.56

Water at 1000 kPa, 250°C is brought to saturated vapor in a piston/cylinder with an isobaric process. Find the specific work and heat transfer. Estimate the specific heat transfer from the area in the T-s diagram and compare it to the correct value.

Solution:

C.V. H<sub>2</sub>O

$$\text{Energy Eq.5.11: } u_2 - u_1 = {}_1q_2 - {}_1w_2$$

$$\text{Entropy Eq.8.3: } s_2 - s_1 = \int dq/T$$

$$\text{Process: } P = C \quad \Rightarrow \quad w = \int P dv = P(v_2 - v_1)$$

$$1: \text{B1.3 } v_1 = 0.23268 \text{ m}^3/\text{kg}, \quad s_1 = 6.9246 \text{ kJ/kgK}, \quad u_1 = 2709.91 \text{ kJ/kg}$$

$$2: \text{B1.3 } v_2 = 0.19444 \text{ m}^3/\text{kg}, \quad s_2 = 6.5864 \text{ kJ/kg K}, \quad u_2 = 2583.64 \text{ kJ/kg}, \\ T_2 = 179.91^\circ\text{C}$$

From the process equation

$${}_1w_2 = P(v_2 - v_1) = 1000(0.1944 - 0.23268) = \mathbf{-38.28 \text{ kJ/kg}}$$

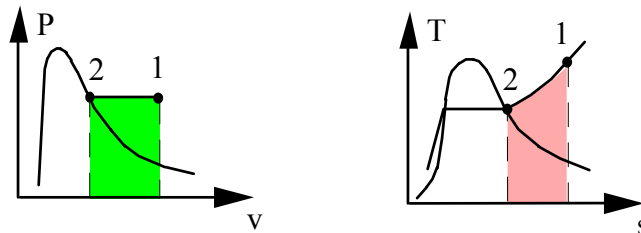
From the energy equation

$${}_1q_2 = u_2 - u_1 + {}_1w_2 = 2583.64 - 2709.91 - 38.28 = \mathbf{-164.55 \text{ kJ/kg}}$$

Now estimate the heat transfer from the T-s diagram.

$${}_1q_2 = \int T ds = \text{AREA} \cong \frac{1}{2}(T_1 + T_2)(s_2 - s_1) \\ = \frac{1}{2}(250 + 179.91 + 2 \times 273.15)(6.5864 - 6.9246) \\ = 488.105 \times (-0.3382) = \mathbf{-165.1 \text{ kJ/kg}}$$

very close approximation. The  $P = C$  curve in the T-s diagram is nearly a straight line. Look at the constant P curves on Fig.E.1. Up over the critical point they curve significantly.



## 8.57

A heavily insulated cylinder/piston contains ammonia at 1200 kPa, 60°C. The piston is moved, expanding the ammonia in a reversible process until the temperature is -20°C. During the process 600 kJ of work is given out by the ammonia. What was the initial volume of the cylinder?

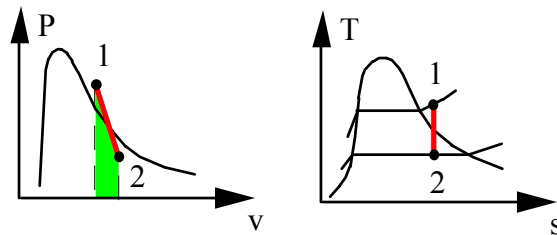
C.V. ammonia. Control mass with no heat transfer.

State 1: Table B.2.2  $v_1 = 0.1238 \text{ m}^3/\text{kg}$ ,  $s_1 = 5.2357 \text{ kJ/kg K}$

$$u_1 = h - Pv = 1553.3 - 1200 \times 0.1238 = 1404.9 \text{ kJ/kg}$$

Entropy Eq.:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2_{\text{gen}}$

Process: reversible ( ${}_1S_2_{\text{gen}} = 0$ ) and adiabatic ( $dQ = 0$ )  $\Rightarrow s_2 = s_1$



State 2:  $T_2, s_2 \Rightarrow x_2 = (5.2357 - 0.3657)/5.2498 = 0.928$

$$u_2 = 88.76 + 0.928 \times 1210.7 = 1211.95 \text{ kJ/kg}$$

$${}_1Q_2 = 0 = m(u_2 - u_1) + {}_1W_2 = m(1211.95 - 1404.9) + 600$$

$$\Rightarrow m = 3.110 \text{ kg}$$

$$V_1 = mv_1 = 3.11 \times 0.1238 = \mathbf{0.385 \text{ m}^3}$$

## 8.58

Water at 1000 kPa, 250°C is brought to saturated vapor in a piston/cylinder with an adiabatic process. Find the final T and the specific work. Estimate the specific work from the area in the P-v diagram and compare it to the correct value.

Solution:

C.V. Water, which is a control mass with unknown size.

$$\text{Energy Eq.5.11: } u_2 - u_1 = 0 - {}_1w_2$$

$$\text{Entropy Eq.8.3: } s_2 - s_1 = \int dq/T = 0$$

Process: Adiabatic  ${}_1q_2 = 0$  and reversible as used above

$$\text{State 1: Table B.1.3 } v_1 = 0.23268 \text{ m}^3/\text{kg}, \quad u_1 = 2709.91 \text{ kJ/kg}, \\ s_1 = 6.9246 \text{ kJ/kg K}$$

$$\text{State 2: Table B.1.1 } x = 1 \quad \text{and} \quad s_2 = s_1 = 6.9246 \text{ kJ/kg K}$$

$$\Rightarrow T_2 \cong 140.56^\circ\text{C}, \quad P_2 \cong 367.34 \text{ kPa}, \quad v_2 = 0.50187 \text{ m}^3/\text{kg}, \\ u_2 \cong 2550.56 \text{ kJ/kg}$$

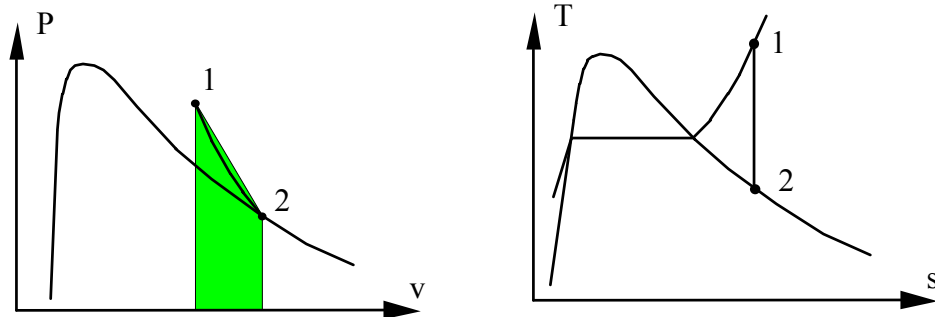
From the energy equation

$${}_1w_2 = u_1 - u_2 = 2709.91 - 2550.56 = 159.35 \text{ kJ/kg}$$

Now estimate the work term from the area in the P-v diagram

$${}_1w_2 \cong \frac{1}{2} (P_1 + P_2)(v_2 - v_1) \\ = \frac{1}{2} (1000 + 367.34)(0.50187 - 0.23268) \\ = \mathbf{184 \text{ kJ/kg}}$$

The  $s = \text{constant}$  curve is not a straight line in the the P-v diagram, notice the straight line overestimates the area slightly.



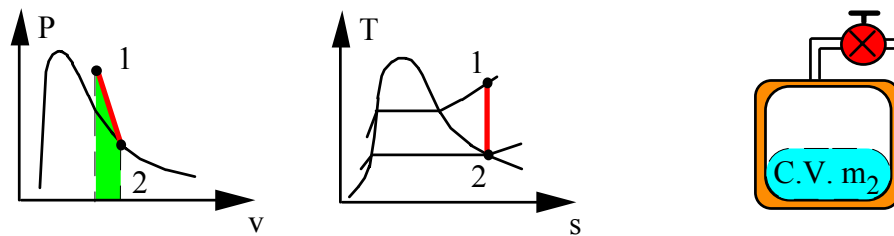
8.59

A rigid, insulated vessel contains superheated vapor steam at 3 MPa, 400°C. A valve on the vessel is opened, allowing steam to escape. The overall process is irreversible, but the steam remaining inside the vessel goes through a reversible adiabatic expansion. Determine the fraction of steam that has escaped, when the final state inside is saturated vapor.

C.V.: steam remaining inside tank. Rev. & Adiabatic (inside only)

Cont.Eq.:  $m_2 = m_1 = m$ ; Energy Eq.:  $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2_{gen}$



Rev ( ${}_1S_2_{gen} = 0$ ) Adiabatic ( $Q = 0$ )  $\Rightarrow s_2 = s_1 = 6.9212 = s_G$  at  $T_2$

$\Rightarrow T_2 = 141^\circ\text{C}$ ,  $v_2 = v_g$  at  $T_2 = 0.4972 \text{ m}^3/\text{kg}$

$\frac{m_e}{m_1} = \frac{m_1 - m_2}{m_1} = 1 - \frac{m_2}{m_1} = 1 - \frac{v_1}{v_2} = 1 - \frac{0.09936}{0.4972} = \mathbf{0.80}$

## 8.60

A piston/cylinder contains 2 kg water at 200°C, 10 MPa. The piston is slowly moved to expand the water in an isothermal process to a pressure of 200 kPa. Any heat transfer takes place with an ambient at 200°C and the whole process may be assumed reversible. Sketch the process in a P-V diagram and calculate both the heat transfer and the total work.

Solution:

C.V. Water.

$$\text{Energy Eq. 5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq. 8.3: } m(s_2 - s_1) = \int dQ/T = {}_1Q_2 / T$$

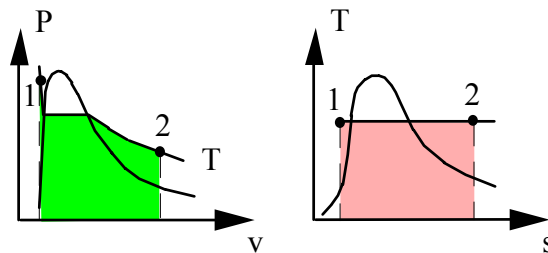
Process:  $T = C$  and reversible as used in entropy equation

$$\text{State 1: Table B.1.4: } v_1 = 0.001148 \text{ m}^3/\text{kg}, \quad u_1 = 844.49 \text{ kJ/kg}, \\ s_1 = 2.3178 \text{ kJ/kg K},$$

$$V_1 = mv_1 = 0.0023 \text{ m}^3$$

$$\text{State 2: Table B.1.3: } v_2 = 1.08034 \text{ m}^3/\text{kg}, \quad u_2 = 2654.4 \text{ kJ/kg} \\ s_2 = 7.5066 \text{ kJ/kg K}$$

$$V_2 = mv_2 = 2.1607 \text{ m}^3,$$



From the entropy equation and the process equation

$${}_1Q_2 = mT(s_2 - s_1) = 2 \times 473.15 (7.5066 - 2.3178) = \mathbf{4910 \text{ kJ}}$$

From the energy equation

$${}_1W_2 = {}_1Q_2 - m(u_2 - u_1) = \mathbf{1290.3 \text{ kJ}}$$



## Entropy generation

## 8.61

One kg water at 500°C and 1 kg saturated water vapor both at 200 kPa are mixed in a constant pressure and adiabatic process. Find the final temperature and the entropy generation for the process.

Solution:

$$\text{Continuity Eq.: } m_2 - m_A - m_B = 0$$

$$\text{Energy Eq.5.11: } m_2 u_2 - m_A u_A - m_B u_B = -{}_1W_2$$

$$\text{Entropy Eq.8.14: } m_2 s_2 - m_A s_A - m_B s_B = \int dQ/T + {}_1S_{2 \text{ gen}}$$

$$\text{Process: } P = \text{Constant} \Rightarrow {}_1W_2 = \int PdV = P(V_2 - V_1)$$

$$Q = 0$$

Substitute the work term into the energy equation and rearrange to get

$$m_2 u_2 + P_2 V_2 = m_2 h_2 = m_A u_A + m_B u_B + P V_1 = m_A h_A + m_B h_B$$

where the last rewrite used  $P V_1 = P V_A + P V_B$ .

$$\text{State A1: Table B.1.3 } h_A = 3487.03 \text{ kJ/kg, } s_A = 8.5132 \text{ kJ/kg K}$$

$$\text{State B1: Table B.1.2 } h_B = 2706.63 \text{ kJ/kg, } s_B = 7.1271 \text{ kJ/kg K}$$

Energy equation gives:

$$h_2 = \frac{m_A}{m_2} h_A + \frac{m_B}{m_2} h_B = \frac{1}{2} 3487.03 + \frac{1}{2} 2706.63 = 3096.83$$

$$\text{State 2: } P_2, h_2 = 3096.83 \text{ kJ/kg} \Rightarrow s_2 = 7.9328 \text{ kJ/kg K; } T_2 = \mathbf{312.2^\circ\text{C}}$$

With the zero heat transfer we have

$${}_1S_{2 \text{ gen}} = m_2 s_2 - m_A s_A - m_B s_B$$

$$= 2 \times 7.9328 - 1 \times 8.5132 - 1 \times 7.1271 = \mathbf{0.225 \text{ kJ/K}}$$

## 8.62

The unrestrained expansion of the reactor water in Problem 5.48 has a final state in the two-phase region. Find the entropy generated in the process.

A water-filled reactor with volume of  $1 \text{ m}^3$  is at 20 MPa,  $360^\circ\text{C}$  and placed inside a containment room as shown in Fig. P5.48. The room is well insulated and initially evacuated. Due to a failure, the reactor ruptures and the water fills the containment room. Find the minimum room volume so the final pressure does not exceed 200 kPa.

Solution:

C.V.: Containment room and reactor.

$$\text{Mass: } m_2 = m_1 = V_{\text{reactor}}/v_1 = 1/0.001823 = 548.5 \text{ kg}$$

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = 0 - 0 = 0$$

$$\text{Entropy Eq.8.14: } m(s_2 - s_1) = \int dQ/T + {}_1S_2_{\text{gen}}$$

$$\text{State 1: (T, P) Table B.1.4 } u_1 = 1702.8 \text{ kJ/kg, } s_1 = 3.877$$

$$\text{Energy equation implies } u_2 = u_1 = 1702.8 \text{ kJ/kg}$$

$$\text{State 2: } P_2 = 200 \text{ kPa, } u_2 < u_g \Rightarrow \text{Two-phase Table B.1.2}$$

$$x_2 = (u_2 - u_f)/u_{fg} = (1702.8 - 504.47)/2025.02 = 0.59176$$

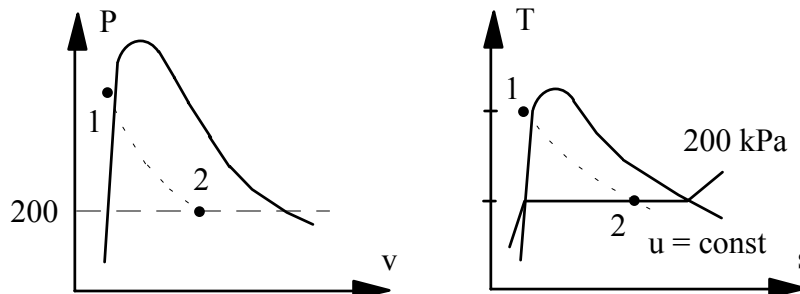
$$v_2 = 0.001061 + 0.59176 \times 0.88467 = 0.52457 \text{ m}^3/\text{kg}$$

$$s_2 = s_f + x_2 s_{fg} = 1.53 + 0.59176 \times 5.597 = 4.8421 \text{ kJ/kg K}$$

$$V_2 = m_2 v_2 = 548.5 \times 0.52457 = \mathbf{287.7 \text{ m}^3}$$

From the entropy equation the generation is

$$\begin{aligned} {}_1S_2_{\text{gen}} &= m(s_2 - s_1) = 548.5 (4.8421 - 3.877) \\ &= \mathbf{529.4 \text{ kJ/K}} \end{aligned}$$



Entropy is generated due to the unrestrained expansion. No work was taken out as the volume goes up.

## 8.63

A mass and atmosphere loaded piston/cylinder contains 2 kg of water at 5 MPa, 100°C. Heat is added from a reservoir at 700°C to the water until it reaches 700°C. Find the work, heat transfer, and total entropy production for the system and surroundings.

Solution:

C.V. Water out to surroundings at 700°C. This is a control mass.

$$\text{Energy Eq.5.11: } U_2 - U_1 = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14: } m(s_2 - s_1) = \int dQ/T + {}_1S_{2 \text{ gen}} = {}_1Q_2/T_{\text{res}} + {}_1S_{2 \text{ gen}}$$

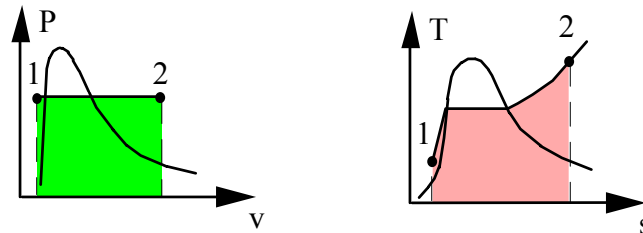
$$\text{Process: } P = \text{constant so } {}_1W_2 = P(V_2 - V_1) = mP(v_2 - v_1)$$

$$\text{State 1: Table B.1.4: } h_1 = 422.72 \text{ kJ/kg, } u_1 = 417.52 \text{ kJ/kg,}$$

$$s_1 = 1.303 \text{ kJ/kg K, } v_1 = 0.00104 \text{ m}^3/\text{kg}$$

$$\text{State 2: Table B.1.3: } h_2 = 3900.1 \text{ kJ/kg, } u_2 = 3457.6 \text{ kJ/kg,}$$

$$s_2 = 7.5122 \text{ kJ/kg K, } v_2 = 0.08849 \text{ m}^3/\text{kg}$$



Work is found from the process (area in P-V diagram)

$${}_1W_2 = mP(v_2 - v_1) = 2 \times 5000(0.08849 - 0.00104) = \mathbf{874.6 \text{ kJ}}$$

The heat transfer from the energy equation is

$${}_1Q_2 = U_2 - U_1 + {}_1W_2 = m(u_2 - u_1) + mP(v_2 - v_1) = m(h_2 - h_1)$$

$${}_1Q_2 = 2(3900.1 - 422.72) = \mathbf{6954.76 \text{ kJ}}$$

Entropy generation from entropy equation (or Eq.8.18)

$${}_1S_{2 \text{ gen}} = m(s_2 - s_1) - {}_1Q_2/T_{\text{res}} = 2(7.5122 - 1.303) - 6954/973 = \mathbf{5.27 \text{ kJ/K}}$$

## 8.64

Ammonia is contained in a rigid sealed tank unknown quality at  $0^\circ\text{C}$ . When heated in boiling water to  $100^\circ\text{C}$  its pressure reaches 1200 kPa. Find the initial quality, the heat transfer to the ammonia and the total entropy generation.

Solution:

C.V. Ammonia, which is a control mass of constant volume.

$$\text{Energy Eq.5.11: } u_2 - u_1 = {}_1q_2 - {}_1w_2$$

$$\text{Entropy Eq.8.14: } s_2 - s_1 = \int dq/T + {}_1s_2 \text{ gen}$$

$$\text{State 2: } 1200 \text{ kPa, } 100^\circ\text{C} \Rightarrow \text{Table B.2.2}$$

$$s_2 = 5.5325 \text{ kJ/kg K, } v_2 = 0.14347 \text{ m}^3/\text{kg, } u_2 = 1485.8 \text{ kJ/kg}$$

$$\text{State 1: } v_1 = v_2 \Rightarrow \text{Table B.2.1}$$

$$x_1 = (0.14347 - 0.001566)/0.28763 = 0.49336$$

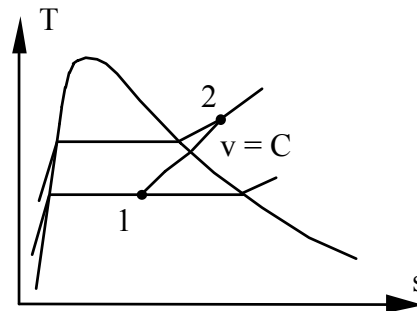
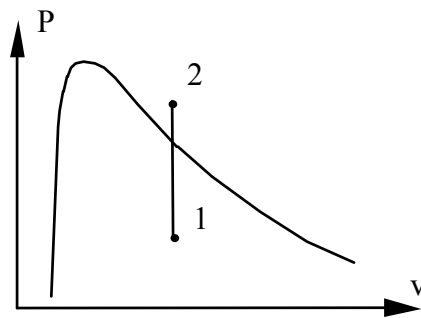
$$u_1 = 741.28 \text{ kJ/kg, } s_1 = 0.7114 + x_1 \times 4.6195 = 2.9905 \text{ kJ/kg K}$$

$$\text{Process: } V = \text{constant} \Rightarrow {}_1w_2 = 0$$

$${}_1q_2 = (u_2 - u_1) = 1485.8 - 741.28 = 744.52 \text{ kJ/kg}$$

To get the total entropy generation take the C.V out to the water at  $100^\circ\text{C}$ .

$$\begin{aligned} {}_1s_2 \text{ gen} &= s_2 - s_1 - {}_1q_2/T = 5.5325 - 2.9905 - 744.52/373.15 \\ &= \mathbf{0.547 \text{ kJ/kg K}} \end{aligned}$$



## 8.65

An insulated cylinder/piston contains R-134a at 1 MPa, 50°C, with a volume of 100 L. The R-134a expands, moving the piston until the pressure in the cylinder has dropped to 100 kPa. It is claimed that the R-134a does 190 kJ of work against the piston during the process. Is that possible?

Solution:

C.V. R-134a in cylinder. Insulated so assume  $Q = 0$ .

State 1: Table B.5.2,  $v_1 = 0.02185 \text{ m}^3/\text{kg}$ ,  $u_1 = 409.39 \text{ kJ/kg}$ ,

$$s_1 = 1.7494 \text{ kJ/kg K}, \quad m = V_1/v_1 = 0.1/0.02185 = 4.577 \text{ kg}$$

Energy Eq.5.11:  $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = 0 - 190 \Rightarrow$

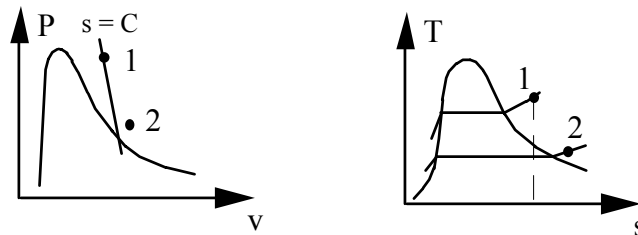
$$u_2 = u_1 - {}_1W_2/m = 367.89 \text{ kJ/kg}$$

State 2:  $P_2, u_2 \Rightarrow$  Table B.5.2:  $T_2 = -19.25^\circ\text{C}$ ;  $s_2 = 1.7689 \text{ kJ/kg K}$

Entropy Eq.8.14:  $m(s_2 - s_1) = \int dQ/T + {}_1S_{2,\text{gen}} = {}_1S_{2,\text{gen}}$

$${}_1S_{2,\text{gen}} = m(s_2 - s_1) = 0.0893 \text{ kJ/K}$$

This is possible since  ${}_1S_{2,\text{gen}} > 0$



## 8.66

A piece of hot metal should be cooled rapidly (quenched) to 25°C, which requires removal of 1000 kJ from the metal. The cold space that absorbs the energy could be one of three possibilities: (1) Submerge the metal into a bath of liquid water and ice, thus melting the ice. (2) Let saturated liquid R-22 at -20°C absorb the energy so that it becomes saturated vapor. (3) Absorb the energy by vaporizing liquid nitrogen at 101.3 kPa pressure.

- Calculate the change of entropy of the cooling media for each of the three cases.
- Discuss the significance of the results.

Solution:

a) Melting or boiling at const P & T

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

$$1) \text{ Ice melting at } 0^\circ\text{C}, \text{ Table B.1.5: } m = {}_1Q_2 / h_{ig} = \frac{1000}{333.41} = 2.9993 \text{ kg}$$

$$\Delta S_{\text{H}_2\text{O}} = ms_{ig} = 2.9993(1.221) = \mathbf{3.662 \text{ kJ/K}}$$

$$2) \text{ R-22 boiling at } -20^\circ\text{C}, \text{ Table B.4.1: } m = {}_1Q_2 / h_{fg} = \frac{1000}{220.327} = 4.539 \text{ kg}$$

$$\Delta S_{\text{R-22}} = ms_{fg} = 4.539(0.8703) = \mathbf{3.950 \text{ kJ/K}}$$

$$3) \text{ N}_2 \text{ boiling at } 101.3 \text{ kPa}, \text{ Table B.6.1: } m = {}_1Q_2 / h_{fg} = \frac{1000}{198.842} = 5.029 \text{ kg}$$

$$\Delta S_{\text{N}_2} = ms_{fg} = 5.029(2.5708) = \mathbf{12.929 \text{ kJ/K}}$$

- The larger the  $\Delta(1/T)$  through which the Q is transferred, the larger the  $\Delta S$ .

## 8.67

A piston cylinder has 2.5 kg ammonia at 50 kPa,  $-20^{\circ}\text{C}$ . Now it is heated to  $50^{\circ}\text{C}$  at constant pressure through the bottom of the cylinder from external hot gas at  $200^{\circ}\text{C}$ . Find the heat transfer to the ammonia and the total entropy generation.

Solution:

C.V. Ammonia plus space out to the hot gas.

$$\text{Energy Eq.5.11:} \quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14:} \quad m(s_2 - s_1) = \int dQ/T + {}_1S_{2,\text{gen}} = {}_1Q_2/T_{\text{gas}} + {}_1S_{2,\text{gen}}$$

$$\text{Process:} \quad P = C \Rightarrow {}_1W_2 = Pm(v_2 - v_1)$$

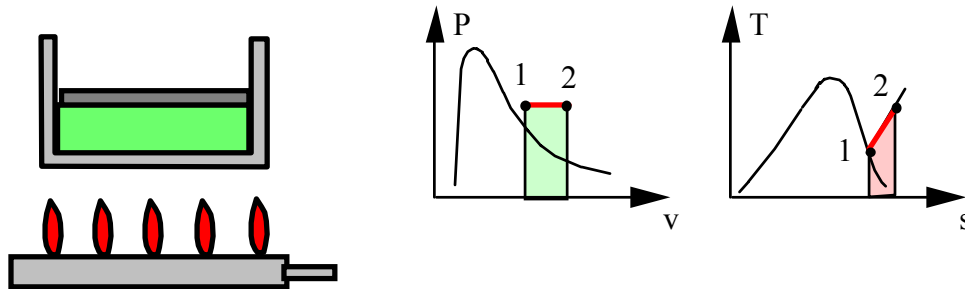
$$\begin{aligned} \text{State 1: Table B.2.2} \quad v_1 &= 2.4463 \text{ m}^3/\text{kg}, \quad h_1 = 1434.6 \text{ kJ/kg}, \\ s_1 &= 6.3187 \text{ kJ/kg K} \end{aligned}$$

$$\begin{aligned} \text{State 2: Table B.2.2} \quad v_2 &= 3.1435 \text{ m}^3/\text{kg}, \quad h_2 = 1583.5 \text{ kJ/kg}, \\ s_2 &= 6.8379 \text{ kJ/kg K} \end{aligned}$$

Substitute the work into the energy equation and solve for the heat transfer

$${}_1Q_2 = m(h_2 - h_1) = 2.5 (1583.5 - 1434.6) = \mathbf{372.25 \text{ kJ}}$$

$$\begin{aligned} {}_1S_{2,\text{gen}} &= m(s_2 - s_1) - {}_1Q_2/T_{\text{gas}} \\ &= 2.5 (6.8379 - 6.3187) - 372.25/473.15 \\ &= \mathbf{0.511 \text{ kJ/K}} \end{aligned}$$



Remark: This is an internally reversible- externally irreversible process. The  $s$  is generated in the space between the  $200^{\circ}\text{C}$  gas and the ammonia. If there are any  $\Delta T$  in the ammonia then it is also internally irreversible.

## 8.68

A cylinder fitted with a movable piston contains water at 3 MPa, 50% quality, at which point the volume is 20 L. The water now expands to 1.2 MPa as a result of receiving 600 kJ of heat from a large source at 300°C. It is claimed that the water does 124 kJ of work during this process. Is this possible?

Solution:

C.V.: H<sub>2</sub>O in Cylinder

State 1: 3 MPa,  $x_1 = 0.5$ , Table B.1.2:  $T_1 = 233.9^\circ\text{C}$

$$v_1 = v_f + x_1 v_{fg} = 0.001216 + 0.5 \times 0.06546 = 0.033948 \text{ m}^3/\text{kg}$$

$$u_1 = u_f + x_1 u_{fg} = 1804.5 \text{ kJ/kg}, \quad s_1 = s_f + x_1 s_{fg} = 4.4162 \text{ kJ/kg-K}$$

$$m_1 = V_1/v_1 = 0.02 / 0.033948 = 0.589 \text{ kg}$$

$$1^{\text{st}} \text{ Law: } 1 \rightarrow 2, \quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2;$$

$${}_1Q_2 = 600 \text{ kJ}, \quad {}_1W_2 = 124 \text{ kJ} ?$$

Now solve for  $u_2$

$$u_2 = 1804.5 + (600 - 124)/0.589 = 2612.6 \text{ kJ/kg}$$

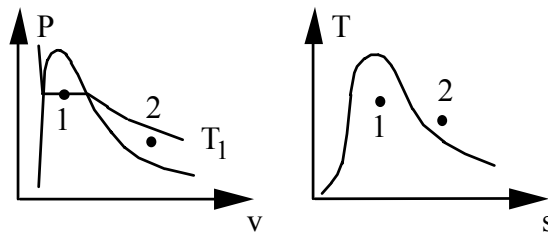
State 2:  $P_2 = 1.2 \text{ MPa}$ :  $u_2 = 2612.6 \text{ kJ/kg}$  Table B.1.3

$$T_2 \cong 200^\circ\text{C}, \quad s_2 = 6.5898 \text{ kJ/kgK}$$

$$2^{\text{nd}} \text{ Law Eq.8.18: } \Delta S_{\text{net}} = m(s_2 - s_1) - \frac{Q_{\text{CV}}}{T_{\text{H}}}; \quad T_{\text{H}} = 300^\circ\text{C}, \quad Q_{\text{CV}} = {}_1Q_2$$

$$\Delta S_{\text{net}} = 0.589 (6.5898 - 4.4162) - \frac{600}{300 + 273} = 0.2335 \text{ kJ/K} \geq 0;$$

**Process is possible**





## 8.69

A piston cylinder loaded so it gives constant pressure has 0.75 kg saturated vapor water at 200 kPa. It is now cooled so the volume becomes half the initial volume by heat transfer to the ambient at 20°C. Find the work, the heat transfer and the total entropy generation.

Solution:

$$\text{Continuity Eq.: } m_2 - m_1 = 0$$

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14: } m(s_2 - s_1) = \int dQ/T + {}_1S_2 \text{ gen}$$

$$\text{Process: } P = C \Rightarrow {}_1W_2 = \int PdV = mP(v_2 - v_1)$$

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

$$\text{State 1: } v_1 = 0.88573 \text{ m}^3/\text{kg}, \quad h_1 = 2706.63 \text{ kJ/kg}, \quad s_1 = 7.1271 \text{ kJ/kg K}$$

$$\text{State 2: } P_2, \quad v_2 = v_1/2 = 0.444286 \text{ m}^3/\text{kg} \quad \Rightarrow \text{ Table B.1.2}$$

$$x_2 = (0.444286 - 0.001061)/0.88467 = 0.501$$

$$h_2 = 504.68 + x_2 \times 2201.96 = 1607.86 \text{ kJ/kg}$$

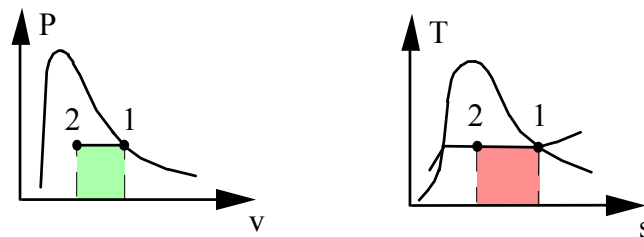
$$s_2 = 1.53 + x_2 \times 5.5970 = 4.3341 \text{ kJ/kg K}$$

$${}_1W_2 = 0.75 \times 200(0.444286 - 0.88573) = \mathbf{-66.22 \text{ kJ}}$$

$${}_1Q_2 = 0.75(1607.86 - 2706.63) = \mathbf{-824.1 \text{ kJ}}$$

$$\begin{aligned} {}_1S_2 \text{ gen} &= m(s_2 - s_1) - {}_1Q_2/T = 0.75(4.3341 - 7.1271) - (-824.1/293.15) \\ &= -2.09475 + 2.81119 = \mathbf{0.716 \text{ kJ/K}} \end{aligned}$$

Notice: The process is externally irreversible (T receiving Q is not T<sub>1</sub>)



## 8.70

A piston/cylinder contains 1 kg water at 150 kPa, 20°C. The piston is loaded so pressure is linear in volume. Heat is added from a 600°C source until the water is at 1 MPa, 500°C. Find the heat transfer and the total change in entropy.

Solution:

CV H<sub>2</sub>O out to the source, both  ${}_1Q_2$  and  ${}_1W_2$

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14: } m(s_2 - s_1) = {}_1Q_2 / T_{\text{SOURCE}} + {}_1S_2_{\text{gen}}$$

$$\text{Process: } P = A + BV \Rightarrow {}_1W_2 = \int P dV = \frac{1}{2} (P_1 + P_2) (V_2 - V_1)$$

State 1: B.1.1 Compressed liquid use saturated liquid at same T:

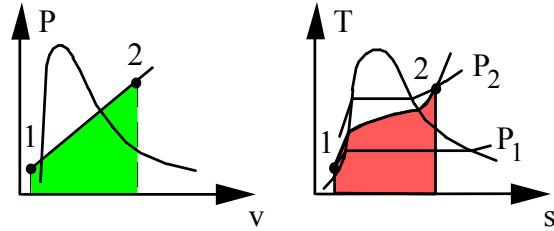
$$v_1 = 0.001002 \text{ m}^3/\text{kg}; \quad u_1 = 83.94 \text{ kJ/kg}; \quad s_1 = 0.2966 \text{ kJ/kg K}$$

State 2: Table B.1.3 sup. vap.

$$v_2 = 0.35411 \text{ m}^3/\text{kg}$$

$$u_2 = 3124.3 \text{ kJ/kg};$$

$$s_2 = 7.7621 \text{ kJ/kg K}$$



$${}_1W_2 = \frac{1}{2} (1000 + 150) 1 (0.35411 - 0.001002) = 203 \text{ kJ}$$

$${}_1Q_2 = 1(3124.3 - 83.94) + 203 = \mathbf{3243.4 \text{ kJ}}$$

$$m(s_2 - s_1) = 1(7.7621 - 0.2968) = 7.4655 \text{ kJ/K}$$

$${}_1Q_2 / T_{\text{source}} = 3.7146 \text{ kJ/K} \quad (\text{for source } Q = -{}_1Q_2 \text{ recall Eq.8.18})$$

$${}_1S_2_{\text{gen}} = m(s_2 - s_1) - {}_1Q_2 / T_{\text{SOURCE}} = \Delta S_{\text{total}}$$

$$= \Delta S_{\text{H}_2\text{O}} + \Delta S_{\text{source}} = 7.4655 - 3.7146 = \mathbf{3.751 \text{ kJ/K}}$$

Remark: This is an external irreversible process (delta T to the source)

## 8.71

A piston/cylinder has ammonia at 2000 kPa, 80°C with a volume of 0.1 m<sup>3</sup>. The piston is loaded with a linear spring and outside ambient is at 20°C, shown in Fig. P8.71. The ammonia now cools down to 20°C at which point it has a quality of 10%. Find the work, the heat transfer and the total entropy generation in the process.

CV Ammonia out to the ambient, both  ${}_1Q_2$  and  ${}_1W_2$

$$\text{Energy Eq.5.11:} \quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14:} \quad m(s_2 - s_1) = {}_1Q_2 / T_{\text{ambient}} + {}_1S_2 \text{ gen}$$

$$\text{Process: } P = A + BV \Rightarrow {}_1W_2 = \int P dV = \frac{1}{2} m(P_1 + P_2)(v_2 - v_1)$$

State 1: Table B.2.2

$$v_1 = 0.07595 \text{ m}^3/\text{kg}, \quad u_1 = 1421.6 \text{ kJ/kg}, \quad s_1 = 5.0707 \text{ kJ/kg K}$$

$$m = V_1/v_1 = 0.1/0.07595 = 1.31665 \text{ kg}$$

State 2: Table B.2.1

$$v_2 = 0.001638 + 0.1 \times 0.14758 = 0.016396 \text{ m}^3/\text{kg}$$

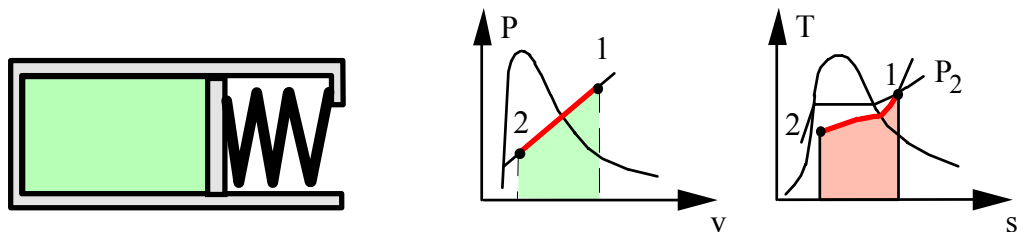
$$u_2 = 272.89 + 0.1 \times 1059.3 = 378.82 \text{ kJ/kg}$$

$$s_2 = 1.0408 + 0.1 \times 4.0452 = 1.44532 \text{ kJ/kg K}$$

$$\begin{aligned} {}_1W_2 &= \frac{1}{2} m(P_1 + P_2)(v_2 - v_1) \\ &= \frac{1}{2} \times 1.31665 (2000 + 857.5)(0.016396 - 0.07595) \\ &= -112 \text{ kJ} \end{aligned}$$

$$\begin{aligned} {}_1Q_2 &= m(u_2 - u_1) + {}_1W_2 = 1.31665 (378.82 - 1421.6) - 112 \\ &= -1484.98 \text{ kJ} \end{aligned}$$

$$\begin{aligned} {}_1S_2 \text{ gen} &= m(s_2 - s_1) - ({}_1Q_2 / T_{\text{amb}}) \\ &= 1.31665 (1.44532 - 5.0707) - \frac{-1484.98}{293.15} \\ &= -4.77336 + 5.0656 = 0.292 \text{ kJ/k} \end{aligned}$$



## 8.72

A cylinder/piston contains water at 200 kPa, 200°C with a volume of 20 L. The piston is moved slowly, compressing the water to a pressure of 800 kPa. The loading on the piston is such that the product  $PV$  is a constant. Assuming that the room temperature is 20°C, show that this process does not violate the second law.

Solution:

C.V.: Water + cylinder out to room at 20°C

$$\text{Energy Eq.5.11:} \quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14:} \quad m(s_2 - s_1) = {}_1Q_2 / T_{\text{room}} + {}_1S_{2, \text{gen}}$$

$$\text{Process: } PV = \text{constant} = Pmv \Rightarrow v_2 = P_1 v_1 / P_2$$

$${}_1W_2 = \int P dv = P_1 v_1 \ln(v_2/v_1)$$

$$\text{State 1: Table B.1.3, } v_1 = 1.0803 \text{ m}^3/\text{kg}, \quad u_1 = 2654.4 \text{ kJ/kg}, \\ s_1 = 7.5066 \text{ kJ/kg K}$$

$$\text{State 2: } P_2, v_2 = P_1 v_1 / P_2 = 200 \times 1.0803 / 800 = 0.2701 \text{ m}^3/\text{kg}$$

$$\text{Table B.1.3: } u_2 = 2655.0 \text{ kJ/kg}, \quad s_2 = 6.8822 \text{ kJ/kg K}$$

$${}_1W_2 = 200 \times 1.0803 \ln\left(\frac{0.2701}{1.0803}\right) = -299.5 \text{ kJ/kg}$$

$${}_1Q_2 = u_2 - u_1 + {}_1W_2 = 2655.0 - 2654.4 - 299.5 = -298.9 \text{ kJ/kg}$$

$${}_1S_{2, \text{gen}} = s_2 - s_1 - \frac{{}_1Q_2}{T_{\text{room}}} = 6.8822 - 7.5066 + \frac{298.9}{293.15}$$

$$= 0.395 \text{ kJ/kg K} > 0 \quad \text{satisfy 2<sup>nd</sup> law.}$$

## 8.73

One kilogram of ammonia ( $\text{NH}_3$ ) is contained in a spring-loaded piston/cylinder, Fig. P8.73, as saturated liquid at  $-20^\circ\text{C}$ . Heat is added from a reservoir at  $100^\circ\text{C}$  until a final condition of 800 kPa,  $70^\circ\text{C}$  is reached. Find the work, heat transfer, and entropy generation, assuming the process is internally reversible.

Solution:

C.V. =  $\text{NH}_3$  out to the reservoir.

Continuity Eq.:  $m_2 = m_1 = m$

Energy Eq.5.11:  $E_2 - E_1 = m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.8.14:  $S_2 - S_1 = \int dQ/T + {}_1S_{2,\text{gen}} = {}_1Q_2/T_{\text{res}} + {}_1S_{2,\text{gen}}$

Process:  $P = A + BV$  linear in  $V \Rightarrow$

$${}_1W_2 = \int P dV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) = \frac{1}{2}(P_1 + P_2)m(v_2 - v_1)$$

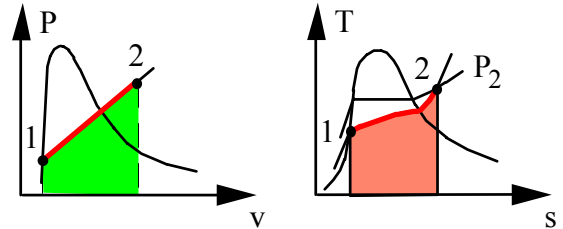
State 1: Table B.2.1

$P_1 = 190.08 \text{ kPa}$ ,

$v_1 = 0.001504 \text{ m}^3/\text{kg}$

$u_1 = 88.76 \text{ kJ/kg}$ ,

$s_1 = 0.3657 \text{ kJ/kg K}$



State 2: Table B.2.2 sup. vapor

$v_2 = 0.199 \text{ m}^3/\text{kg}$ ,  $u_2 = 1438.3 \text{ kJ/kg}$ ,  $s_2 = 5.5513 \text{ kJ/kg K}$

$${}_1W_2 = \frac{1}{2}(190.08 + 800)1(0.1990 - 0.001504) = \mathbf{97.768 \text{ kJ}}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1(1438.3 - 88.76) + 97.768 = \mathbf{1447.3 \text{ kJ}}$$

$${}_1S_{2,\text{gen}} = m(s_2 - s_1) - {}_1Q_2/T_{\text{res}} = 1(5.5513 - 0.3657) - \frac{1447.3}{373.15} = \mathbf{1.307 \text{ kJ/K}}$$

## 8.74

A piston/cylinder device keeping a constant pressure has 1 kg water at 20°C and 1 kg of water at 100°C both at 500 kPa separated by a thin membrane. The membrane is broken and the water comes to a uniform state with no external heat transfer. Find the final temperature and the entropy generation for the process.

Solution:

$$\text{Continuity Eq.: } m_2 - m_A - m_B = 0$$

$$\text{Energy Eq.5.11: } m_2 u_2 - m_A u_A - m_B u_B = -{}_1W_2$$

$$\text{Entropy Eq.8.14: } m_2 s_2 - m_A s_A - m_B s_B = \int dQ/T + {}_1S_2 \text{ gen}$$

$$\text{Process: } P = \text{Constant} \Rightarrow {}_1W_2 = \int PdV = P(V_2 - V_1)$$

$$Q = 0$$

Substitute the work term into the energy equation and rearrange to get

$$m_2 u_2 + P_2 V_2 = m_2 h_2 = m_A u_A + m_B u_B + P V_1 = m_A h_A + m_B h_B$$

where the last rewrite used  $P V_1 = P V_A + P V_B$ .

$$\text{State A1: Table B.1.4 } h_A = 84.41 \text{ kJ/kg} \quad s_A = 0.2965 \text{ kJ/kg K}$$

$$\text{State B1: Table B.1.4 } h_B = 419.32 \text{ kJ/kg} \quad s_B = 1.3065 \text{ kJ/kg K}$$

Energy equation gives:

$$h_2 = \frac{m_A}{m_2} h_A + \frac{m_B}{m_2} h_B = \frac{1}{2} 84.41 + \frac{1}{2} 419.32 = 251.865 \text{ kJ/kg}$$

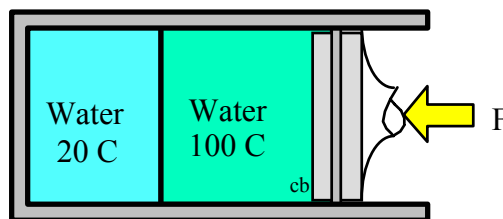
$$\text{State 2: } h_2 = 251.865 \text{ kJ/kg} \ \& \ P_2 = 500 \text{ kPa} \ \text{from Table B.1.4}$$

$$T_2 = 60.085^\circ\text{C}, \quad s_2 = 0.83184 \text{ kJ/kg K}$$

With the zero heat transfer we have

$${}_1S_2 \text{ gen} = m_2 s_2 - m_A s_A - m_B s_B$$

$$= 2 \times 0.83184 - 1 \times 0.2965 - 1 \times 1.3065 = \mathbf{0.0607 \text{ kJ/K}}$$



## Entropy of a liquid or a solid

## 8.75

A piston cylinder has constant pressure of 2000 kPa with water at 20°C. It is now heated up to 100°C. Find the heat transfer and the entropy change using the steam tables. Repeat the calculation using constant heat capacity and incompressibility.

Solution:

C.V. Water. Constant pressure heating.

$$\text{Energy Eq.5.11:} \quad u_2 - u_1 = {}_1q_2 - {}_1w_2$$

$$\text{Entropy Eq.8.3:} \quad s_2 - s_1 = {}_1q_2 / T_{\text{SOURCE}} + {}_1s_2 \text{ gen}$$

$$\text{Process:} \quad P = P_1 \Rightarrow {}_1w_2 = P(v_2 - v_1)$$

The energy equation then gives the heat transfer as

$${}_1q_2 = u_2 - u_1 + {}_1w_2 = h_2 - h_1$$

$$\text{Steam Tables B.1.4:} \quad h_1 = 85.82 \text{ kJ/kg}; \quad s_1 = 0.2962 \text{ kJ/kg K}$$

$$h_2 = 420.45 \text{ kJ/kg}; \quad s_2 = 1.3053 \text{ kJ/kg K}$$

$${}_1q_2 = h_2 - h_1 = -85.82 + 420.45 = \mathbf{334.63 \text{ kJ/kg}}$$

$$s_2 - s_1 = 1.3053 - 0.2962 = \mathbf{1.0091 \text{ kJ/kg K}}$$

Now using values from Table A.4: Liquid water  $C_p = 4.18 \text{ kJ/kg K}$

$$h_2 - h_1 \cong C_p(T_2 - T_1) = 4.18 \times 80 = \mathbf{334.4 \text{ kJ/kg}}$$

$$s_2 - s_1 \cong C_p \ln(T_2/T_1) = 4.18 \ln \frac{373.15}{293.15} = \mathbf{1.0086 \text{ kJ/kg K}}$$

**Approximations are very good**

## 8.76

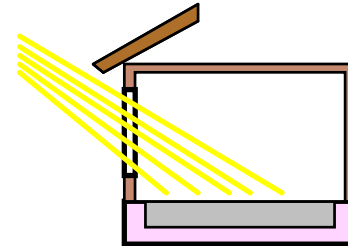
A large slab of concrete,  $5 \times 8 \times 0.3$  m, is used as a thermal storage mass in a solar-heated house. If the slab cools overnight from  $23^\circ\text{C}$  to  $18^\circ\text{C}$  in an  $18^\circ\text{C}$  house, what is the net entropy change associated with this process?

Solution:

C.V.: Control mass concrete.

$$V = 5 \times 8 \times 0.3 = 12 \text{ m}^3$$

$$m = \rho V = 2200 \times 12 = 26\,400 \text{ kg}$$



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

Entropy Eq.:  $m(s_2 - s_1) = \frac{{}_1Q_2}{T_0} + {}_1S_{2 \text{ gen}}$

Process:  $V = \text{constant}$  so  ${}_1W_2 = 0$

Use heat capacity (Table A.3) for change in  $u$  of the slab

$${}_1Q_2 = mC\Delta T = 26400 \times 0.88(-5) = -116\,160 \text{ kJ}$$

Eq.8.18 provides the equivalent of total entropy generation:

$$\Delta S_{\text{SYST}} = m(s_2 - s_1) = mC \ln \frac{T_2}{T_1} = 26400 \times 0.88 \ln \frac{291.2}{296.2} = -395.5 \text{ kJ/K}$$

$$\Delta S_{\text{SURR}} = \frac{-{}_1Q_2}{T_0} = \frac{+116\,160}{291.2} = +398.9 \text{ kJ/K}$$

$$\Delta S_{\text{NET}} = -395.5 + 398.9 = +3.4 \text{ kJ/K}$$

$$= m(s_2 - s_1) - \frac{{}_1Q_2}{T_0} = {}_1S_{2 \text{ gen}}$$



## 8.77

A 4 L jug of milk at 25°C is placed in your refrigerator where it is cooled down to the refrigerator's inside constant temperature of 5°C. Assume the milk has the property of liquid water and find the entropy generated in the cooling process.

Solution:

C.V. Jug of milk. Control mass at constant pressure.

Continuity Eq.:  $m_2 = m_1 = m$  ;

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

Entropy Eq.8.14:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2_{gen}$

State 1: Table B.1.1:  $v_1 \cong v_f = 0.001003 \text{ m}^3/\text{kg}$ ,  $h = h_f = 104.87 \text{ kJ/kg}$ ;  
 $s_f = 0.3673 \text{ kJ/kg K}$

State 2: Table B.1.1:  $h = h_f = 20.98 \text{ kJ/kg}$ ,  $s = s_f = 0.0761 \text{ kJ/kg K}$

Process:  $P = \text{constant} = 101 \text{ kPa} \Rightarrow {}_1W_2 = mP(v_2 - v_1)$

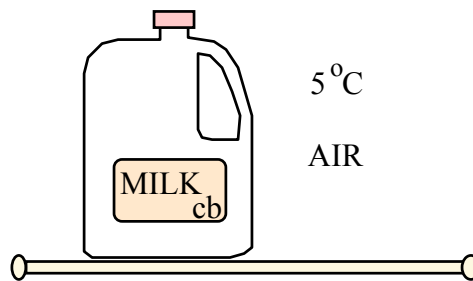
$$m = V/v_1 = 0.004 / 0.001003 = 3.988 \text{ kg}$$

Substitute the work into the energy equation and solve for the heat transfer

$${}_1Q_2 = m(h_2 - h_1) = 3.988 (20.98 - 104.87) = -3.988 \times 83.89 = -334.55 \text{ kJ}$$

The entropy equation gives the generation as

$$\begin{aligned} {}_1S_2_{gen} &= m(s_2 - s_1) - {}_1Q_2/T_{refrig} \\ &= 3.988 (0.0761 - 0.3673) - (-334.55 / 278.15) \\ &= -1.1613 + 1.2028 = \mathbf{0.0415 \text{ kJ/K}} \end{aligned}$$



## 8.78

A foundry form box with 25 kg of 200°C hot sand is dumped into a bucket with 50 L water at 15°C. Assuming no heat transfer with the surroundings and no boiling away of liquid water, calculate the net entropy change for the process.

Solution:

C.V. Sand and water, constant pressure process

$$m_{\text{sand}}(u_2 - u_1)_{\text{sand}} + m_{\text{H}_2\text{O}}(u_2 - u_1)_{\text{H}_2\text{O}} = -P(V_2 - V_1)$$

$$\Rightarrow m_{\text{sand}}\Delta h_{\text{sand}} + m_{\text{H}_2\text{O}}\Delta h_{\text{H}_2\text{O}} = 0$$

For this problem we could also have said that the work is nearly zero as the solid sand and the liquid water will not change volume to any measurable extent. Now we get changes in  $u$ 's instead of  $h$ 's. For these phases  $C_V = C_P = C$  which is a consequence of the incompressibility. Now the energy equation becomes

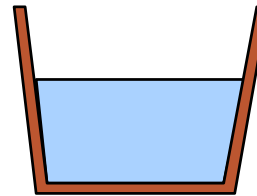
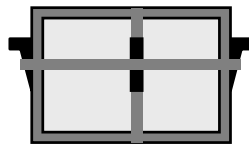
$$m_{\text{sand}}C\Delta T_{\text{sand}} + m_{\text{H}_2\text{O}}C_{\text{H}_2\text{O}}\Delta T_{\text{H}_2\text{O}} = 0$$

$$25 \times 0.8 \times (T_2 - 200) + (50 \times 10^{-3} / 0.001001) \times 4.184 \times (T_2 - 15) = 0$$

$$T_2 = 31.2^\circ\text{C}$$

$$\Delta S = 25 \times 0.8 \ln\left(\frac{304.3}{473.15}\right) + 49.95 \times 4.184 \ln\left(\frac{304.3}{288.15}\right) = \mathbf{2.57 \text{ kJ/K}}$$

Box holds the sand for form of the cast part



## 8.79

A 5-kg steel container is cured at 500°C. An amount of liquid water at 15°C, 100 kPa is added to the container so a final uniform temperature of the steel and the water becomes 75°C. Neglect any water that might evaporate during the process and any air in the container. How much water should be added and how much entropy was generated?

Heat steel

$$m(u_2 - u_1) = {}_1Q_2 = mC (T_2 + T_4)$$

$${}_1Q_2 = 5(0.46)(500-20) = \mathbf{1104 \text{ kJ}}$$

$$m_{\text{H}_2\text{O}}(u_3 - u_2)_{\text{H}_2\text{O}} + m_{\text{st}}(u_3 - u_2) = 0$$

$$m_{\text{H}_2\text{O}}(313.87 - 62.98) + m_{\text{st}}C (T_3 - T_2) = 0$$

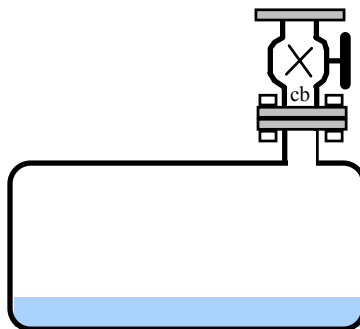
$$m_{\text{H}_2\text{O}} 250.89 + 5 \times 0.46 \times (75 - 500) = 0$$

$$m_{\text{H}_2\text{O}} = 977.5/250.89 = \mathbf{3.896 \text{ kg}}$$

$$m_{\text{H}_2\text{O}}(s_3 - s_2) + m_{\text{st}}(s_3 - s_2) = \emptyset + {}_2S_3 \text{ gen}$$

$$3.986(1.0154 - 0.2245) + 5 \times 0.46 \ln \frac{75+273}{773} = {}_2S_3 \text{ gen}$$

$${}_2S_3 \text{ gen} = 3.0813 - 1.8356 = \mathbf{1.246 \text{ kJ/K}}$$



## 8.80

A pan in an autoshop contains 5 L of engine oil at 20°C, 100 kPa. Now 2 L of hot 100°C oil is mixed into the pan. Neglect any work term and find the final temperature and the entropy generation.

Solution:

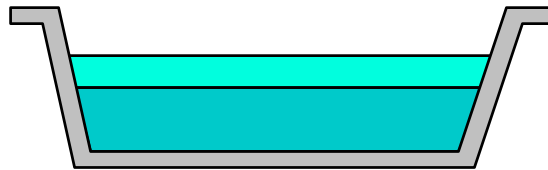
Since we have no information about the oil density, we assume the same for both from Table A.4:  $\rho = 885 \text{ kg/m}^3$

Energy Eq.:  $m_2 u_2 - m_A u_A - m_B u_B \cong 0 - 0$

$\Delta u \cong C_v \Delta T$  so same  $C_v = 1.9 \text{ kJ/kg K}$  for all oil states.

$$T_2 = \frac{m_A}{m_2} T_A + \frac{m_B}{m_2} T_B = \frac{5}{7} \times 20 + \frac{2}{7} \times 100 = 42.868^\circ\text{C} = 316.02 \text{ K}$$

$$\begin{aligned} S_2 - S_1 &= m_2 s_2 - m_A s_A - m_B s_B = m_A (s_2 - s_A) + m_B (s_2 - s_B) \\ &= 0.005 \times 885 \times 1.9 \ln \frac{316.02}{293.15} + 0.002 \times 885 \times 1.9 \ln \frac{316.02}{373.15} \\ &= 0.6316 - 0.5588 = + \mathbf{0.0728 \text{ kJ/K}} \end{aligned}$$



Oils shown before mixed to final uniform state.

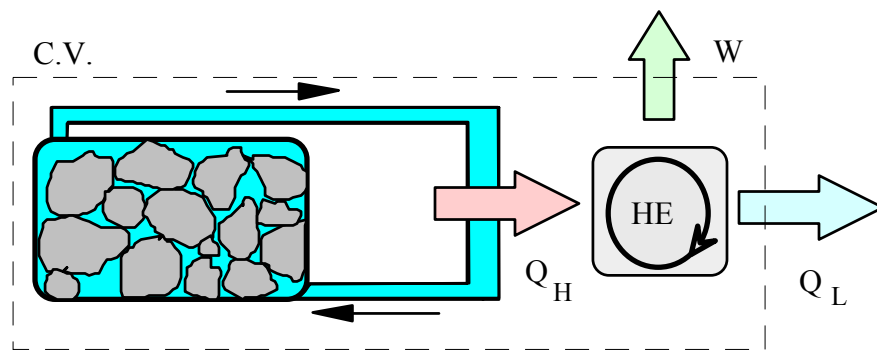
## 8.81

Find the total work the heat engine can give out as it receives energy from the rock bed as described in Problem 7.61 (see Fig.P 8.81). Hint: write the entropy balance equation for the control volume that is the combination of the rock bed and the heat engine.

Solution:

To get the work we must integrate over the process or do the 2<sup>nd</sup> law for a control volume around the whole setup out to  $T_0$

C.V. Heat engine plus rock bed out to  $T_0$ .  $W$  and  $Q_L$  goes out.



$$\text{Energy Eq.5.11: } (U_2 - U_1)_{\text{rock}} = -Q_L - W$$

$$\begin{aligned} \text{Entropy Eq.8.3: } (S_2 - S_1)_{\text{rock}} &= -\frac{Q_L}{T_0} = mC \ln\left(\frac{T_2}{T_1}\right) \\ &= 5500 \times 0.89 \ln\frac{290}{400} = -1574.15 \text{ kJ/K} \end{aligned}$$

$$Q_L = -T_0 (S_2 - S_1)_{\text{rock}} = -290 (-1574.15) = 456\,504 \text{ kJ}$$

The energy drop of the rock  $-(U_2 - U_1)_{\text{rock}}$  equals  $Q_H$  into heat engine

$$(U_2 - U_1)_{\text{rock}} = mC (T_2 - T_1) = 5500 \times 0.89 (290 - 400) = -538\,450 \text{ kJ}$$

$$W = -(U_2 - U_1)_{\text{rock}} - Q_L = 538450 - 456504 = \mathbf{81\,946 \text{ kJ}}$$

## 8.82

Two kg of liquid lead initially at 500°C are poured into a form. It then cools at constant pressure down to room temperature of 20°C as heat is transferred to the room. The melting point of lead is 327°C and the enthalpy change between the phases,  $h_{if}$ , is 24.6 kJ/kg. The specific heats are in Tables A.3 and A.4. Calculate the net entropy change for this process.

Solution:

C.V. Lead, constant pressure process

$$m_{Pb}(u_2 - u_1)_{Pb} = {}_1Q_2 - P(V_2 - V_1)$$

We need to find changes in enthalpy ( $u + Pv$ ) for each phase separately and then add the enthalpy change for the phase change.

Consider the process in several steps:

Cooling liquid to the melting temperature

Solidification of the liquid to solid

Cooling of the solid to the final temperature

$$\begin{aligned} {}_1Q_2 &= m_{Pb}(h_2 - h_1) = m_{Pb}(h_2 - h_{327,sol} - h_{if} + h_{327,f} - h_{500}) \\ &= 2 \times (0.138 \times (20 - 327) - 24.6 + 0.155 \times (327 - 500)) \\ &= -84.732 - 49.2 - 53.63 = -187.56 \text{ kJ} \end{aligned}$$

$$\begin{aligned} \Delta S_{CV} &= m_{Pb} \left[ C_{p,sol} \ln(T_2/600) - (h_{if}/600) + C_{p,liq} \ln(600/T_1) \right] \\ &= 2 \times \left[ 0.138 \ln \frac{293.15}{600} - \frac{24.6}{600} + 0.155 \ln \frac{600}{773.15} \right] = -0.358 \text{ kJ/K} \end{aligned}$$

$$\Delta S_{SUR} = -{}_1Q_2/T_0 = 187.56/293.15 = 0.64 \text{ kJ/K}$$

The net entropy change from Eq.8.18 is equivalent to total entropy generation

$$\Delta S_{net} = \Delta S_{CV} + \Delta S_{SUR} = \mathbf{0.282 \text{ kJ/K}}$$



## 8.83

A 12 kg steel container has 0.2 kg superheated water vapor at 1000 kPa, both at 200°C. The total mass is now cooled to ambient temperature 30°C. How much heat transfer was taken out and what is the total entropy generation?

Solution:

C.V.: Steel and the water, control mass of constant volume.

$$\text{Energy Eq.5.11: } U_2 - U_1 = {}_1Q_2 - {}_1W_2$$

$$\text{Process: } V = \text{constant} \Rightarrow {}_1W_2 = 0$$

$$\text{State 1: } \text{H}_2\text{O Table B.1.3: } u_1 = 2621.9 \text{ kJ/kg, } v_1 = 0.20596 \text{ m}^3/\text{kg}, \\ s_1 = 6.6939 \text{ kJ/kg K}$$

$$\text{State 2: } \text{H}_2\text{O: } T_2, v_2 = v_1 \Rightarrow \text{from Table B.1.1}$$

$$x_2 = \frac{v - v_f}{v_{fg}} = \frac{0.20596 - 0.001004}{32.8922} = 0.006231$$

$$u_2 = 125.77 + x_2 \times 2290.81 = 140.04 \text{ kJ/kg}$$

$$s_2 = 0.4369 + x_2 \times 8.0164 = 0.48685 \text{ kJ/kg K}$$

$${}_1Q_2 = m(u_2 - u_1) = m_{\text{steel}}C_{\text{steel}}(T_2 - T_1) + m_{\text{H}_2\text{O}}(u_2 - u_1)_{\text{H}_2\text{O}} \\ = 12 \times 0.42(30 - 200) + 0.2(140.04 - 2621.9) \\ = \mathbf{-1353.2 \text{ kJ}}$$

Entropy generation from Eq.8.18

$${}_1S_2 \text{ gen} = m_2 s_2 - m_1 s_1 - \frac{{}_1Q_2}{T_{\text{amb}}} \\ = m_{\text{steel}}C_{\text{steel}} \ln\left(\frac{T_2}{T_1}\right) + m_{\text{H}_2\text{O}}(s_2 - s_1)_{\text{H}_2\text{O}} - \frac{{}_1Q_2}{T_{\text{amb}}} \\ = 12 \times 0.42 \ln\left(\frac{303.15}{473.15}\right) + 0.2(0.48685 - 6.6939) - \left(\frac{-1353.2}{303.15}\right) \\ = -2.2437 - 1.2414 + 4.4638 \\ = \mathbf{0.9787 \text{ kJ/K}}$$

## 8.84

A 5 kg aluminum radiator holds 2 kg of liquid R-134a both at  $-10^{\circ}\text{C}$ . The setup is brought indoors and heated with 220 kJ from a heat source at  $100^{\circ}\text{C}$ . Find the total entropy generation for the process assuming the R-134a remains a liquid.

Solution:

C.V. The aluminum radiator and the R-134a.

$$\text{Energy Eq.5.11: } m_2u_2 - m_1u_1 = {}_1Q_2 - 0$$

Process: No change in volume so no work as used above.

The energy equation now becomes (summing over the mass)

$$m_{\text{al}}(u_2 - u_1)_{\text{al}} + m_{\text{R134a}}(u_2 - u_1)_{\text{R134a}} = {}_1Q_2$$

Use specific heat from Table A.3 and A.4

$$m_{\text{al}}C_{\text{al}}(T_2 - T_1) + m_{\text{R134a}}C_{\text{R134a}} \ln(T_2 - T_1) = {}_1Q_2$$

$$T_2 - T_1 = {}_1Q_2 / [m_{\text{al}}C_{\text{al}} + m_{\text{R134a}}C_{\text{R134a}}]$$

$$= 220 / [5 \times 0.9 + 2 \times 1.43] = 29.89^{\circ}\text{C}$$

$$T_2 = -10 + 29.89 = 19.89^{\circ}\text{C}$$

Entropy generation from Eq.8.18

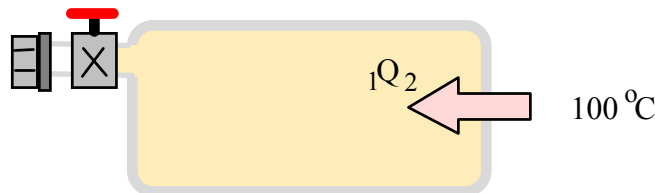
$${}_1S_2_{\text{gen}} = m(s_2 - s_1) - {}_1Q_2/T$$

$$= m_{\text{al}}C_{\text{al}} \ln(T_2/T_1) + m_{\text{R134a}}C_{\text{R134a}} \ln(T_2/T_1) - \frac{{}_1Q_2}{T_{\text{amb}}}$$

$$= (5 \times 0.9 + 2 \times 1.43) \ln \frac{(19.89 + 273.15)}{-10 + 273.15} - \frac{220}{373.15}$$

$$= 0.7918 - 0.5896$$

$$= \mathbf{0.202 \text{ kJ/K}}$$





## 8.85

A piston/cylinder of total 1 kg steel contains 0.5 kg ammonia at 1600 kPa both masses at 120°C. Some stops are placed so a minimum volume is 0.02 m<sup>3</sup>, shown in Fig. P8.85. Now the whole system is cooled down to 30°C by heat transfer to the ambient at 20°C, and during the process the steel keeps same temperature as the ammonia. Find the work, the heat transfer and the total entropy generation in the process.

$$1: v_1 = 0.11265 \text{ m}^3/\text{kg}, \quad u_1 = 1516.6 \text{ kJ/kg}, \quad s_1 = 5.5018 \text{ kJ/kg K}$$

$$V_1 = mv_1 = 0.05634 \text{ m}^3$$

$$\text{Stop 1a: } v_{\text{stop}} = V/m = 0.02/0.5 = 0.04 \text{ m}^3/\text{kg}$$

$$P_{\text{stop}} = P_1 \Rightarrow T \sim 42^\circ\text{C (saturated)}$$

$$2: \quad 30^\circ\text{C} < T_{\text{stop}} \text{ so } v_2 = v_{\text{stop}} = 0.04 \text{ m}^3/\text{kg}$$

$$x_2 = \left( \frac{v_2 - v_f}{v_{fg}} \right) = \frac{0.04 - 0.00168}{0.10881} = 0.35217$$

$$u_2 = 320.46 + x_2 \times 1016.9 = 678.58 \text{ kJ/kg}$$

$$s_2 = 1.2005 + x_2 \times 3.7734 = 2.5294 \text{ kJ/kg K}$$

$${}_1W_2 = \int P \, dV = P_1 m (v_2 - v_1) = 1600 \times 0.5 (0.004 - 0.11268) = -58.14 \text{ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + m_{\text{st}}(u_2 - u_1) + {}_1W_2$$

$$= 0.5(678.58 - 1516.6) + 1 \times 0.46(30 - 120) - 58.14$$

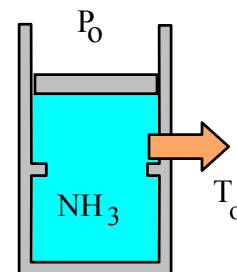
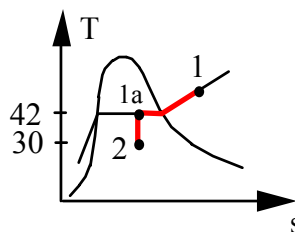
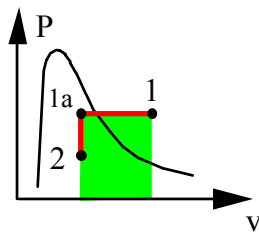
$$= -419.01 - 41.4 - 58.14 = \mathbf{-518.55 \text{ kJ}}$$

$${}_1S_2 \text{ gen} = m(s_2 - s_1) + m_{\text{st}}(s_2 - s_1) - {}_1Q_2/T_{\text{amb}}$$

$$= 0.5(2.5294 - 5.5018) + 1 \times 0.46 \ln \frac{273+30}{273+120} - \frac{-518.5}{293.15}$$

$$= -1.4862 - 0.1196 + 1.6277$$

$$= \mathbf{0.02186 \text{ kJ/K}}$$



## 8.86

A hollow steel sphere with a 0.5-m inside diameter and a 2-mm thick wall contains water at 2 MPa, 250°C. The system (steel plus water) cools to the ambient temperature, 30°C. Calculate the net entropy change of the system and surroundings for this process.

C.V.: Steel + water. This is a control mass.

$$\text{Energy Eq.: } U_2 - U_1 = {}_1Q_2 - {}_1W_2 = m_{\text{H}_2\text{O}}(u_2 - u_1) + m_{\text{steel}}(u_2 - u_1)$$

$$\text{Process: } V = \text{constant} \Rightarrow {}_1W_2 = 0$$

$$m_{\text{steel}} = (\rho V)_{\text{steel}} = 8050 \times (\pi/6)[(0.504)^3 - (0.5)^3] = 12.746 \text{ kg}$$

$$V_{\text{H}_2\text{O}} = (\pi/6)(0.5)^3, \quad m_{\text{H}_2\text{O}} = V/v = 6.545 \times 10^{-2} / 0.11144 = 0.587 \text{ kg}$$

$$v_2 = v_1 = 0.11144 = 0.001004 + x_2 \times 32.889 \Rightarrow x_2 = 3.358 \times 10^{-3}$$

$$u_2 = 125.78 + 3.358 \times 10^{-3} \times 2290.8 = 133.5 \text{ kJ/kg}$$

$$s_2 = 0.4639 + 3.358 \times 10^{-3} \times 8.0164 = 0.4638 \text{ kJ/kg K}$$

$${}_1Q_2 = m_{\text{H}_2\text{O}}(u_2 - u_1) + m_{\text{steel}}(u_2 - u_1)$$

$$= 0.587(133.5 - 2679.6) + 12.746 \times 0.48(30 - 250)$$

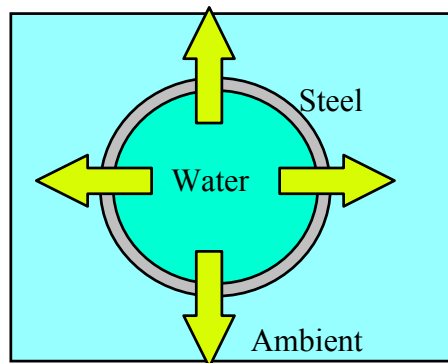
$$= -1494.6 + (-1346) = -2840.6 \text{ kJ}$$

$$\Delta S_{\text{TOT}} = \Delta S_{\text{STEEL}} + \Delta S_{\text{H}_2\text{O}} = 12.746 \times 0.48 \ln(303.15 / 523.15)$$

$$+ 0.587(0.4638 - 6.545) = -6.908 \text{ kJ/K}$$

$$\Delta S_{\text{SURR}} = -{}_1Q_2/T_0 = +2840.6/303.2 = +9.370 \text{ kJ/K}$$

$$\Delta S_{\text{NET}} = -6.908 + 9.370 = +2.462 \text{ kJ/K}$$



## Entropy of ideal gases

## 8.87

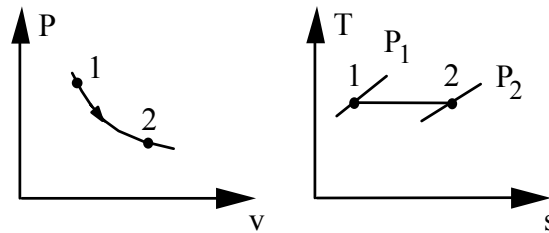
A mass of 1 kg of air contained in a cylinder at 1.5 MPa, 1000 K, expands in a reversible isothermal process to a volume 10 times larger. Calculate the heat transfer during the process and the change of entropy of the air.

Solution:

C.V. Air, control mass.

$$\text{Energy Eq. 5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = 0$$

$$\text{Process: } T = \text{constant so with ideal gas} \Rightarrow u_2 = u_1$$



From the process equation and ideal gas law

$$PV = mRT = \text{constant}$$

we can calculate the work term as in Eq.4.5

$$\begin{aligned} {}_1Q_2 = {}_1W_2 &= \int Pdv = P_1V_1 \ln(V_2/V_1) = mRT_1 \ln(V_2/V_1) \\ &= 1 \times 0.287 \times 1000 \ln(10) = \mathbf{660.84 \text{ kJ}} \end{aligned}$$

The change of entropy from Eq.8.3 is

$$\Delta S_{\text{air}} = m(s_2 - s_1) = {}_1Q_2/T = 660.84/1000 = \mathbf{0.661 \text{ kJ/K}}$$

If instead we use Eq.8.26 we would get

$$\begin{aligned} \Delta S_{\text{air}} &= m(s_2 - s_1) = m\left(C_{v0} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}\right) \\ &= 1 [0 + 0.287 \ln(10)] = 0.661 \text{ kJ/K} \end{aligned}$$

consistent with the above result.

## 8.88

A piston/cylinder setup contains air at 100 kPa, 400 K which is compressed to a final pressure of 1000 kPa. Consider two different processes (i) a reversible adiabatic process and (ii) a reversible isothermal process. Show both processes in P-v and a T-s diagram. Find the final temperature and the specific work for both processes.

Solution:

C.V. Air, control mass of unknown size and mass.

$$\text{Energy Eq.5.11: } u_2 - u_1 = {}_1q_2 - {}_1w_2$$

$$\text{Entropy Eq.8.14: } s_2 - s_1 = \int dq/T + {}_1s_{2\text{ gen}}$$

$$\text{Process: Reversible } {}_1s_{2\text{ gen}} = 0$$

$$\text{i) } dq = 0 \text{ so } {}_1q_2 = 0$$

$$\text{ii) } T = C \text{ so } \int dq/T = {}_1q_2/T$$

i) For this process the entropy equation reduces to:

$$s_2 - s_1 = 0 + 0 \text{ so we have constant } s, \text{ an isentropic process.}$$

The relation for an ideal gas, constant  $s$  and  $k$  becomes Eq.8.32

$$T_2 = T_1 (P_2 / P_1)^{\frac{k-1}{k}} = 400 \left( \frac{1000}{100} \right)^{\frac{0.4}{1.4}} = 400 \times 10^{0.28575} = 772 \text{ K}$$

From the energy equation we get the work term

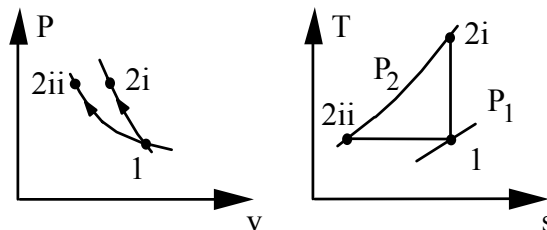
$${}_1w_2 = u_1 - u_2 = C_v(T_1 - T_2) = 0.717(400 - 772) = -266.7 \text{ kJ/kg}$$

ii) For this process  $T_2 = T_1$  so since ideal gas we get

$$u_2 = u_1 \text{ also } s_{T_2}^\circ = s_{T_1}^\circ \Rightarrow \text{Energy Eq.: } {}_1w_2 = {}_1q_2$$

Now from the entropy equation we solve for  ${}_1q_2$

$$\begin{aligned} {}_1w_2 = {}_1q_2 &= T(s_2 - s_1) = T[s_{T_2}^\circ - s_{T_1}^\circ - R \ln \frac{P_2}{P_1}] = -RT \ln \frac{P_2}{P_1} \\ &= -0.287 \times 400 \ln 10 = -264 \text{ kJ/kg} \end{aligned}$$

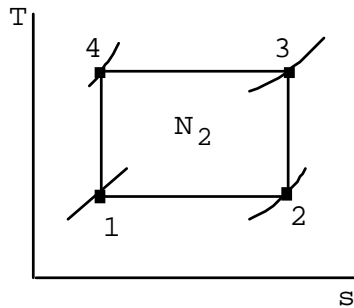


## 8.89

Consider a Carnot-cycle heat pump having 1 kg of nitrogen gas in a cylinder/piston arrangement. This heat pump operates between reservoirs at 300 K and 400 K. At the beginning of the low-temperature heat addition, the pressure is 1 MPa. During this process the volume triples. Analyze each of the four processes in the cycle and determine

- The pressure, volume, and temperature at each point
- The work and heat transfer for each process

Solution:



$$T_1 = T_2 = 300 \text{ K}, \quad T_3 = T_4 = 400 \text{ K},$$

$$P_1 = 1 \text{ MPa}, \quad V_2 = 3 \times V_1$$

$$a) \quad P_2 V_2 = P_1 V_1 \Rightarrow P_2 = P_1/3 = 0.3333 \text{ MPa}$$

$$V_1 = \frac{mRT_1}{P_1} = \frac{1 \times 0.2968 \times 300}{1000} = 0.08904 \text{ m}^3$$

$$V_2 = 0.26712 \text{ m}^3$$

$$P_3 = P_2 (T_3/T_2)^{\frac{k}{k-1}} = 0.3333 \left( \frac{400}{300} \right)^{3.5} = 0.9123 \text{ MPa}$$

$$V_3 = V_2 \times \frac{P_2}{P_3} \times \frac{T_3}{T_2} = 0.26712 \times \frac{0.3333}{0.9123} \times \frac{400}{300} = 0.1302 \text{ m}^3$$

$$P_4 = P_1 (T_3/T_1)^{\frac{k}{k-1}} = 1 \left( \frac{400}{300} \right)^{3.5} = 2.73707 \text{ MPa}$$

$$V_4 = V_1 \times \frac{P_1}{P_4} \times \frac{T_4}{T_1} = 0.08904 \times \frac{1}{2.737} \times \frac{400}{300} = 0.04337 \text{ m}^3$$

$$b) \quad {}_1W_2 = {}_1Q_2 = mRT_1 \ln(P_1/P_2)$$

$$= 1 \times 0.2968 \times 300 \ln(1/0.333) = 97.82 \text{ kJ}$$

$${}_3W_4 = {}_3Q_4 = mRT_3 \ln(P_3/P_4)$$

$$= 1 \times 0.2968 \times 400 \ln(0.9123/2.737) = -130.43 \text{ kJ}$$

$${}_2W_3 = -mC_{V0}(T_3 - T_2) = -1 \times 0.7448(400 - 300) = -74.48 \text{ kJ}$$

$${}_4W_1 = -mC_{V0}(T_1 - T_4) = -1 \times 0.7448(300 - 400) = +74.48 \text{ kJ}$$

$${}_2Q_3 = 0, \quad {}_4Q_1 = 0$$

## 8.90

Consider a small air pistol with a cylinder volume of  $1 \text{ cm}^3$  at  $250 \text{ kPa}$ ,  $27^\circ\text{C}$ . The bullet acts as a piston initially held by a trigger. The bullet is released so the air expands in an adiabatic process. If the pressure should be  $100 \text{ kPa}$  as the bullet leaves the cylinder find the final volume and the work done by the air.

Solution:

C.V. Air. Assume a reversible, adiabatic process.

$$\text{Energy Eq.5.11:} \quad u_2 - u_1 = 0 - {}_1w_2 \quad ;$$

$$\text{Entropy Eq.8.14:} \quad s_2 - s_1 = \int dq/T + {}_1s_2 \text{ gen} = 0$$

$$\text{State 1:} \quad (T_1, P_1) \quad \text{State 2:} \quad (P_2, ?)$$

So we realize that one piece of information is needed to get state 2.

$$\text{Process:} \quad \text{Adiabatic} \quad {}_1q_2 = 0 \quad \text{Reversible} \quad {}_1s_2 \text{ gen} = 0$$

With these two terms zero we have a zero for the entropy change. So this is a constant  $s$  (isentropic) expansion process giving  $s_2 = s_1$ . From Eq.8.32

$$T_2 = T_1 (P_2 / P_1)^{\frac{k-1}{k}} = 300 \left( \frac{100}{250} \right)^{\frac{0.4}{1.4}} = 300 \times 0.4^{0.28575} = 230.9 \text{ K}$$

The ideal gas law  $PV = mRT$  at both states leads to

$$V_2 = V_1 P_1 T_2 / P_2 T_1 = 1 \times 250 \times 230.9 / 100 \times 300 = \mathbf{1.92 \text{ cm}^3}$$

The work term is from Eq.8.38 or Eq.4.4 with polytropic exponent  $n = k$

$$\begin{aligned} {}_1W_2 &= \frac{1}{1-k} (P_2 V_2 - P_1 V_1) = \frac{1}{1-1.4} (100 \times 1.92 - 250 \times 1) \times 10^{-6} \\ &= \mathbf{0.145 \text{ J}} \end{aligned}$$

## 8.91

Oxygen gas in a piston cylinder at 300 K, 100 kPa with volume  $0.1 \text{ m}^3$  is compressed in a reversible adiabatic process to a final temperature of 700 K. Find the final pressure and volume using Table A.5.

Solution:

C.V. Air. Assume a reversible, adiabatic process.

$$\text{Energy Eq.5.11:} \quad u_2 - u_1 = 0 - {}_1w_2 \quad ;$$

$$\text{Entropy Eq.8.14:} \quad s_2 - s_1 = \int dq/T + {}_1s_2 \text{ gen} = 0$$

$$\text{Process:} \quad \text{Adiabatic} \quad {}_1q_2 = 0 \quad \text{Reversible} \quad {}_1s_2 \text{ gen} = 0$$

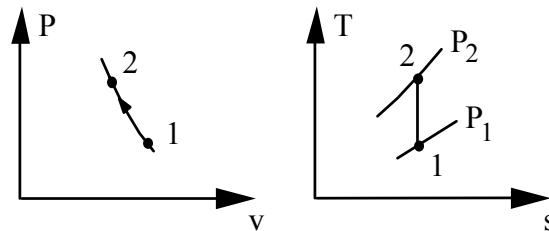
$$\text{Properties:} \quad \text{Table A.5:} \quad k = 1.393$$

With these two terms zero we have a zero for the entropy change. So this is a constant s (isentropic) expansion process. From Eq.8.32

$$P_2 = P_1 \left( T_2 / T_1 \right)^{\frac{k}{k-1}} = \mathbf{2015 \text{ kPa}}$$

Using the ideal gas law to eliminate P from this equation leads to Eq.8.33

$$V_2 = V_1 \left( T_2 / T_1 \right)^{\frac{1}{1-k}} = 0.1 \times \left( \frac{700}{300} \right)^{\frac{1}{1-1.393}} = \mathbf{0.0116 \text{ m}^3}$$



## 8.92

Oxygen gas in a piston cylinder at 300 K, 100 kPa with volume  $0.1 \text{ m}^3$  is compressed in a reversible adiabatic process to a final temperature of 700 K. Find the final pressure and volume using constant heat capacity from Table A.8.

Solution:

C.V. Air. Assume a reversible, adiabatic process.

$$\text{Energy Eq.5.11:} \quad u_2 - u_1 = 0 - {}_1w_2 \quad ;$$

$$\text{Entropy Eq.8.14:} \quad s_2 - s_1 = \int dq/T + {}_1s_2 \text{ gen} = 0$$

$$\text{Process:} \quad \text{Adiabatic} \quad {}_1q_2 = 0 \quad \text{Reversible} \quad {}_1s_2 \text{ gen} = 0$$

With these two terms zero we have a zero for the entropy change. So this is a constant  $s$  (isentropic) expansion process. From Eq.8.28

$$s_{T2}^o - s_{T1}^o = R \ln \frac{P_2}{P_1}$$

$$\text{Properties:} \quad \text{Table A.8:} \quad s_{T1}^o = 6.4168, \quad s_{T2}^o = 7.2336 \text{ kJ/kg K}$$

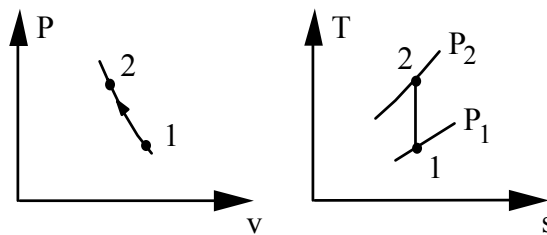
$$\frac{P_2}{P_1} = \exp [(s_{T2}^o - s_{T1}^o)/R] = \exp\left(\frac{7.2336 - 6.4168}{0.2598}\right) = 23.1955$$

$$P_2 = 100 \times 23.1955 = \mathbf{2320 \text{ kPa}}$$

$$\text{Ideal gas law:} \quad P_1 V_1 = mRT_1 \quad \text{and} \quad P_2 V_2 = mRT_2$$

Take the ratio of these so  $mR$  drops out to give

$$V_2 = V_1 \times (T_2 / T_1) \times (P_1 / P_2) = 0.1 \times \left(\frac{700}{300}\right) \times \left(\frac{100}{2320}\right) = \mathbf{0.01 \text{ m}^3}$$





## 8.93

A handheld pump for a bicycle has a volume of  $25 \text{ cm}^3$  when fully extended. You now press the plunger (piston) in while holding your thumb over the exit hole so that an air pressure of 300 kPa is obtained. The outside atmosphere is at  $P_0, T_0$ . Consider two cases: (1) it is done quickly ( $\sim 1 \text{ s}$ ), and (2) it is done very slowly ( $\sim 1 \text{ h}$ ).

- State assumptions about the process for each case.
- Find the final volume and temperature for both cases.

Solution:

C.V. Air in pump. Assume that both cases result in a reversible process.

State 1:  $P_0, T_0$       State 2: 300 kPa, ?

One piece of information must resolve the ? for a state 2 property.

Case I) Quickly means no time for heat transfer

$Q = 0$ , so a reversible adiabatic compression.

$$u_2 - u_1 = -{}_1w_2 ; \quad s_2 - s_1 = \int dq/T + {}_1s_2 \text{ gen} = 0$$

With constant  $s$  and constant heat capacity we use Eq.8.32

$$T_2 = T_1 (P_2 / P_1)^{\frac{k-1}{k}} = 298 \left( \frac{300}{101.325} \right)^{\frac{0.4}{1.4}} = \mathbf{405.3 \text{ K}}$$

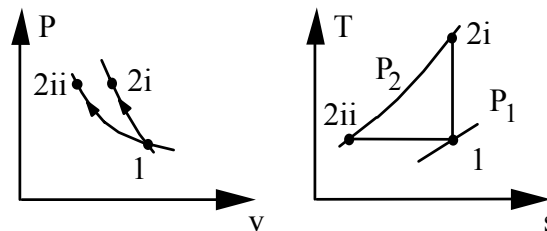
Use ideal gas law  $PV = mRT$  at both states so ratio gives

$$\Rightarrow V_2 = P_1 V_1 T_2 / T_1 P_2 = \mathbf{11.48 \text{ cm}^3}$$

Case II) Slowly, time for heat transfer so  $T = \text{constant} = T_0$ .

The process is then a reversible isothermal compression.

$$T_2 = T_0 = \mathbf{298 \text{ K}} \quad \Rightarrow \quad V_2 = V_1 P_1 / P_2 = \mathbf{8.44 \text{ cm}^3}$$



## 8.94

An insulated cylinder/piston contains carbon dioxide gas at 120 kPa, 400 K. The gas is compressed to 2.5 MPa in a reversible adiabatic process. Calculate the final temperature and the work per unit mass, assuming

- Variable specific heat, Table A.8
- Constant specific heat, value from Table A.5
- Constant specific heat, value at an intermediate temperature from Table A.6

Solution:

C.V. Air, a control mass undergoing a reversible, adiabatic process.

$$\text{Energy Eq.5.11: } u_2 - u_1 = 0 - {}_1w_2 ;$$

$$\text{Entropy Eq.8.14: } s_2 - s_1 = \int dq/T + {}_1s_2 \text{ gen} = 0$$

$$\text{Process: } \quad \text{Adiabatic } {}_1q_2 = 0 \quad \text{Reversible } {}_1s_2 \text{ gen} = 0$$

$$\text{State 1: (400 K, 120 kPa)} \quad \text{State 2: (2500 kPa, ?)}$$

With two terms zero in the entropy equation we have a zero for the entropy change. So this is a constant  $s$  (isentropic) expansion process,  $s_2 = s_1$ .

- a) Table A.8 for  $\text{CO}_2$  and Eq.8.28

$$s_2 - s_1 = 0 = s_{T_2}^\circ - s_{T_1}^\circ - R \ln(P_2/P_1)$$

$$s_{T_2}^\circ = s_{T_1}^\circ + R \ln(P_2/P_1) = 5.1196 + 0.1889 \ln(2500/120) = 5.6932$$

Now interpolate in A.8 to find  $T_2$

$$T_2 = 650 + 50 (5.6932 - 5.6151)/(5.6976 - 5.6151) = \mathbf{697.3 \text{ K}}$$

$${}_1w_2 = -(u_2 - u_1) = -(481.5 - 228.19) = \mathbf{-253.3 \text{ kJ/kg}}$$

- b) Table A.5:  $k = 1.289$ ,  $C_{V_0} = 0.653 \text{ kJ/kg K}$  and now Eq.8.32

$$T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} = 400 \left( \frac{2.5}{0.12} \right)^{0.224} = \mathbf{789.7 \text{ K}}$$

$${}_1w_2 = -C_{V_0}(T_2 - T_1) = -0.653 (789.7 - 400) = \mathbf{-254.5 \text{ kJ/kg}}$$

- c) Find a heat capacity at an average temperature from Table A.6.

$$\text{Estimate } T_2 \sim 700 \text{ K giving } T_{\text{AVE}} \sim 550 \text{ K} \Rightarrow \theta = 0.55$$

$$C_{P_0} = 0.45 + 1.67 \times 0.55 - 1.27 \times 0.55^2 + 0.39 \times 0.55^3 = 1.049 \text{ kJ/kg K}$$

$$C_{V_0} = C_{P_0} - R = 1.049 - 0.1889 = 0.8601, \quad k = C_{P_0}/C_{V_0} = 1.2196$$

$$\text{Eq.8.32: } T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} = 400 \left( \frac{2.5}{0.12} \right)^{0.18006} = \mathbf{691 \text{ K}}$$

$${}_1w_2 = -C_{V_0}(T_2 - T_1) = -0.8601 (691 - 400) = \mathbf{-250.3 \text{ kJ/kg}}$$

## 8.95

A piston/cylinder, shown in Fig. P8.95, contains air at 1380 K, 15 MPa, with  $V_1 = 10 \text{ cm}^3$ ,  $A_{\text{cyl}} = 5 \text{ cm}^2$ . The piston is released, and just before the piston exits the end of the cylinder the pressure inside is 200 kPa. If the cylinder is insulated, what is its length? How much work is done by the air inside?

Solution:

C.V. Air, Cylinder is insulated so adiabatic,  $Q = 0$ .

Continuity Eq.:  $m_2 = m_1 = m$ ,

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

Entropy Eq.8.14:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2_{\text{gen}} = 0 + {}_1S_2_{\text{gen}}$

State 1:  $(T_1, P_1)$       State 2:  $(P_2, ?)$

So one piece of information is needed for the ?, assume reversible process.

$${}_1S_2_{\text{gen}} = 0 \Rightarrow s_2 - s_1 = 0$$

State 1: Table A.7:  $u_1 = 1095.2 \text{ kJ/kg}$ ,  $s_{T1}^{\circ} = 8.5115 \text{ kJ/kg K}$

$$m = P_1 V_1 / RT_1 = \frac{15000 \times 10 \times 10^{-6}}{0.287 \times 1380} = 0.000379 \text{ kg}$$

State 2:  $P_2$  and from Entropy eq.:  $s_2 = s_1$  so from Eq.8.28

$$s_{T2}^{\circ} = s_{T1}^{\circ} + R \ln \frac{P_2}{P_1} = 8.5115 + 0.287 \ln \left( \frac{200}{15000} \right) = 7.2724 \text{ kJ/kg K}$$

Now interpolate in Table A.7 to get  $T_2$

$$T_2 = 440 + 20 (7.2724 - 7.25607) / (7.30142 - 7.25607) = \mathbf{447.2 \text{ K}}$$

$$u_2 = 315.64 + (330.31 - 315.64) 0.36 = 320.92 \text{ kJ/kg}$$

$$V_2 = V_1 \frac{T_2 P_1}{T_1 P_2} = \frac{10 \times 447.2 \times 15000}{1380 \times 200} = \mathbf{243 \text{ cm}^3}$$

$$\Rightarrow L_2 = V_2 / A_{\text{cyl}} = 243/5 = \mathbf{48.6 \text{ cm}}$$

$${}_1w_2 = u_1 - u_2 = 774.3 \text{ kJ/kg}, \quad {}_1W_2 = m_1 w_2 = \mathbf{0.2935 \text{ kJ}}$$

## 8.96

Two rigid tanks, shown in Fig. P8.96, each contain 10 kg  $N_2$  gas at 1000 K, 500 kPa. They are now thermally connected to a reversible heat pump, which heats one and cools the other with no heat transfer to the surroundings. When one tank is heated to 1500 K the process stops. Find the final ( $P$ ,  $T$ ) in both tanks and the work input to the heat pump, assuming constant heat capacities.

Solution:

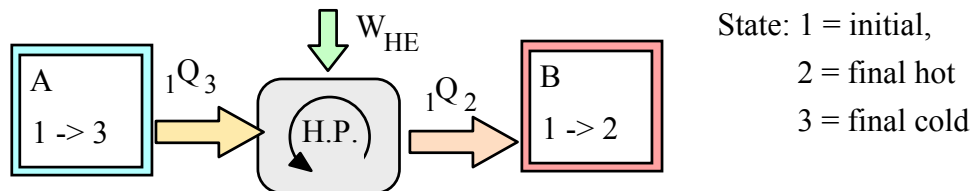
Control volume of hot tank B,

Process = constant volume & mass so no work

Energy equation Eq.5.11 and specific heat in Eq.5.20 gives

$$U_2 - U_1 \cong mC_v(T_2 - T_1) = {}_1Q_2 = 10 \times 0.7448 \times 500 = 3724 \text{ kJ}$$

$$P_2 = P_1 T_2 / T_1 = 1.5(P_1) = \mathbf{750 \text{ kPa}}$$



To fix temperature in cold tank, C.V.: total

For this CV only  $W_{HP}$  cross the control surface no heat transfer. The entropy equation Eq.8.14 for a reversible process becomes

$$(S_2 - S_1)_{tot} = 0 = m_{hot}(s_2 - s_1) + m_{cold}(s_3 - s_1)$$

Use specific heats to evaluate the changes in  $s$  from Eq.8.25 and division by  $m$

$$C_{p,hot} \ln(T_2 / T_1) - R \ln(P_2 / P_1) + C_{p,cold} \ln(T_3 / T_1) - R \ln(P_3 / P_1) = 0$$

$$P_3 = P_1 T_3 / T_1 \quad \text{and} \quad P_2 = P_1 T_2 / T_1$$

Now everything is in terms of  $T$  and  $C_p = C_v + R$ , so

$$C_{v,hot} \ln(T_2 / T_1) + C_{v,cold} \ln(T_3 / T_1) = 0$$

$$\text{same } C_v: \quad T_3 = T_1(T_1 / T_2) = \mathbf{667 \text{ K}}, \quad P_3 = \mathbf{333 \text{ kPa}}$$

$$Q_{cold} = -{}_1Q_3 = mC_v(T_3 - T_1) = -2480 \text{ kJ},$$

$$W_{HP} = {}_1Q_2 + Q_{cold} = {}_1Q_2 - {}_1Q_3 = \mathbf{1244 \text{ kJ}}$$

## 8.97

A spring loaded piston cylinder contains 1.5 kg air at 27°C and 160 kPa. It is now heated in a process where pressure is linear in volume,  $P = A + BV$ , to twice the initial volume where it reaches 900 K. Find the work, the heat transfer and the total entropy generation assuming a source at 900 K.

Solution:

C.V. Air out to the 900 K source. Since air T is lower than the source temperature we know that this is an irreversible process.

Continuity Eq.:  $m_2 = m_1 = m$ ,

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

Entropy Eq.8.14:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2_{\text{gen}} = {}_1Q_2/T_{\text{SOURCE}} + {}_1S_2_{\text{gen}}$

Process:  $P = A + BV$

State 1:  $(T_1, P_1)$  Table A.7  $u_1 = 214.36$  kJ/kg

$$V_1 = mRT_1/P_1 = (1.5 \times 0.287 \times 300) / 160 = 0.8072 \text{ m}^3$$

State 2:  $(T_2, v_2 = 2 v_1)$  Table A.7  $u_2 = 674.824$  kJ/kg

$$\begin{aligned} P_2 &= RT_2/v_2 = RT_2/2v_1 = T_2 P_1 / 2T_1 = P_1 T_2 / 2 T_1 \\ &= 160 \times 900 / 2 \times 300 = \mathbf{240 \text{ kPa}} \end{aligned}$$

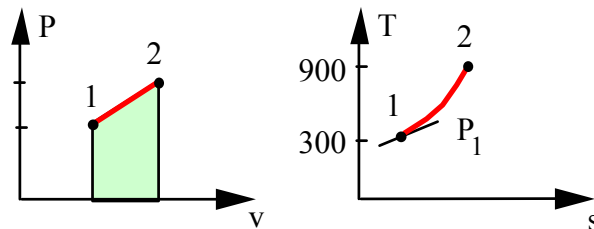
From the process equation we can express the work as

$$\begin{aligned} {}_1W_2 &= \int PdV = 0.5 \times (P_1 + P_2) (V_2 - V_1) = 0.5 \times (P_1 + P_2) V_1 \\ &= 0.5 \times (160 + 240) 0.8072 = \mathbf{161.4 \text{ kJ}} \end{aligned}$$

$${}_1Q_2 = 1.5 \times (674.824 - 214.36) + 161.4 = \mathbf{852.1 \text{ kJ}}$$

Change in s from Eq.8.28 and Table A.7 values

$$\begin{aligned} {}_1S_2_{\text{gen}} &= m(s_{T_2}^0 - s_{T_1}^0 - R \ln \frac{P_2}{P_1}) - {}_1Q_2/T_{\text{SOURCE}} \\ &= 1.5 \times [8.0158 - 6.8693 - 0.287 \ln (\frac{240}{160})] - (\frac{852.1}{900}) \\ &= 1.545 - 0.947 = \mathbf{0.598 \text{ kJ/K}} \end{aligned}$$



## 8.98

A rigid storage tank of  $1.5 \text{ m}^3$  contains  $1 \text{ kg}$  argon at  $30^\circ\text{C}$ . Heat is then transferred to the argon from a furnace operating at  $1300^\circ\text{C}$  until the specific entropy of the argon has increased by  $0.343 \text{ kJ/kg K}$ . Find the total heat transfer and the entropy generated in the process.

Solution:

C.V. Argon out to  $1300^\circ\text{C}$ . Control mass. ,  $m = 1 \text{ kg}$

Argon is an ideal gas with constant heat capacity.

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = m C_v (T_2 - T_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14: } m(s_2 - s_1) = {}_1Q_2/T_{\text{res}} + {}_1S_2 \text{ gen tot}$$

$$\text{Process: } V = \text{constant} \Rightarrow v_2 = v_1 \text{ also } {}_1W_2 = 0$$

$$\text{Properties: Table A.5 } R = 0.20813, C_v = 0.312 \text{ kJ/kg K}$$

$$\text{State 1: } (T_1, v_1 = V/m) \quad P_1 = mRT_1/V = 42.063 \text{ kPa}$$

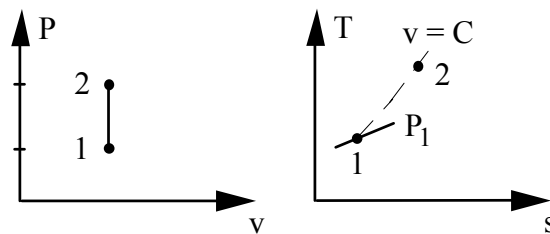
$$\text{State 2: } s_2 = s_1 + 0.343, \text{ and change in } s \text{ from Eq.8.28 or Eq.8.26}$$

$$s_2 - s_1 = C_p \ln(T_2/T_1) - R \ln(T_2/T_1) = C_v \ln(T_2/T_1)$$

$$T_2/T_1 = \exp\left[\frac{s_2 - s_1}{C_v}\right] = \exp\left[\frac{0.343}{0.312}\right] = \exp(1.09936) = 3.0$$

$$Pv = RT \Rightarrow (P_2/P_1)(v_2/v_1) = T_2/T_1 = P_2/P_1$$

$$T_2 = 3.0 \times T_1 = 909.45 \text{ K}, \quad P_2 = 3.0 \times P_1 = 126.189 \text{ kPa}$$



Heat transfer from energy equation

$${}_1Q_2 = 1 \times 0.312 (909.45 - 303.15) = 189.2 \text{ kJ}$$

Entropy generation from entropy equation (2nd law)

$$\begin{aligned} {}_1S_2 \text{ gen tot} &= m(s_2 - s_1) - {}_1Q_2/T_{\text{res}} \\ &= 1 \times 0.343 - 189.2 / (1300 + 273) = \mathbf{0.223 \text{ kJ/K}} \end{aligned}$$

## 8.99

A rigid tank contains 2 kg of air at 200 kPa and ambient temperature, 20°C. An electric current now passes through a resistor inside the tank. After a total of 100 kJ of electrical work has crossed the boundary, the air temperature inside is 80°C. Is this possible?

Solution:

C.V.: Air in tank out to ambient;

$$\text{Energy Eq. 5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2, \quad {}_1W_2 = -100 \text{ kJ}$$

$$\text{Entropy Eq. 8.14, 8.18: } m(s_2 - s_1) = \int dQ/T + {}_1S_2 \text{ gen} = {}_1Q_2/T_{\text{amb}} + {}_1S_2 \text{ gen}$$

Process: Constant volume and mass so  $v_2 = v_1$

State 1:  $T_1 = 20^\circ\text{C}$ ,  $P_1 = 200 \text{ kPa}$ ,  $m_1 = 2 \text{ kg}$

State 2:  $T_2 = 80^\circ\text{C}$ ,  $v_2 = v_1$

Ideal gas, Table A.5:  $R = 0.287 \text{ kJ/kg-K}$ ,  $C_v = 0.717 \text{ kJ/kg-K}$

Assume constant specific heat then energy equation gives

$${}_1Q_2 = mC_v(T_2 - T_1) + {}_1W_2 = 2 \times 0.717(80 - 20) - 100 = -14.0 \text{ kJ}$$

Change in  $s$  from Eq. 8.26 (since second term drops out)

$$s_2 - s_1 = C_v \ln(T_2/T_1) + R \ln \frac{v_2}{v_1}; \quad v_2 = v_1, \quad \ln \frac{v_2}{v_1} = 0$$

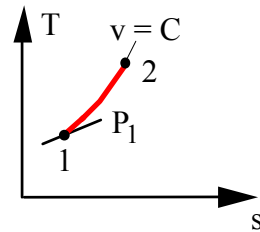
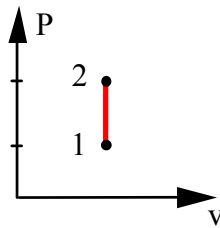
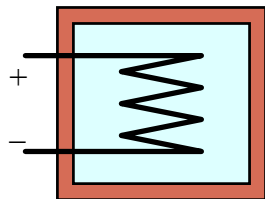
$$s_2 - s_1 = C_v \ln(T_2/T_1) = 0.1336 \text{ kJ/kg-K}$$

Now Eq. 8.18 or from Eq. 8.14

$${}_1S_2 \text{ gen} = m(s_2 - s_1) - {}_1Q_2/T_{\text{amb}} = 2 \times 0.1336 + \frac{14}{293} = 0.315 \text{ kJ/K} \geq 0,$$

**Process is Possible**

Note:  $P_2 = P_1 \frac{T_2}{T_1}$  in Eq. 8.28  $s_2 - s_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$ , results in the same answer as Eq. 8.26.



## 8.100

Argon in a light bulb is at 90 kPa and heated from 20°C to 60°C with electrical power. Do not consider any radiation, nor the glass mass. Find the total entropy generation per unit mass of argon.

Solution:

C.V. Argon gas. Neglect any heat transfer.

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1W_2 \text{ electrical in}$$

$$\text{Entropy Eq.8.14: } s_2 - s_1 = \int dq/T + {}_1s_2 \text{ gen} = {}_1s_2 \text{ gen}$$

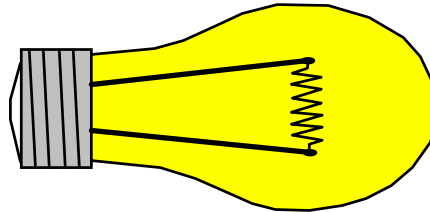
$$\text{Process: } v = \text{constant and ideal gas} \Rightarrow P_2/P_1 = T_2/T_1$$

Evaluate changes in  $s$  from Eq.8.26 or 8.28

$${}_1s_2 \text{ gen} = s_2 - s_1 = C_p \ln (T_2/T_1) - R \ln (P_2/P_1) \quad \text{Eq.8.28}$$

$$= C_p \ln (T_2/T_1) - R \ln (T_2/T_1) = C_v \ln(T_2/T_1) \quad \text{Eq.8.26}$$

$$= 0.312 \ln [ (60 + 273)/(20 + 273) ] = \mathbf{0.04 \text{ kJ/kg K}}$$



Since there was no heat transfer but work input all the change in  $s$  is generated by the process (irreversible conversion of  $W$  to internal energy)

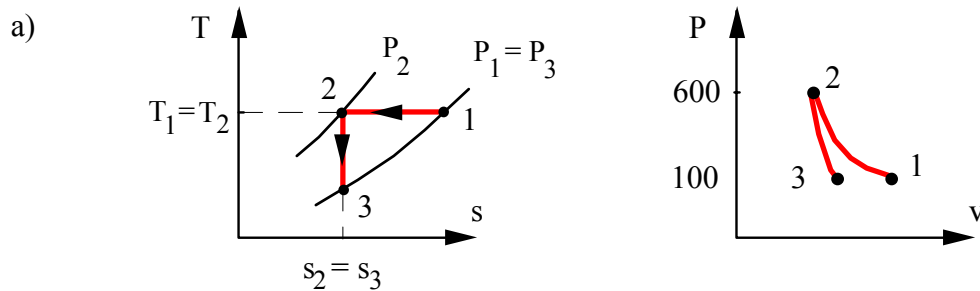


## 8.101

We wish to obtain a supply of cold helium gas by applying the following technique. Helium contained in a cylinder at ambient conditions, 100 kPa, 20°C, is compressed in a reversible isothermal process to 600 kPa, after which the gas is expanded back to 100 kPa in a reversible adiabatic process.

- Show the process on a  $T$ - $s$  diagram.
- Calculate the final temperature and the net work per kilogram of helium.

Solution:



- b) The adiabatic reversible expansion gives constant  $s$  from the entropy equation Eq.8.14. With ideal gas and constant specific heat this gives relation in Eq.8.32

$$T_3 = T_2(P_3/P_2)^{\frac{k-1}{k}} = 293.15 (100/600)^{0.4} = \mathbf{143.15 \text{ K}}$$

The net work is summed up over the two processes. The isothermal process has work as Eq.8.41

$${}_1w_2 = -RT_1 \ln(P_2/P_1) = -2.0771 \times 293.15 \times \ln(600/100) = -1091.0 \text{ kJ/kg}$$

The adiabatic process has a work term from energy equation with no  $q$

$${}_2w_3 = C_{V_o}(T_2 - T_3) = 3.116 (293.15 - 143.15) = +467.4 \text{ kJ/kg}$$

The net work is the sum

$$w_{\text{NET}} = -1091.0 + 467.4 = \mathbf{-623.6 \text{ kJ/kg}}$$

## 8.102

A 1-m<sup>3</sup> insulated, rigid tank contains air at 800 kPa, 25°C. A valve on the tank is opened, and the pressure inside quickly drops to 150 kPa, at which point the valve is closed. Assuming that the air remaining inside has undergone a reversible adiabatic expansion, calculate the mass withdrawn during the process.

Solution:

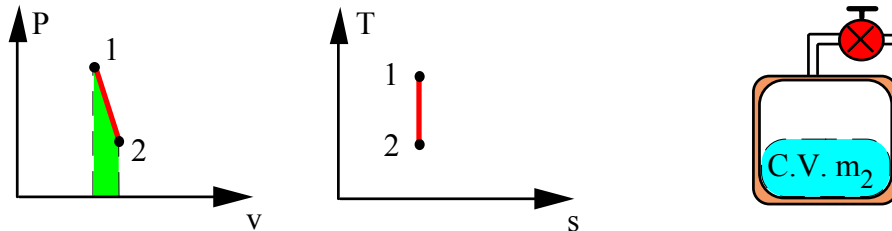
C.V.: Air remaining inside tank,  $m_2$ .

Cont.Eq.:  $m_2 = m$  ;

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

Entropy Eq.8.14:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2_{\text{gen}}$

Process: adiabatic  ${}_1Q_2 = 0$  and reversible  ${}_1S_2_{\text{gen}} = 0$



Entropy eq. then gives  $s_2 = s_1$  and ideal gas gives the relation in Eq.8.32

$$T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 298.2(150/800)^{0.286} = \mathbf{184.8 \text{ K}}$$

$$m_1 = P_1V/RT_1 = (800 \times 1)/(0.287 \times 298.2) = 9.35 \text{ kg}$$

$$m_2 = P_2V/RT_2 = (150 \times 1)/(0.287 \times 184.8) = 2.83 \text{ kg}$$

$$m_e = m_1 - m_2 = \mathbf{6.52 \text{ kg}}$$

## 8.103

Nitrogen at 200°C, 300 kPa is in a piston cylinder, volume 5 L, with the piston locked with a pin. The forces on the piston require a pressure inside of 200 kPa to balance it without the pin. The pin is removed and the piston quickly comes to its equilibrium position without any heat transfer. Find the final P, T and V and the entropy generation due to this partly unrestrained expansion.

Solution:

C.V. Nitrogen gas.

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = - \int P_{\text{eq}} dV = -P_2 (V_2 - V_1)$$

$$\text{Entropy Eq.8.14: } m(s_2 - s_1) = 0 + {}_1S_{2 \text{ gen}}$$

Process:  ${}_1Q_2 = 0$  (already used),  $P = P_{\text{eq}}$  after pin is out.

State 1: 200 °C, 300 kPa                      State 2:  $P_2 = P_{\text{eq}} = 200$  kPa

$$m = P_1 V_1 / RT_1 = 300 \times 0.005 / 0.2968 \times 473.15 = 0.01068 \text{ kg}$$

The energy equation becomes

$$mu_2 + P_2 V_2 = mu_1 + P_2 V_1 = mh_2 \Rightarrow$$

$$h_2 = u_1 + P_2 V_1 / m = u_1 + P_2 V_1 RT_1 / P_1 V_1 = u_1 + (P_2 / P_1) RT_1$$

Solve using constant  $C_p$ ,  $C_v$

$$C_p T_2 = C_v T_1 + (P_2 / P_1) RT_1$$

$$T_2 = T_1 [C_v + (P_2 / P_1) R] / C_p$$

$$= 473.15 [0.745 + (200 / 300) \times 0.2368] / 1.042$$

$$= \mathbf{428.13 \text{ K}}$$

$$V_2 = V_1 (T_2 / T_1) \times (P_1 / P_2) = 0.005 \times \frac{428.13}{473.15} \times \frac{300}{200}$$

$$= 0.00679 \text{ m}^3$$

$${}_1S_{2 \text{ gen}} = m(s_2 - s_1) \cong m[C_p \ln (T_2 / T_1) - R \ln (P_2 / P_1)]$$

$$= P_1 V_1 / RT_1 [C_p \ln (T_2 / T_1) - R \ln (P_2 / P_1)]$$

$$= 0.01068 [1.042 \times \ln (428.13 / 473.15) - 0.2968 \times \ln (200 / 300)]$$

$$= \mathbf{0.000173 \text{ kJ/K}}$$

**8.104**

A rigid container with volume 200 L is divided into two equal volumes by a partition, shown in Fig. P8.104. Both sides contain nitrogen, one side is at 2 MPa, 200°C, and the other at 200 kPa, 100°C. The partition ruptures, and the nitrogen comes to a uniform state at 70°C. Assume the temperature of the surroundings is 20°C, determine the work done and the net entropy change for the process.

Solution:

$$C.V. : A + B \text{ no change in volume. } \quad {}_1W_2 = 0$$

$$m_{A1} = P_{A1} V_{A1} / RT_{A1} = (2000 \times 0.1) / (0.2968 \times 473.2) = 1.424 \text{ kg}$$

$$m_{B1} = P_{B1} V_{B1} / RT_{B1} = (200 \times 0.1) / (0.2968 \times 373.2) = 0.1806 \text{ kg}$$

$$P_2 = m_{TOT} RT_2 / V_{TOT} = (1.6046 \times 0.2968 \times 343.2) / 0.2 = 817 \text{ kPa}$$

From Eq.8.25

$$\begin{aligned} \Delta S_{\text{SYST}} &= 1.424 \left[ 1.042 \ln \frac{343.2}{473.2} - 0.2968 \ln \frac{817}{2000} \right] \\ &\quad + 0.1806 \left[ 1.042 \ln \frac{343.2}{373.2} - 0.2968 \ln \frac{817}{200} \right] = -0.1894 \text{ kJ/K} \end{aligned}$$

$$\begin{aligned} {}_1Q_2 = U_2 - U_1 &= 1.424 \times 0.745(70 - 200) + 0.1806 \times 0.745(70 - 100) \\ &= -141.95 \text{ kJ} \end{aligned}$$

From Eq.8.18

$$\Delta S_{\text{SURR}} = -{}_1Q_2 / T_0 = 141.95 / 293.2 = +0.4841 \text{ kJ/K}$$

$$\Delta S_{\text{NET}} = -0.1894 + 0.4841 = +\mathbf{0.2947 \text{ kJ/K}}$$

## 8.105

Nitrogen at 600 kPa, 127°C is in a 0.5 m<sup>3</sup> insulated tank connected to a pipe with a valve to a second insulated initially empty tank of volume 0.5 m<sup>3</sup>, shown in Fig. P8.105. The valve is opened and the nitrogen fills both tanks at a uniform state. Find the final pressure and temperature and the entropy generation this process causes. Why is the process irreversible?

Solution:

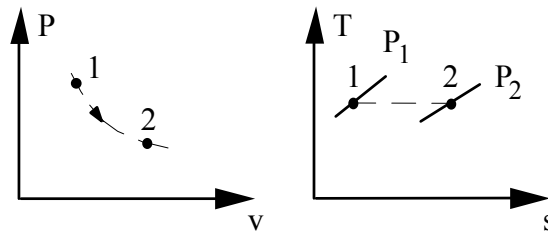
CV Both tanks + pipe + valve Insulated :  $Q = 0$       Rigid:  $W = 0$

Energy Eq.5.11:  $m(u_2 - u_1) = 0 - 0 \Rightarrow u_2 = u_1 = u_{a1}$

Entropy Eq.8.14:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2{}_{\text{gen}} = {}_1S_2{}_{\text{gen}} \quad (dQ = 0)$

1:  $P_1, T_1, V_a \Rightarrow m = PV/RT = (600 \times 0.5)/(0.2968 \times 400) = 2.527$

2:  $V_2 = V_a + V_b$  ; uniform state       $v_2 = V_2/m$  ;  $u_2 = u_{a1}$



Ideal gas  $u(T) \Rightarrow u_2 = u_{a1} \Rightarrow T_2 = T_{a1} = 400 \text{ K}$

$P_2 = mR T_2 / V_2 = (V_1 / V_2) P_1 = \frac{1}{2} \times 600 = 300 \text{ kPa}$

From entropy equation and Eq.8.28 for entropy change

$S_{\text{gen}} = m(s_2 - s_1) = m[s_{T2} - s_{T1} - R \ln(P_2 / P_1)]$

$= m [0 - R \ln(P_2 / P_1)] = -2.527 \times 0.2968 \ln \frac{1}{2} = 0.52 \text{ kJ/K}$

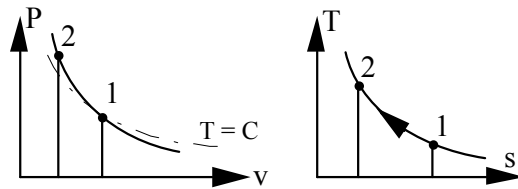
Irreversible due to unrestrained expansion in valve  $P \downarrow$  but no work out.

## Polytropic processes

## 8.106

Neon at 400 kPa, 20°C is brought to 100°C in a polytropic process with  $n = 1.4$ . Give the sign for the heat transfer and work terms and explain.

Solution:



Neon Table A.5

$$k = \gamma = 1.667 \quad \text{so } n < k$$

$$C_v = 0.618, \quad R = 0.412$$

$$\begin{array}{ll} \text{From definition Eq.8.2} & ds = dq/T \quad \text{so} \quad dq = T ds \\ \text{From work term} & dw = P dv \end{array}$$

From figures:  $v$  goes down so work in ( $\mathbf{W} < \mathbf{0}$ );

$s$  goes down so  $Q$  out ( $\mathbf{Q} < \mathbf{0}$ )

We can also calculate the actual specific work from Eq.8.38 and heat transfer from the energy equation as:

$${}_1w_2 = [R/(1-n)](T_2 - T_1) = -82.39 \text{ kJ/kg}$$

$$u_2 - u_1 = C_v(T_2 - T_1) = 49.432, \quad {}_1q_2 = \Delta u + {}_1w_2 = -32.958$$

**${}_1W_2$  Negative and  ${}_1Q_2$  Negative**

**8.107**

A mass of 1 kg of air contained in a cylinder at 1.5 MPa, 1000 K, expands in a reversible adiabatic process to 100 kPa. Calculate the final temperature and the work done during the process, using

- Constant specific heat, value from Table A.5
- The ideal gas tables, Table A.7

Solution:

C.V. Air.

Continuity Eq.:  $m_2 = m_1 = m$  ;

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

Entropy Eq.8.14:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2_{\text{gen}}$

Process:  ${}_1Q_2 = 0$ ,  ${}_1S_2_{\text{gen}} = 0 \Rightarrow s_2 = s_1$

- Using constant  $C_p$  from Table A.5 gives the power relation Eq.8.32.

$$T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 1000\left(\frac{0.1}{1.5}\right)^{0.286} = \mathbf{460.9 \text{ K}}$$

$$\begin{aligned} {}_1W_2 &= -(U_2 - U_1) = mC_{V_o}(T_1 - T_2) \\ &= 1 \times 0.717(1000 - 460.9) = \mathbf{386.5 \text{ kJ}} \end{aligned}$$

- Use the standard entropy function that includes variable heat capacity from A.7.1 and Eq.8.28

$$s_2 - s_1 = s_{T_2}^o - s_{T_1}^o - R \ln \frac{P_2}{P_1} = 0 \Rightarrow s_{T_2}^o = s_{T_1}^o + R \ln \frac{P_2}{P_1}$$

$$s_{T_2}^o = 8.13493 + 0.287 \ln(100/1500) = 7.35772$$

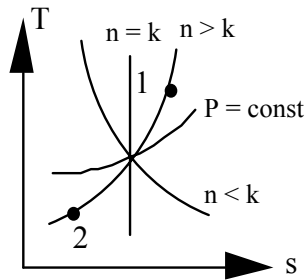
Interpolation gives  $T_2 = \mathbf{486 \text{ K}}$  and  $u_2 = 349.5 \text{ kJ/kg}$

$${}_1W_2 = m(u_1 - u_2) = 1(759.2 - 349.5) = \mathbf{409.7 \text{ kJ}}$$

## 8.108

An ideal gas having a constant specific heat undergoes a reversible polytropic expansion with exponent,  $n = 1.4$ . If the gas is carbon dioxide will the heat transfer for this process be positive, negative, or zero?

Solution:



CO<sub>2</sub>: Table A.5  $k = 1.289 < n$

Since  $n > k$  and  $P_2 < P_1$

it follows that  $s_2 < s_1$  and thus Q flows out.

$${}_1Q_2 < 0$$



## 8.109

A cylinder/piston contains 1 kg methane gas at 100 kPa, 20°C. The gas is compressed reversibly to a pressure of 800 kPa. Calculate the work required if the process is

- a. Adiabatic b. Isothermal  
 c. Polytropic, with exponent  $n = 1.15$

Solution:

C.V. Methane gas of constant mass  $m_2 = m_1 = m$  and reversible process.

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14: } m(s_2 - s_1) = \int dQ/T + {}_1S_2 \text{ gen} = \int dQ/T$$

a)

$$\text{Process: } {}_1Q_2 = 0 \Rightarrow s_2 = s_1$$

thus isentropic process  $s = \text{const}$  and ideal gas gives relation in Eq.8.32

$$T_2 = T_1 (P_2/P_1)^{\frac{k-1}{k}} = 293.2 \left( \frac{800}{100} \right)^{0.230} = 473.0 \text{ K}$$

$${}_1W_2 = -mC_{V0}(T_2 - T_1) = -1 \times 1.7354 (473.0 - 293.2) = \mathbf{-312.0 \text{ kJ}}$$

b)

Process:  $T = \text{constant}$ . For ideal gas then  $u_2 = u_1$  and  $s_{T2}^\circ = s_{T1}^\circ$

$$\text{Energy eq. gives } {}_1W_2 = {}_1Q_2 \text{ and } \int dQ/T = {}_1Q_2/T$$

with the entropy change found from Eq.8.28

$$\begin{aligned} \Rightarrow {}_1W_2 &= {}_1Q_2 = mT(s_2 - s_1) = -mRT \ln(P_2/P_1) \\ &= -0.51835 \times 293.2 \ln(800/100) = \mathbf{-316.0 \text{ kJ}} \end{aligned}$$

c)

Process:  $Pv^n = \text{constant}$  with  $n = 1.15$ ;

The T-P relation is given in Eq.8.37

$$T_2 = T_1 (P_2/P_1)^{\frac{n-1}{n}} = 293.2 \left( \frac{800}{100} \right)^{0.130} = 384.2 \text{ K}$$

and the work term is given by Eq.8.38

$$\begin{aligned} {}_1W_2 &= \int mP dv = m(P_2v_2 - P_1v_1)/(1 - n) = mR (T_2 - T_1)/(1 - n) \\ &= 1 \times \frac{0.51835(384.2 - 293.2)}{1 - 1.15} = \mathbf{-314.5 \text{ kJ}} \end{aligned}$$

**8.110**

Helium in a piston/cylinder at 20°C, 100 kPa is brought to 400 K in a reversible polytropic process with exponent  $n = 1.25$ . You may assume helium is an ideal gas with constant specific heat. Find the final pressure and both the specific heat transfer and specific work.

Solution:

C.V. Helium

Continuity Eq.:  $m_2 = m_1 = m$  ;

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

Process:  $Pv^n = C$  &  $Pv = RT \Rightarrow T v^{n-1} = C$

Table A.5:  $C_v = 3.116 \text{ kJ/kg K}$ ,  $R = 2.0771 \text{ kJ/kg K}$

From the process equation and  $T_1 = 293.15$ ,  $T_2 = 400 \text{ K}$

$$T_1 v_1^{n-1} = T_2 v_2^{n-1} \Rightarrow v_2 / v_1 = (T_1 / T_2)^{1/n-1} = 0.2885$$

$$P_2 / P_1 = (v_1 / v_2)^n = 4.73 \Rightarrow P_2 = \mathbf{473 \text{ kPa}}$$

The work is from Eq.8.38 per unit mass

$$\begin{aligned} {}_1w_2 &= \int P dv = \int C v^{-n} dv = [ C / (1-n) ] \times ( v_2^{1-n} - v_1^{1-n} ) \\ &= \frac{1}{1-n} (P_2 v_2 - P_1 v_1) = \frac{R}{1-n} (T_2 - T_1) = \mathbf{-887.7 \text{ kJ/kg}} \end{aligned}$$

The heat transfer follows from the energy equation

$${}_1q_2 = u_2 - u_1 + {}_1w_2 = C_v (T_2 - T_1) + (-887.7) = \mathbf{-554.8 \text{ kJ/kg}}$$

## 8.111

The power stroke in an internal combustion engine can be approximated with a polytropic expansion. Consider air in a cylinder volume of 0.2 L at 7 MPa, 1800 K, shown in Fig. P8.111. It now expands in a reversible polytropic process with exponent,  $n = 1.5$ , through a volume ratio of 8:1. Show this process on  $P$ - $v$  and  $T$ - $s$  diagrams, and calculate the work and heat transfer for the process.

Solution:

C.V. Air of constant mass  $m_2 = m_1 = m$ .

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14: } m(s_2 - s_1) = \int dQ/T + {}_1S_2_{\text{gen}} = \int dQ/T$$

$$\text{Process: } PV^{1.50} = \text{constant}, \quad V_2/V_1 = 8$$

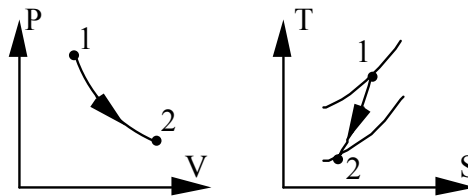
$$\text{State 1: } P_1 = 7 \text{ MPa}, T_1 = 1800 \text{ K}, V_1 = 0.2 \text{ L}$$

$$m_1 = \frac{P_1 V_1}{RT_1} = \frac{7000 \times 0.2 \times 10^{-3}}{0.287 \times 1800} = 2.71 \times 10^{-3} \text{ kg}$$

$$\text{State 2: } (v = V_2/m, ?) \text{ Must be on process curve so Eq.8.37 gives}$$

$$T_2 = T_1 (V_1/V_2)^{n-1} = 1800 (1/8)^{0.5} = 636.4 \text{ K}$$

$$\text{Table A.7: } u_1 = 1486.331 \text{ kJ/kg and interpolate } u_2 = 463.05 \text{ kJ/kg}$$



Notice:  
 $n = 1.5, k = 1.4$

$$n > k$$

Work from the process expressed in Eq.8.38

$$\begin{aligned} {}_1W_2 &= \int PdV = mR(T_2 - T_1)/(1 - n) \\ &= \frac{2.71 \times 10^{-3} \times 0.287(636.4 - 1800)}{1 - 1.5} = \mathbf{1.81 \text{ kJ}} \end{aligned}$$

Heat transfer from the energy equation

$$\begin{aligned} {}_1Q_2 &= m(u_2 - u_1) + {}_1W_2 \\ &= 2.71 \times 10^{-3} \times (463.05 - 1486.331) + 1.81 = \mathbf{-0.963 \text{ kJ}} \end{aligned}$$

## 8.112

A piston/cylinder contains air at 300 K, 100 kPa. It is now compressed in a reversible adiabatic process to a volume 7 times as small. Use constant heat capacity and find the final pressure and temperature, the specific work and specific heat transfer for the process.

Solution:

$$\text{Expansion ratio: } v_2/v_1 = 1/7$$

Process eq.: Rev. adiabatic and ideal gas gives  $Pv^n = C$ , with  $n = k$

$$P_2/P_1 = (v_2/v_1)^{-k} = 7^{1.4} = 15.245$$

$$P_2 = P_1 (7^{1.4}) = 100 \times 15.245 = \mathbf{1524.5 \text{ kPa}}$$

$$T_2 = T_1 (v_1/v_2)^{k-1} = 300 \times 7^{0.4} = \mathbf{653.4 \text{ K}}$$

$${}_1q_2 = \mathbf{0 \text{ kJ/kg}}$$

Polytropic process work term from Eq.8.38

$${}_1w_2 = \frac{R}{1-k} (T_2 - T_1) = \frac{0.287}{-0.4} (653.4 - 300) = \mathbf{-253.6 \text{ kJ/kg}}$$

Notice:  $C_v = R/(k-1)$  so the work term is also the change in  $u$  consistent with the energy equation.

## 8.113

A cylinder/piston contains carbon dioxide at 1 MPa, 300°C with a volume of 200 L. The total external force acting on the piston is proportional to  $V^3$ . This system is allowed to cool to room temperature, 20°C. What is the total entropy generation for the process?

Solution:

C.V. Carbon dioxide gas of constant mass  $m_2 = m_1 = m$  out to ambient.

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14,18: } m(s_2 - s_1) = \int dQ/T + {}_1S_2 \text{ gen} = {}_1Q_2/T_{\text{amb}} + {}_1S_2 \text{ gen}$$

Process:  $P = CV^3$  or  $PV^{-3} = \text{constant}$ , which is polytropic with  $n = -3$

$$\text{State 1: (T, P)} \Rightarrow m = P_1 V_1 / RT_1 = \frac{1000 \times 0.2}{0.18892 \times 573.2} = 1.847 \text{ kg}$$

State 2: (T, ?) state must be on process curve. This and ideal gas leads to Eq.8.37

$$\Rightarrow P_2 = P_1 (T_2/T_1)^{\frac{n}{n-1}} = 1000 (293.2/573.2)^{3/4} = 604.8 \text{ kPa}$$

$$V_2 = V_1 (T_1/T_2)^{\frac{1}{n-1}} = 0.16914 \text{ m}^3$$

$${}_1W_2 = \int PdV = (P_2 V_2 - P_1 V_1) / (1-n)$$

$$= [604.8 \times 0.16914 - 1000 \times 0.2] / [1 - (-3)] = -24.4 \text{ kJ}$$

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

$$= 1.847 \times 0.653 (20 - 300) - 24.4 = -362.1 \text{ kJ}$$

From Eq.8.25

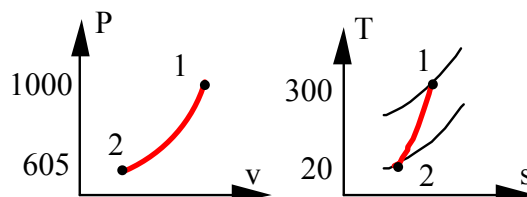
$$m(s_2 - s_1) = 1.847 \left[ 0.842 \ln \frac{293.2}{573.2} - 0.18892 \ln \frac{604.8}{1000} \right]$$

$$= 1.847 [-0.4694] = -0.87 \text{ kJ/K}$$

$$\Delta S_{\text{SURR}} = -{}_1Q_2/T_{\text{amb}} = +362.1 / 293.2 = +1.235 \text{ kJ/K}$$

From Eq.8.18

$$\begin{aligned} {}_1S_2 \text{ gen} &= m(s_2 - s_1) - {}_1Q_2/T_{\text{amb}} = \Delta S_{\text{NET}} = \Delta S_{\text{CO}_2} + \Delta S_{\text{SURR}} \\ &= -0.87 + 1.235 = +0.365 \text{ kJ/K} \end{aligned}$$



Notice:  
 $n = -3$ ,  $k = 1.3$

$n < k$

## 8.114

A device brings 2 kg of ammonia from 150 kPa,  $-20^\circ\text{C}$  to 400 kPa,  $80^\circ\text{C}$  in a polytropic process. Find the polytropic exponent,  $n$ , the work and the heat transfer. Find the total entropy generated assuming a source at  $100^\circ\text{C}$ .

Solution:

C.V. Ammonia of constant mass  $m_2 = m_1 = m$  out to source.

$$\text{Energy Eq. 5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq. 8.14, 8.18: } m(s_2 - s_1) = \int dQ/T + {}_1S_{2\text{ gen}} = {}_1Q_2/T + {}_1S_{2\text{ gen}}$$

$$\text{Process: } P_1 v_1^n = P_2 v_2^n \quad \text{Eq. (8.36)}$$

State 1: Table B.2.2

$$v_1 = 0.79774 \text{ m}^3/\text{kg}, \quad s_1 = 5.7465 \text{ kJ/kg K}, \quad u_1 = 1303.3 \text{ kJ/kg}$$

State 2: Table B.2.2

$$v_2 = 0.4216 \text{ m}^3/\text{kg}, \quad s_2 = 5.9907 \text{ kJ/kg K}, \quad u_2 = 1468.0 \text{ kJ/kg}$$

$$\ln(P_2/P_1) = \ln(v_2/v_1)^n = n \times \ln(v_2/v_1)$$

$$\ln\left(\frac{480}{150}\right) = n \times \ln\left(\frac{0.4216}{0.79774}\right) = 0.98083 = n \times 0.63773$$

$$\Rightarrow \quad n = \mathbf{1.538}$$

The work term is integration of  $PdV$  as done in text leading to Eq. 8.38

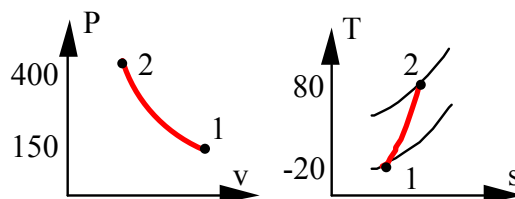
$$\begin{aligned} {}_1W_2 &= \frac{m}{1-n} (P_2 v_2 - P_1 v_1) \\ &= \frac{2}{1-1.538} \times (400 \times 0.4216 - 150 \times 0.79774) = \mathbf{-182.08 \text{ kJ}} \end{aligned}$$

Notice we did not use  $Pv = RT$  as we used the ammonia tables.

$$\begin{aligned} {}_1Q_2 &= m(u_2 - u_1) + {}_1W_2 = 2(1468 - 1303.3) - 182.08 \\ &= \mathbf{147.3 \text{ kJ}} \end{aligned}$$

From Eq. 8.18

$$\begin{aligned} {}_1S_{2\text{ gen}} &= m(s_2 - s_1) - {}_1Q_2/T = 2(5.9907 - 5.7465) - \frac{147.3}{373.15} \\ &= \mathbf{0.0936 \text{ kJ/K}} \end{aligned}$$



Notice:  
 $n = 1.54$ ,  $k = 1.3$   
 $n > k$

## 8.115

A cylinder/piston contains 100 L of air at 110 kPa, 25°C. The air is compressed in a reversible polytropic process to a final state of 800 kPa, 200°C. Assume the heat transfer is with the ambient at 25°C and determine the polytropic exponent  $n$  and the final volume of the air. Find the work done by the air, the heat transfer and the total entropy generation for the process.

Solution:

C.V. Air of constant mass  $m_2 = m_1 = m$  out to ambient.

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14,18: } m(s_2 - s_1) = \int dQ/T + {}_1S_{2, \text{gen}} = {}_1Q_2/T_0 + {}_1S_{2, \text{gen}}$$

$$\text{Process: } P_1 V_1^n = P_2 V_2^n \quad \text{Eq.8.36}$$

$$\text{State 1: } (T_1, P_1) \quad \text{State 2: } (T_2, P_2)$$

Thus the unknown is the exponent  $n$ .

$$m = P_1 V_1 / (RT_1) = 110 \times 0.1 / (0.287 \times 298.15) = 0.1286 \text{ kg}$$

The relation from the process and ideal gas is in Eq.8.37

$$T_2/T_1 = (P_2/P_1)^{\frac{n-1}{n}} \Rightarrow \frac{473.15}{298.15} = \left(\frac{800}{110}\right)^{\frac{n-1}{n}} \Rightarrow \frac{n-1}{n} = 0.2328$$

$$n = \mathbf{1.3034}, \quad V_2 = V_1 (P_1/P_2)^{\frac{1}{n}} = 0.1 \left(\frac{110}{800}\right)^{0.7672} = \mathbf{0.02182 \text{ m}^3}$$

The work is from Eq.8.38

$${}_1W_2 = \int P dV = \frac{P_2 V_2 - P_1 V_1}{1 - n} = \frac{800 \times 0.02182 - 110 \times 0.1}{1 - 1.3034} = \mathbf{-21.28 \text{ kJ}}$$

Heat transfer from the energy equation

$$\begin{aligned} {}_1Q_2 &= mC_v(T_2 - T_1) + {}_1W_2 \\ &= 0.1286 \times 0.717 \times (200 - 25) - 21.28 = \mathbf{-5.144 \text{ kJ}} \end{aligned}$$

Entropy change from Eq.8.25

$$\begin{aligned} s_2 - s_1 &= C_{p0} \ln(T_2/T_1) - R \ln(P_2/P_1) \\ &= 1.004 \ln\left(\frac{473.15}{298.15}\right) - 0.287 \ln\left(\frac{800}{110}\right) = -0.106 \frac{\text{kJ}}{\text{kg K}} \end{aligned}$$

From the entropy equation (also Eq.8.18)

$$\begin{aligned} {}_1S_{2, \text{gen}} &= m(s_2 - s_1) - {}_1Q_2/T_0 \\ &= 0.1286 \times (-0.106) + (5.144/298.15) = \mathbf{0.00362 \text{ kJ/K}} \end{aligned}$$

## 8.116

A mass of 2 kg ethane gas at 500 kPa, 100°C, undergoes a reversible polytropic expansion with exponent,  $n = 1.3$ , to a final temperature of the ambient, 20°C. Calculate the total entropy generation for the process if the heat is exchanged with the ambient.

Solution:

C.V. Ethane gas of constant mass  $m_2 = m_1 = m$  out to ambient.

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14,18: } m(s_2 - s_1) = \int dQ/T + {}_1S_2 \text{ gen} = {}_1Q_2/T_{\text{amb}} + {}_1S_2 \text{ gen}$$

$$\text{Process: } Pv_1^n = P_2v_2^n \quad \text{Eq.8.36}$$

State 1:  $(T_1, P_1)$       State 2:  $(T_2, ?)$  on process curve

$$P_2 = P_1 (T_2/T_1)^{\frac{n}{n-1}} = 500 \left( \frac{293.2}{373.2} \right)^{4.333} = 175.8 \text{ kPa}$$

Work is integrated in Eq.8.38

$${}_1W_2 = \int_1^2 Pdv = \frac{P_2v_2 - P_1v_1}{1-n} = \frac{R(T_2 - T_1)}{1-n} = \frac{0.2765(293.2 - 373.2)}{1-1.30} = +73.7 \text{ kJ/kg}$$

Heat transfer is from the energy equation

$${}_1q_2 = C_{V0}(T_2 - T_1) + {}_1w_2 = 1.49(293.2 - 373.2) + 73.7 = -45.5 \text{ kJ/kg}$$

Entropy change from Eq.8.25

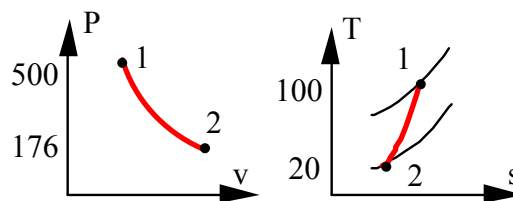
$$\begin{aligned} s_2 - s_1 &= C_{P0} \ln(T_2/T_1) - R \ln(P_2/P_1) \\ &= 1.766 \ln \frac{293.2}{373.2} - 0.2765 \ln \frac{175.8}{500} = -0.1371 \text{ kJ/kg K} \end{aligned}$$

$$m(s_2 - s_1) = \Delta S_{\text{SYST}} = 2(-0.1371) = -0.2742 \text{ kJ/K}$$

$$\Delta S_{\text{SURR}} = -{}_1Q_2/T_0 = +2 \times 45.5/293.2 = +0.3104 \text{ kJ/K}$$

Generation from entropy equation or Eq.8.18

$$\begin{aligned} {}_1S_2 \text{ gen} &= m(s_2 - s_1) - {}_1Q_2/T_{\text{amb}} = \Delta S_{\text{NET}} = \Delta S_{\text{SYST}} + \Delta S_{\text{SURR}} \\ &= -0.2742 + 0.3104 = +0.0362 \text{ kJ/K} \end{aligned}$$



Notice:  
 $n = 1.3$ ,  $k = 1.186$

$n > k$



## 8.117

A piston/cylinder contains air at 300 K, 100 kPa. A reversible polytropic process with  $n = 1.3$  brings the air to 500 K. Any heat transfer if it comes in is from a 325°C reservoir and if it goes out it is to the ambient at 300 K. Sketch the process in a P-v and a T-s diagram. Find the specific work and specific heat transfer in the process. Find the specific entropy generation (external to the air) in the process.

Solution:

$$\text{Process : } Pv^n = C$$

$$\begin{aligned} {}_1w_2 &= \int P \, dv = \left( \frac{P_2 v_2 - P_1 v_1}{1-n} \right) = \frac{R}{1-n} (T_2 - T_1) \\ &= \frac{0.287}{1-1.3} (500 - 300) = \mathbf{-191.3 \text{ kJ/kg}} \end{aligned}$$

Energy equation

$$\begin{aligned} {}_1q_2 &= u_2 - u_1 + {}_1w_2 = C_v (T_2 - T_1) + {}_1w_2 \\ &= 0.717 (500 - 300) - 191.3 = \mathbf{-47.93 \text{ kJ/kg}} \end{aligned}$$

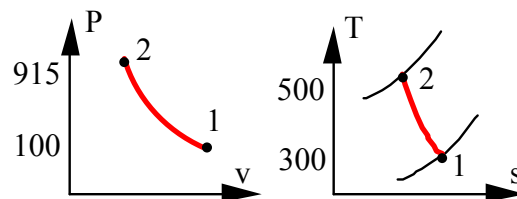
The  ${}_1q_2$  is negative and thus goes out. Entropy is generated between the air and ambient.

$$s_2 - s_1 = {}_1q_2/T_{\text{amb}} + {}_1s_2 \text{ gen}$$

$${}_1s_2 \text{ gen} = s_2 - s_1 - {}_1q_2/T_{\text{amb}} = C_p \ln (T_2/T_1) - R \ln (P_2/P_1) - {}_1q_2/T_{\text{amb}}$$

$$P_2/P_1 = (T_2/T_1)^{n/(n-1)} = (500/300)^{1.3/0.3} = 9.148$$

$$\begin{aligned} {}_1s_2 \text{ gen} &= 1.004 \ln \left( \frac{500}{300} \right) - 0.287 \ln 9.148 - \left( \frac{-47.93}{300} \right) \\ &= 0.51287 - 0.635285 + 0.15977 \\ &= \mathbf{0.03736 \text{ kJ/kg K}} \end{aligned}$$



Notice:

$$n = 1.3, \quad k = 1.4$$

$$n < k$$

**8.118**

A cylinder/piston contains saturated vapor R-22 at 10°C; the volume is 10 L. The R-22 is compressed to 2 MPa, 60°C in a reversible (internally) polytropic process. If all the heat transfer during the process is with the ambient at 10°C, calculate the net entropy change.

Solution:

C.V. R-22 of constant mass  $m_2 = m_1 = m$  out to ambient.

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14,18: } m(s_2 - s_1) = \int dQ/T + {}_1S_2 \text{ gen} = {}_1Q_2/T_{\text{amb}} + {}_1S_2 \text{ gen}$$

$$\text{Process: } P_1 v_1^n = P_2 v_2^n \quad \text{Eq.8.36}$$

$$\text{State 1: } (T_1, x_1) \text{ Table B.4.1 } \quad P_1 = 0.681 \text{ MPa, } v_1 = 0.03471$$

$$m = V_1/v_1 = 0.01/0.03471 = 0.288 \text{ kg}$$

$$\text{State 2: } (T_2, P_2) \text{ Table B.4.2 } \quad v_2 = 0.01214 \text{ m}^3/\text{kg}$$

$$\text{From process eq. } P_2/P_1 = \frac{2.0}{0.681} = \left(\frac{0.03471}{0.01214}\right)^n \Rightarrow n = 1.0255$$

The work is from Eq.8.38

$$\begin{aligned} {}_1W_2 &= \int P dV = m \frac{P_2 v_2 - P_1 v_1}{1-n} = 0.288 \frac{2000 \times 0.01214 - 681 \times 0.03471}{1 - 1.0255} \\ &= -7.26 \text{ kJ} \end{aligned}$$

Heat transfer from energy equation

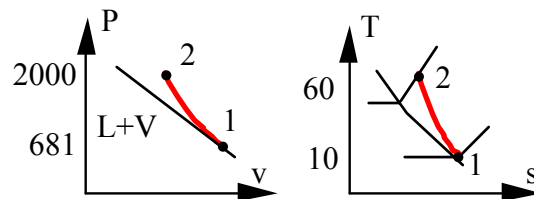
$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.288(247.3 - 229.8) - 7.26 = -2.22 \text{ kJ}$$

$$\Delta S_{\text{SYST}} = m(s_2 - s_1) = 0.288(0.8873 - 0.9129) = -0.00737 \text{ kJ/K}$$

$$\Delta S_{\text{SURR}} = -{}_1Q_2/T_0 = +2.22/283.2 = +0.00784 \text{ kJ/K}$$

Generation is from entropy equation or Eq.8.18

$$\begin{aligned} {}_1S_2 \text{ gen} &= m(s_2 - s_1) - {}_1Q_2/T_{\text{amb}} = \Delta S_{\text{NET}} = \Delta S_{\text{SYST}} + \Delta S_{\text{SURR}} \\ &= -0.00737 + 0.00784 = +\mathbf{0.00047 \text{ kJ/K}} \end{aligned}$$



Notice:

$$n = 1.03, \quad k = 1.17$$

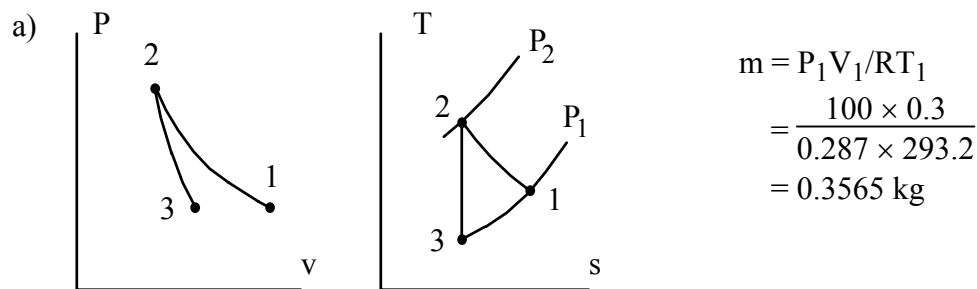
$$n < k$$

## 8.119

A cylinder/piston contains air at ambient conditions, 100 kPa and 20°C with a volume of 0.3 m<sup>3</sup>. The air is compressed to 800 kPa in a reversible polytropic process with exponent,  $n = 1.2$ , after which it is expanded back to 100 kPa in a reversible adiabatic process.

- Show the two processes in  $P-v$  and  $T-s$  diagrams.
- Determine the final temperature and the net work.

Solution:



- b) The process equation is expressed in Eq.8.37

$$T_2 = T_1 (P_2/P_1)^{\frac{n-1}{n}} = 293.2 \left( \frac{800}{100} \right)^{0.167} = 414.9 \text{ K}$$

The work is from Eq.8.38

$${}_1w_2 = \int_1^2 P dv = \frac{P_2 v_2 - P_1 v_1}{1-n} = \frac{R(T_2 - T_1)}{1-n} = \frac{0.287(414.9 - 293.2)}{1-1.20} = -174.6 \text{ kJ/kg}$$

Isentropic relation is from Eq.8.32

$$T_3 = T_2 (P_3/P_2)^{\frac{k-1}{k}} = 414.9 \left( \frac{100}{800} \right)^{0.286} = \mathbf{228.9 \text{ K}}$$

With zero heat transfer the energy equation gives the work

$${}_2w_3 = C_{V0}(T_2 - T_3) = 0.717(414.9 - 228.9) = +133.3 \text{ kJ/kg}$$

$$w_{\text{NET}} = 0.3565(-174.6 + 133.3) = \mathbf{-14.7 \text{ kJ}}$$

## Rates or fluxes of entropy

## 8.120

A reversible heat pump uses 1 kW of power input to heat a 25°C room, drawing energy from the outside at 15°C. Assuming every process is reversible, what are the total rates of entropy into the heat pump from the outside and from the heat pump to the room?

Solution:

C.V.TOT.

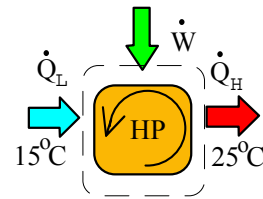
$$\text{Energy Eq.: } \dot{Q}_L + \dot{W} = \dot{Q}_H$$

$$\text{Entropy Eq.: } \frac{\dot{Q}_L}{T_L} - \frac{\dot{Q}_H}{T_H} = 0 \Rightarrow \dot{Q}_L = \dot{Q}_H \frac{T_L}{T_H}$$

$$\dot{Q}_H \frac{T_L}{T_H} + \dot{W} = \dot{Q}_H \Rightarrow \dot{Q}_H = \frac{T_H}{T_H - T_L} \dot{W}$$

$$\frac{\dot{Q}_H}{T_H} = \frac{1}{T_H - T_L} \dot{W} = \frac{1}{25 - 15} (1) = \mathbf{0.1 \text{ kW/K}}$$

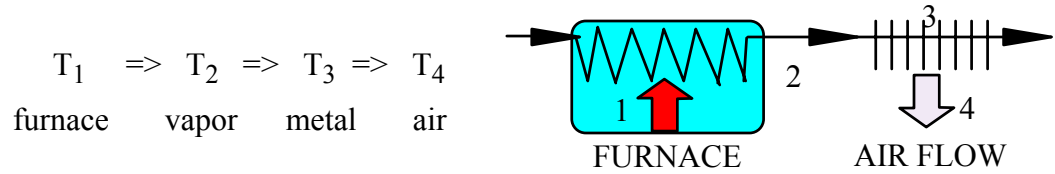
$$\frac{\dot{Q}_L}{T_L} = \frac{\dot{Q}_H}{T_H} = \mathbf{0.1 \text{ kW/K}}$$



8.121

An amount of power, say 1000 kW, comes from a furnace at 800°C going into water vapor at 400°C. From the water the power goes to a solid metal at 200°C and then into some air at 70°C. For each location calculate the flux of s through a surface as ( $\dot{Q}/T$ ). What makes the flux larger and larger?

Solution:



$T_1 \Rightarrow T_2 \Rightarrow T_3 \Rightarrow T_4$   
 furnace    vapor    metal    air

Flux of s:  $F_s = \dot{Q}/T$  with T as absolute temperature.

$$F_{s1} = 1000/1073.15 = 0.932 \text{ kW/K}, \quad F_{s2} = 1000/673.15 = 1.486 \text{ kW/K}$$

$$F_{s3} = 1000/473.15 = 2.11 \text{ kW/K}, \quad F_{s4} = 1000/343.15 = 2.91 \text{ kW/K}$$

T	800	400	200	70	(°C)
T <sub>amb</sub>	1073	673	476	646	K
Q/T	0.932	1.486	2.114	2.915	kW/K

${}_1S_2$  gen for every change in T

Q over  $\Delta T$  is an irreversible process

## 8.122

Room air at 23°C is heated by a 2000 W space heater with a surface filament temperature of 700 K, shown in Fig. P8.122. The room at steady state loses the power to the outside which is at 7°C. Find the rate(s) of entropy generation and specify where it is made.

Solution:

For any C.V at steady state.

The entropy equation as a rate form is Eq.8.43

$$\frac{dS_{c.v.}}{dt} = 0 = \int d\dot{Q}/T + \dot{S}_{gen}$$

C.V. Heater Element

$$\dot{S}_{gen} = -\int d\dot{Q}/T = -(-2000/700) = \mathbf{2.857 \text{ W/K}}$$

C.V. Space between heater 700 K and room 23°C

$$\dot{S}_{gen} = -\int d\dot{Q}/T = (-2000 / 700) - [-2000 / (23+273)] = \mathbf{3.9 \text{ W/K}}$$

C.V. Wall between 23°C inside and 7°C outside

$$\dot{S}_{gen} = -\int d\dot{Q}/T = [-2000 / (23+273)] - [2000 / (7 + 273)] = \mathbf{0.389 \text{ W/K}}$$

Notice biggest  $\dot{S}_{gen}$  is for the largest change in 1/T.

## 8.123

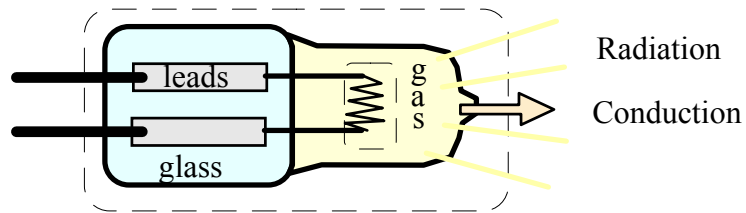
A small halogen light bulb receives an electrical power of 50 W. The small filament is at 1000 K and gives out 20% of the power as light and the rest as heat transfer to the gas, which is at 500 K; the glass is at 400 K. All the power is absorbed by the room walls at 25°C. Find the rate of generation of entropy in the filament, in the total bulb including glass and the total room including bulb.

Solution:

$$\dot{W}_{el} = 50 \text{ W}$$

$$\dot{Q}_{RAD} = 10 \text{ W}$$

$$\dot{Q}_{COND} = 40 \text{ W}$$



We will assume steady state and no storage in the bulb, air or room walls.

C.V. Filament steady-state

$$\text{Energy Eq.5.31: } dE_{c.v.}/dt = 0 = \dot{W}_{el} - \dot{Q}_{RAD} - \dot{Q}_{COND}$$

$$\text{Entropy Eq.8.43: } dS_{c.v.}/dt = 0 = -\frac{\dot{Q}_{RAD}}{T_{FILA}} - \frac{\dot{Q}_{COND}}{T_{FILA}} + \dot{S}_{gen}$$

$$\dot{S}_{gen} = (\dot{Q}_{RAD} + \dot{Q}_{COND})/T_{FILA} = \dot{W}_{el}/T_{FILA} = \frac{50}{1000} = \mathbf{0.05 \text{ W/K}}$$

C.V. Bulb including glass

$$\dot{Q}_{RAD} \text{ leaves at } 1000 \text{ K} \qquad \dot{Q}_{COND} \text{ leaves at } 400 \text{ K}$$

$$\dot{S}_{gen} = \int d\dot{Q}/T = -(-10/1000) - (-40/400) = \mathbf{0.11 \text{ W/K}}$$

C.V. Total room. All energy leaves at 25°C

$$\text{Eq.5.31: } dE_{c.v.}/dt = 0 = \dot{W}_{el} - \dot{Q}_{RAD} - \dot{Q}_{COND}$$

$$\text{Eq.8.43: } dS_{c.v.}/dt = 0 = -\frac{\dot{Q}_{TOT}}{T_{WALL}} + \dot{S}_{gen}$$

$$\dot{S}_{gen} = \frac{\dot{Q}_{TOT}}{T_{WALL}} = 50/(25+273) = \mathbf{0.168 \text{ W/K}}$$

## 8.124

A farmer runs a heat pump using 2 kW of power input. It keeps a chicken hatchery at a constant 30°C while the room loses 10 kW to the colder outside ambient at 10°C. What is the rate of entropy generated in the heat pump? What is the rate of entropy generated in the heat loss process?

Solution:

C.V. Hatchery, steady state.

To have steady state at 30°C for the hatchery

$$\text{Energy Eq.: } 0 = \dot{Q}_H - \dot{Q}_{\text{Loss}} \Rightarrow \dot{Q}_H = \dot{Q}_{\text{Loss}} = 10 \text{ kW}$$

C.V. Heat pump, steady state

$$\text{Energy eq.: } 0 = \dot{Q}_L + \dot{W} - \dot{Q}_H \Rightarrow \dot{Q}_L = \dot{Q}_H - \dot{W} = 8 \text{ kW}$$

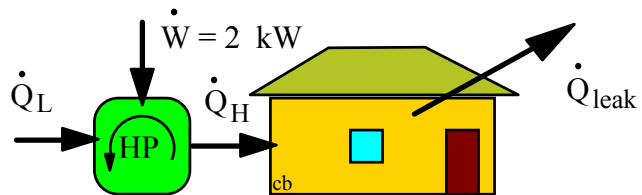
$$\text{Entropy Eq.: } 0 = \frac{\dot{Q}_L}{T_L} - \frac{\dot{Q}_H}{T_H} + \dot{S}_{\text{gen HP}}$$

$$\dot{S}_{\text{gen HP}} = \frac{\dot{Q}_H}{T_H} - \frac{\dot{Q}_L}{T_L} = \frac{10}{273 + 30} - \frac{8}{273 + 10} = \mathbf{0.00473 \text{ kW/K}}$$

C.V. From hatchery at 30°C to the ambient 10°C. This is typically the walls and the outer thin boundary layer of air. Through this goes  $\dot{Q}_{\text{Loss}}$ .

$$\text{Entropy Eq.: } 0 = \frac{\dot{Q}_{\text{Loss}}}{T_H} - \frac{\dot{Q}_{\text{Loss}}}{T_{\text{amb}}} + \dot{S}_{\text{gen walls}}$$

$$\dot{S}_{\text{gen walls}} = \frac{\dot{Q}_{\text{Loss}}}{T_{\text{amb}}} - \frac{\dot{Q}_{\text{Loss}}}{T_H} = \frac{10}{283} - \frac{10}{303} = \mathbf{0.00233 \text{ kW/K}}$$





## 8.125

The automatic transmission in a car receives 25 kW shaft work and gives out 24 kW to the drive shaft. The balance is dissipated in the hydraulic fluid and metal casing, all at 45°C, which in turn transmits it to the outer atmosphere at 20°C. What is the rate of entropy generation inside the transmission unit? What is it outside the unit?

Solution:

C.V. Total unit. Steady state and surface at 45°C

Energy Eq:

$$0 = \dot{W}_{\text{in}} - \dot{W}_{\text{out}} - \dot{Q}_{\text{out}}$$

$$\text{Entropy Eq.: } 0 = -\frac{\dot{Q}_{\text{out}}}{T_{\text{oil}}} + \dot{S}_{\text{gen}}$$

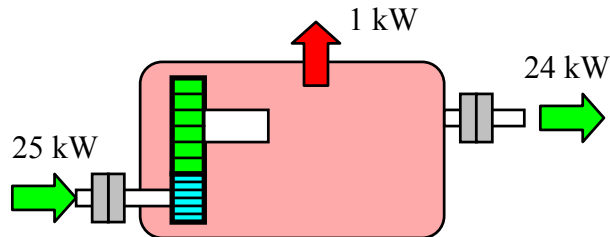
$$\text{From energy Eq.: } \dot{Q}_{\text{out}} = \dot{W}_{\text{in}} - \dot{W}_{\text{out}} = 25 - 24 = 1 \text{ kW}$$

$$\text{From entropy Eq.: } \dot{S}_{\text{gen}} = \frac{\dot{Q}_{\text{out}}}{T_{\text{oil}}} = \frac{1}{273.15 + 45} \frac{\text{kW}}{\text{K}} = \mathbf{3.1 \text{ W/K}}$$

C.V. From surface at 45°C to atm. at 20°C.

$$\text{Entropy Eq.: } 0 = \frac{\dot{Q}_{\text{out}}}{T_{\text{oil}}} - \frac{\dot{Q}_{\text{out}}}{T_{\text{amb}}} + \dot{S}_{\text{gen outside}}$$

$$\dot{S}_{\text{gen outside}} = \dot{Q}_{\text{out}} \left[ \frac{1}{T_{\text{amb}}} - \frac{1}{T_{\text{oil}}} \right] = 1 \text{ kW} \left[ \frac{1}{293} - \frac{1}{318} \right] = \mathbf{0.268 \text{ W/K}}$$



## Review problems

## 8.126

An insulated cylinder/piston has an initial volume of  $0.15 \text{ m}^3$  and contains steam at  $400 \text{ kPa}$ ,  $200^\circ\text{C}$ . The steam is expanded adiabatically, and the work output is measured very carefully to be  $30 \text{ kJ}$ . It is claimed that the final state of the water is in the two-phase (liquid and vapor) region. What is your evaluation of the claim?

Solution:

C.V. Water.

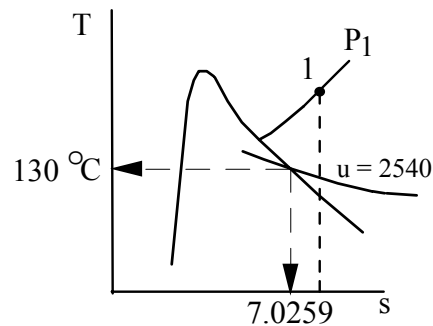
$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.3: } m(s_2 - s_1) = \int dQ/T$$

Process:  ${}_1Q_2 = 0$  and reversible

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

$$v_1 = 0.5342, \quad u_1 = 2646.8, \quad s_1 = 7.1706 \text{ kJ/kg K}$$



$$m = \frac{V_1}{v_1} = \frac{0.15}{0.5342} = 0.2808 \text{ kg}$$

With the assumed reversible process we have from entropy equation

$$s_2 = s_1 = 7.1706 \text{ kJ/kg K}$$

and from the energy equation

$$u_2 = u_1 - {}_1W_2/m = 2646.8 - \frac{30}{0.2808} = 2540.0 \text{ kJ/kg}$$

State 2 given by (u, s) check Table B.1.1:  $s_G$  (at  $u_G = 2540$ ) =  $7.0259 < s_1$

⇒ **State 2 must be in superheated vapor region.**

8.127

A closed tank,  $V = 10 \text{ L}$ , containing  $5 \text{ kg}$  of water initially at  $25^\circ\text{C}$ , is heated to  $175^\circ\text{C}$  by a heat pump that is receiving heat from the surroundings at  $25^\circ\text{C}$ . Assume that this process is reversible. Find the heat transfer to the water and the work input to the heat pump.

C.V.: Water from state 1 to state 2.

Process: constant volume (reversible isometric)

$$1: v_1 = V/m = 0.002 \Rightarrow x_1 = (0.002 - 0.001003)/43.358 = 0.000023$$

$$u_1 = 104.86 + 0.000023 \times 2304.9 = 104.93 \text{ kJ/kg}$$

$$s_1 = 0.3673 + 0.000023 \times 8.1905 = 0.36759 \text{ kJ/kg K}$$

Continuity eq. (same mass) and  $V = C$  fixes  $v_2$

$$2: T_2, v_2 = v_1 \Rightarrow$$

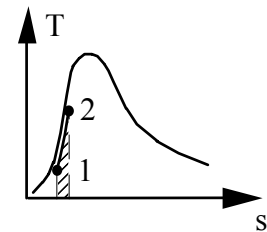
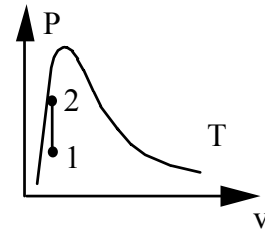
$$x_2 = (0.002 - 0.001121)/0.21568 = 0.004075$$

$$u_2 = 740.16 + 0.004075 \times 1840.03 = 747.67 \text{ kJ/kg}$$

$$s_2 = 2.0909 + 0.004075 \times 4.5347 = 2.1094 \text{ kJ/kg K}$$

Energy eq. has  $W = 0$ , thus provides heat transfer as

$${}_1Q_2 = m(u_2 - u_1) = \mathbf{3213.7 \text{ kJ}}$$

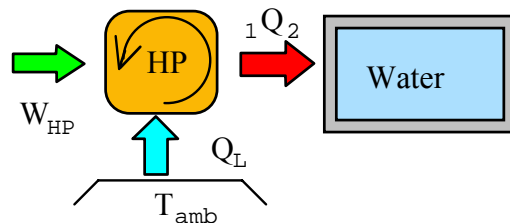


Entropy equation for the total (tank plus heat pump) control volume gives for a reversible process:

$$m(s_2 - s_1) = Q_L/T_0 \quad \Rightarrow \quad Q_L = mT_0(s_2 - s_1) = 2596.6 \text{ kJ}$$

and then the energy equation for the heat pump gives

$$W_{HP} = {}_1Q_2 - Q_L = \mathbf{617.1 \text{ kJ}}$$



## 8.128

Two tanks contain steam, and they are both connected to a piston/cylinder as shown in Fig. P8.128. Initially the piston is at the bottom and the mass of the piston is such that a pressure of 1.4 MPa below it will be able to lift it. Steam in A is 4 kg at 7 MPa, 700°C and B has 2 kg at 3 MPa, 350°C. The two valves are opened, and the water comes to a uniform state. Find the final temperature and the total entropy generation, assuming no heat transfer.

Solution:

Control mass: All water  $m_A + m_B$ .

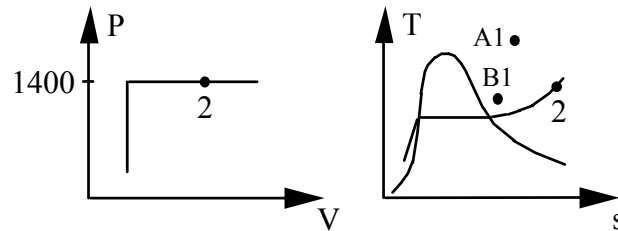
Continuity Eq.:  $m_2 = m_A + m_B = 6 \text{ kg}$

Energy Eq.5.11:  $m_2 u_2 - m_A u_{A1} - m_B u_{B1} = {}_1Q_2 - {}_1W_2 = - {}_1W_2$

Entropy Eq.8.14:  $m_2 s_2 - m_A s_{A1} - m_B s_{B1} = {}_1S_2 \text{ gen}$

B.1.3:  $v_{A1} = 0.06283$ ,  $u_{A1} = 3448.5$ ,  $s_{A1} = 7.3476$ ,  $V_A = 0.2513 \text{ m}^3$

B.1.3:  $v_{B1} = 0.09053$ ,  $u_{B1} = 2843.7$ ,  $s_{B1} = 6.7428$ ,  $V_B = 0.1811 \text{ m}^3$



The only possible  $P$ ,  $V$  combinations for state 2 are on the two lines.

Assume  $V_2 > V_A + V_B \Rightarrow P_2 = P_{\text{lift}}$ ,  ${}_1W_2 = P_2(V_2 - V_A - V_B)$

Substitute into energy equation:

$$\begin{aligned} m_2 h_2 &= m_A u_{A1} + m_B u_{B1} + P_2(V_A + V_B) \\ &= 4 \times 3448.5 + 2 \times 2843.7 + 1400 \times 0.4324 \end{aligned}$$

State 2:  $h_2 = 3347.8 \text{ kJ/kg}$ ,  $P_2 = 1400 \text{ kPa}$ ,  $v_2 = 0.2323$ ,  $s_2 = 7.433$

$$T_2 = 441.9 \text{ }^\circ\text{C},$$

Check assumption:  $V_2 = m_2 v_2 = 1.394 \text{ m}^3 > V_A + V_B$  **OK.**

$${}_1S_2 \text{ gen} = 6 \times 7.433 - 4 \times 7.3476 - 2 \times 6.7428 = 1.722 \text{ kJ/K}$$

8.129

A piston/cylinder with constant loading of piston contains 1 L water at 400 kPa, quality 15%. It has some stops mounted so the maximum possible volume is 11 L. A reversible heat pump extracting heat from the ambient at 300 K, 100 kPa heats the water to 300°C. Find the total work and heat transfer for the water and the work input to the heat pump.

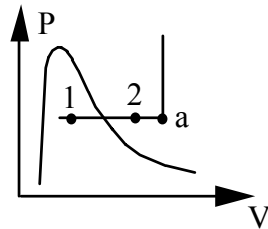
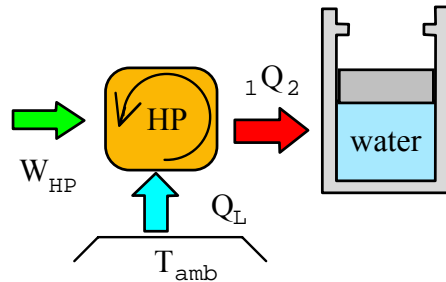
Solution: Take CV around the water and check possible P-V combinations.

State 1:  $v_1 = 0.001084 + 0.15 \times 0.46138 = 0.07029 \text{ m}^3/\text{kg}$

$u_1 = 604.29 + 0.15 \times 1949.26 = 896.68 \text{ kJ/kg}$

$s_1 = 1.7766 + 0.15 \times 5.1193 = 2.5445 \text{ kJ/kg K}$

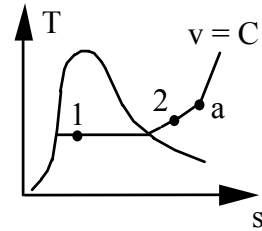
$m_1 = V_1/v_1 = 0.001/0.07029 = 0.0142 \text{ kg}$



State a:  $v = 11 v_1 = 0.77319 \text{ m}^3/\text{kg}$ ,

400 kPa

$\Rightarrow$  Sup. vapor  $T_a = 400^\circ\text{C} > T_2$



State 2: Since  $T_2 < T_a$  then piston is not at stops but floating so  $P_2 = 400 \text{ kPa}$ .

$(T, P) \Rightarrow v_2 = 0.65484 \text{ m}^3/\text{kg} \Rightarrow V_2 = (v_2/v_1) \times V_1 = 9.316 \text{ L}$

${}_1W_2 = \int P \, dV = P(V_2 - V_1) = 400 (9.316 - 1) \times 0.001 = \mathbf{3.33 \text{ kJ}}$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.0142 (2804.8 - 896.68) + 3.33 = \mathbf{30.43 \text{ kJ}}$

Take CV as water plus the heat pump out to the ambient.

$m(s_2 - s_1) = Q_L/T_o \Rightarrow$

$Q_L = mT_o (s_2 - s_1) = 300 \times 0.0142 (7.5661 - 2.5445) = 21.39 \text{ kJ}$

$W_{HP} = {}_1Q_2 - Q_L = \mathbf{9.04 \text{ kJ}}$

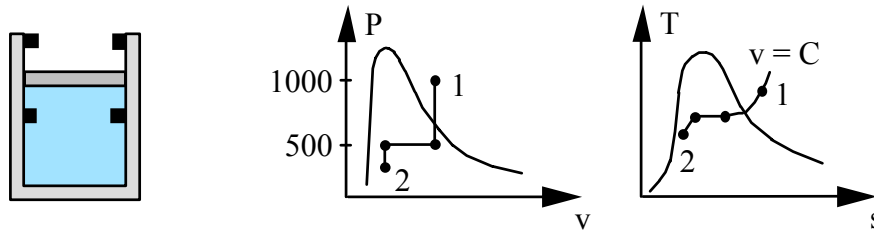
## 8.130

Water in a piston/cylinder is at 1 MPa, 500°C. There are two stops, a lower one at which  $V_{\min} = 1 \text{ m}^3$  and an upper one at  $V_{\max} = 3 \text{ m}^3$ . The piston is loaded with a mass and outside atmosphere such that it floats when the pressure is 500 kPa. This setup is now cooled to 100°C by rejecting heat to the surroundings at 20°C. Find the total entropy generated in the process.

C.V. Water.

Initial state: Table B.1.3:  $v_1 = 0.35411 \text{ m}^3/\text{kg}$ ,  $u_1 = 3124.3$ ,  $s_1 = 7.7621$

$$m = V/v_1 = 3/0.35411 = 8.472 \text{ kg}$$



Final state: 100°C and on line in P-V diagram.

Notice the following:  $v_g(500 \text{ kPa}) = 0.3749 > v_1$ ,  $v_1 = v_g(154^\circ\text{C})$

$T_{\text{sat}}(500 \text{ kPa}) = 152^\circ\text{C} > T_2$ , so now piston hits bottom stops.

State 2:  $v_2 = v_{\text{bot}} = V_{\text{bot}}/m = 0.118 \text{ m}^3/\text{kg}$ ,

$$x_2 = (0.118 - 0.001044)/1.67185 = 0.0699,$$

$$u_2 = 418.91 + 0.0699 \times 2087.58 = 564.98 \text{ kJ/kg},$$

$$s_2 = 1.3068 + 0.0699 \times 6.048 = 1.73 \text{ kJ/kg K}$$

Now we can do the work and then the heat transfer from the energy equation

$${}_1W_2 = \int P dV = 500(V_2 - V_1) = -1000 \text{ kJ} \quad ({}_1w_2 = -118 \text{ kJ/kg})$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = -22683.4 \text{ kJ} \quad ({}_1q_2 = -2677.5 \text{ kJ/kg})$$

Take C.V. total out to where we have 20°C:

$$m(s_2 - s_1) = {}_1Q_2/T_0 + S_{\text{gen}} \Rightarrow$$

$$S_{\text{gen}} = m(s_2 - s_1) - {}_1Q_2/T_0 = 8.472 (1.73 - 7.7621) + 22683 / 293.15$$

$$= \mathbf{26.27 \text{ kJ/K}} \quad (= \Delta S_{\text{water}} + \Delta S_{\text{sur}})$$

8.131

A cylinder fitted with a frictionless piston contains water. A constant hydraulic pressure on the back face of the piston maintains a cylinder pressure of 10 MPa. Initially, the water is at 700°C, and the volume is 100 L. The water is now cooled and condensed to saturated liquid. The heat released during this process is the  $Q$  supply to a cyclic heat engine that in turn rejects heat to the ambient at 30°C. If the overall process is reversible, what is the net work output of the heat engine?

C.V.:  $H_2O$ , 1→3, this is a control mass:

Continuity Eq.:  $m_1 = m_3 = m$

Energy Eq.:  $m(u_3 - u_1) = {}_1Q_3 - {}_1W_3$ ;

Process:  $P = C \Rightarrow {}_1W_3 = \int P dV = Pm(v_3 - v_1)$

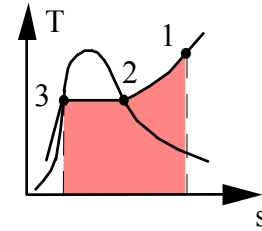
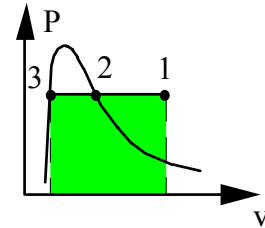
State 1: 700°C, 10 MPa,  $V_1 = 100$  L Table B.1.4

$v_1 = 0.04358$  m<sup>3</sup>/kg  $\Rightarrow m = m_1 = V_1/v_1 = 2.295$  kg

$h_1 = 3870.5$  kJ/kg,  $s_1 = 7.1687$  kJ/kg K

State 3:  $P_3 = P_1 = 10$  MPa,  $x_3 = 0$  Table B.1.2

$h_3 = h_f = 1407.5$  kJ/kg,  $s_3 = s_f = 3.3595$  kJ/kg K



$${}_1Q_3 = m(u_3 - u_1) + Pm(v_3 - v_1) = m(h_3 - h_1)$$

$$= -5652.6 \text{ kJ}$$

Heat transfer to the heat engine:

$$Q_H = -{}_1Q_3 = 5652.6 \text{ kJ}$$

Take control volume as total water and heat engine.

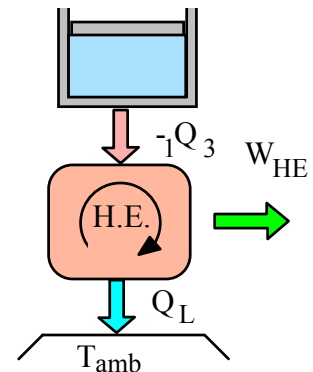
Process: Rev.,  $\Delta S_{net} = 0$ ;  $T_L = 30^\circ\text{C}$

2<sup>nd</sup> Law:  $\Delta S_{net} = m(s_3 - s_1) - Q_{CV}/T_L$ ;

$$Q_{CV} = T_o m(s_3 - s_1) = -2650.6 \text{ kJ}$$

$$\Rightarrow Q_L = -Q_{CV} = 2650.6 \text{ kJ}$$

$$W_{net} = W_{HE} = Q_H - Q_L = \mathbf{3002 \text{ kJ}}$$



## 8.132

A cylinder/piston contains 3 kg of water at 500 kPa, 600°C. The piston has a cross-sectional area of 0.1 m<sup>2</sup> and is restrained by a linear spring with spring constant 10 kN/m. The setup is allowed to cool down to room temperature due to heat transfer to the room at 20°C. Calculate the total (water and surroundings) change in entropy for the process.

State 1: Table B.1.3,  $v_1 = 0.8041$ ,  $u_1 = 3299.6$ ,  $s_1 = 7.3522$

State 2:  $T_2$  & on line in P-V diagram.

$$P = P_1 + (k_s/A_{\text{cyl}}^2)(V - V_1)$$

Assume state 2 is two-phase,  $P_2 = P_{\text{sat}}(T_2) = 2.339$  kPa

$$v_2 = v_1 + (P_2 - P_1)A_{\text{cyl}}^2/mk_s$$

$$v_2 = 0.8041 + (2.339 - 500)0.01/(3 \times 10) = 0.6382 = v_f + x_2v_{fg}$$

$$x_2 = (0.6382 - 0.001002)/57.7887 = 0.011, \quad u_2 = 109.46, \quad s_2 = 0.3887$$

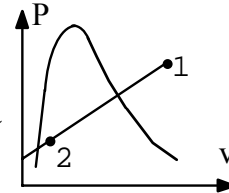
$${}_1W_2 = \frac{1}{2}(P_1 + P_2)m \times (v_2 - v_1)$$

$$= \frac{1}{2}(500 + 2.339) \times 3 \times (0.6382 - 0.8041) = -125 \text{ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 3(109.46 - 3299.6) - 125 = -9695.4 \text{ kJ}$$

$$\Delta S_{\text{tot}} = S_{\text{gen,tot}} = m(s_2 - s_1) - {}_1Q_2/T_{\text{room}}$$

$$= 3(0.3887 - 7.3522) + 9695.4/293.15 = \mathbf{12.18 \text{ kJ/K}}$$





## 8.133

An insulated cylinder fitted with a frictionless piston contains saturated vapor R-12 at ambient temperature, 20°C. The initial volume is 10 L. The R-12 is now expanded to a temperature of -30°C. The insulation is then removed from the cylinder, allowing it to warm at constant pressure to ambient temperature. Calculate the net work and the net entropy change for the overall process.

C.V.: R-12

State 1:  $T_1 = 20^\circ\text{C}$ ,  $V_1 = 10 \text{ L} = 0.01 \text{ m}^3$ , Sat. Vapor  $\rightarrow x_1 = 1.0$

$$P_1 = P_g = 567 \text{ kPa}, \quad v_1 = v_g = 0.03078 \text{ m}^3/\text{kg}, \quad m_1 = V_1/v_1 = 0.325 \text{ kg}$$

$$u_1 = u_g = 178.32 \text{ kJ/kg}, \quad s_1 = s_g = 0.68841 \text{ kJ/kg-K}$$

State 2:  $T_2 = -30^\circ\text{C}$

Assume 1 $\rightarrow$ 2 Adiabatic & Reversible:  $s_2 = s_1 = 0.68841 \text{ kJ/kg-K}$

$$s_2 = s_f + x_2 s_{fg}; \Rightarrow x_2 = 0.95789, \quad P_2 = P_g = 100.4 \text{ kPa}$$

$$v_2 = v_f + x_2 v_{fg} = 0.15269 \text{ m}^3/\text{kg}, \quad h_2 = h_f + x_2 h_{fg} = 167.23 \text{ kJ/kg}$$

$$u_2 = h_2 - P_2 v_2 = 151.96 \text{ kJ/kg}$$

State 3:  $T_3 = 20^\circ\text{C}$ ,  $P_3 = P_2 = 100.41 \text{ kPa}$

$$v_3 = 0.19728 \text{ m}^3/\text{kg}, \quad h_3 = 203.86 \text{ kJ/kg}, \quad s_3 = 0.82812 \text{ kJ/kg-K}$$

1<sup>st</sup> Law: 1 $\rightarrow$ 2,  ${}_1Q_2 = m(u_2 - u_1) + {}_1W_2$ ;  ${}_1Q_2 = 0$

$${}_1W_2 = m(u_1 - u_2) = 8.57 \text{ kJ}$$

2 $\rightarrow$ 3: Process:  $P = \text{constant} \Rightarrow {}_2W_3 = \int P m dv = Pm(v_3 - v_2) = 1.45 \text{ kJ}$

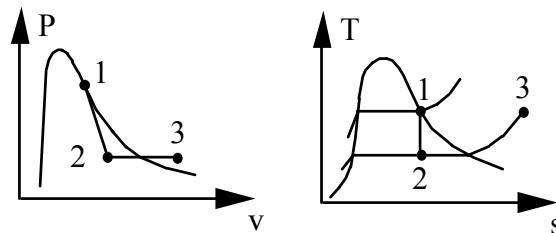
$$W_{\text{TOT}} = {}_1W_2 + {}_2W_3 = 8.57 + 1.45 = \mathbf{10.02 \text{ kJ}}$$

b) 1<sup>st</sup> Law: 2 $\rightarrow$ 3  ${}_2Q_3 = m(u_3 - u_2) + {}_2W_3$ ;  ${}_2W_3 = Pm(v_3 - v_2)$

$${}_2Q_3 = m(u_3 - u_2) + Pm(v_3 - v_2) = m(h_3 - h_2) = 11.90 \text{ kJ}$$

2<sup>nd</sup> Law: 1 $\rightarrow$ 3:  $T_0 = 20^\circ\text{C}$ ,  $Q_{\text{CV}} = {}_1Q_2 + {}_2Q_3$ ;  ${}_1Q_2 = 0$

$$\Delta S_{\text{net}} = m(s_3 - s_1) - Q_{\text{CV}}/T_0 = \mathbf{0.0048 \text{ kJ/K}}$$



## 8.134

A piston/cylinder assembly contains 2 kg of liquid water at 20°C, 100 kPa and it is now heated to 300°C by a source at 500°C. A pressure of 1000 kPa will lift the piston off the lower stops. Find the final volume, work, heat transfer and total entropy generation.

Solution:

C.V. Water out to source at 500°C. This is a control mass.

$$\text{Energy Eq.5.11:} \quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14:} \quad m(s_2 - s_1) = {}_1Q_2 / T_{\text{SOURCE}} + {}_1S_2_{\text{gen}}$$

$$\text{Process:} \quad V = V_1 \text{ if } P < P_{\text{LIFT}} \text{ or } P = P_{\text{LIFT}} \text{ if } V > V_1$$

Any state of this system must be on the two lines shown in the P-v diagram.

$$\text{Initial state: Table B.1.1: } v_1 = 0.001002, \quad u_1 = 83.94, \quad s_1 = 0.2966$$

$$V_1 = mv_1 = 2 \times 0.001002 = 0.002 \text{ m}^3$$

Final state: 300°C and on line in P-V diagram. Now check at state 1a.

$$\text{State 1a: } v_{1a} = v_1, \quad P = 1000 \text{ kPa} \Rightarrow \text{compressed liquid } T_{1a} < 180^\circ\text{C}$$

As final state is at 300°C higher than  $T_{1a}$  we must be further out so

State 2: 1000 kPa, 300°C  $\Rightarrow$  Superheated vapor in Table B.1.3

$$v_2 = 0.25794, \quad u_2 = 2793.2, \quad s_2 = 7.1228$$

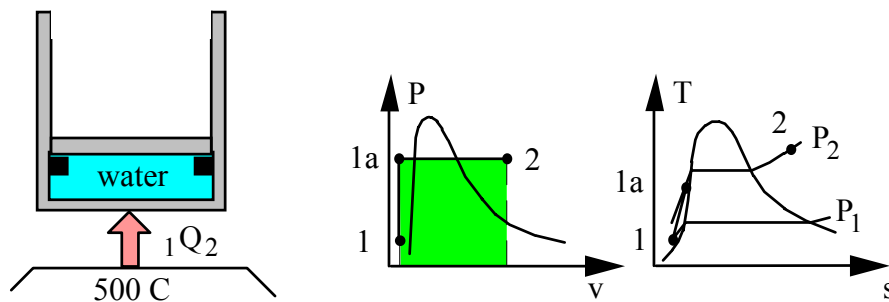
$$V_2 = mv_2 = 2 \times 0.25794 = 0.51588 \text{ m}^3$$

$${}_1W_2 = \int PdV = P_2(V_2 - V_1) = 1000 (0.51588 - 0.002) = \mathbf{513.9 \text{ kJ}}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 2(2793.2 - 83.94) + 513.9 = \mathbf{5932 \text{ kJ}}$$

$${}_1S_2_{\text{gen}} = m(s_2 - s_1) - {}_1Q_2 / T_{\text{SOURCE}} = 2 (7.1228 - 0.2966) - \frac{5932}{773.15}$$

$$= 13.652 - 7.673 = \mathbf{5.98 \text{ kJ/K}} \quad (= \Delta S_{\text{water}} + \Delta S_{\text{sur}})$$



## 8.135

An uninsulated cylinder fitted with a piston contains air at 500 kPa, 200°C, at which point the volume is 10 L. The external force on the piston is now varied in such a manner that the air expands to 150 kPa, 25 L volume. It is claimed that in this process the air produces 70% of the work that would have resulted from a reversible, adiabatic expansion from the same initial pressure and temperature to the same final pressure. Room temperature is 20°C.

- a) What is the amount of work claimed?  
 b) Is this claim possible?

Solution:

C.V.: Air;  $R = 0.287 \text{ kJ/kg-K}$ ,  $C_p = 1.004 \text{ kJ/kg K}$ ,  $C_v = 0.717 \text{ kJ/kg K}$

State 1:  $T_1 = 200^\circ\text{C}$ ,  $P_1 = 500 \text{ kPa}$ ,  $V_1 = 10 \text{ L} = 0.01 \text{ m}^3$ ;

$$m_1 = V_1/v_1 = P_1 V_1 / RT_1 = 0.0368 \text{ kg}$$

State 2:  $P_2 = 150 \text{ kPa}$ ,  $V_2 = 25 \text{ L} = 0.025 \text{ m}^3$

$\eta_s = 70\%$ ; Actual Work is 70% of Isentropic Work

- a) Assume Reversible and Adiabatic Process;  $s_1 = s_{2s}$

$$T_{2s} = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} = 473.15 (150 / 500) = 335.4 \text{ K}$$

1<sup>st</sup> Law:  ${}_1Q_{2s} = m(u_{2s} - u_1) + {}_1W_{2s}$ ;  ${}_1Q_{2s} = 0$

Assume constant specific heat

$${}_1W_{2s} = mC_v(T_1 - T_{2s}) = 3.63 \text{ kJ}$$

$${}_1W_{2ac} = 0.7 \times {}_1W_{2s} = \mathbf{2.54 \text{ kJ}}$$

- b) Use Ideal Gas Law;  $T_{2ac} = T_1 P_2 V_2 / P_1 V_1 = 354.9 \text{ K}$

1<sup>st</sup> Law:  ${}_1Q_{2ac} = mC_v(T_{2ac} - T_1) + {}_1W_{2ac} = -0.58 \text{ kJ}$

2<sup>nd</sup> Law:  $\Delta S_{net} = m(s_2 - s_1) - \frac{Q_{cv}}{T_0}$ ;  $Q_{cv} = {}_1Q_{2ac}$ ,  $T_0 = 20^\circ\text{C}$

$$s_2 - s_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} = 0.0569 \text{ kJ/kg-K}$$

$$\Delta S_{net} = 0.00406 \text{ kJ/K} \geq 0; \quad \mathbf{\text{Process is Possible}}$$

## 8.136

A cylinder fitted with a piston contains 0.5 kg of R-134a at 60°C, with a quality of 50 percent. The R-134a now expands in an internally reversible polytropic process to ambient temperature, 20°C at which point the quality is 100 percent. Any heat transfer is with a constant-temperature source, which is at 60°C. Find the polytropic exponent  $n$  and show that this process satisfies the second law of thermodynamics.

Solution:

C.V.: R-134a, Internally Reversible, Polytropic Expansion:  $PV^n = \text{Const.}$

Cont.Eq.:  $m_2 = m_1 = m$ ; Energy Eq.:  $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2 \text{ gen}$

State 1:  $T_1 = 60^\circ\text{C}$ ,  $x_1 = 0.5$ , Table B.5.1:  $P_1 = P_g = 1681.8 \text{ kPa}$ ,

$$v_1 = v_f + x_1 v_{fg} = 0.000951 + 0.5 \times 0.010511 = 0.006207 \text{ m}^3/\text{kg}$$

$$s_1 = s_f + x_1 s_{fg} = 1.2857 + 0.5 \times 0.4182 = 1.4948 \text{ kJ/kg K},$$

$$u_1 = u_f + x_1 u_{fg} = 286.19 + 0.5 \times 121.66 = 347.1 \text{ kJ/kg}$$

State 2:  $T_2 = 20^\circ\text{C}$ ,  $x_2 = 1.0$ ,  $P_2 = P_g = 572.8 \text{ kPa}$ , Table B.5.1

$$v_2 = v_g = 0.03606 \text{ m}^3/\text{kg}, \quad s_2 = s_g = 1.7183 \text{ kJ/kg-K}$$

$$u_2 = u_g = 389.19 \text{ kJ/kg}$$

$$\text{Process: } PV^n = \text{Const.} \Rightarrow \frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^n \Rightarrow n = \ln \frac{P_1}{P_2} / \ln \frac{v_2}{v_1} = \mathbf{0.6122}$$

$$\begin{aligned} {}_1W_2 &= \int PdV = \frac{P_2V_2 - P_1V_1}{1-n} \\ &= 0.5(572.8 \times 0.03606 - 1681.8 \times 0.006207)/(1 - 0.6122) = 13.2 \text{ kJ} \end{aligned}$$

2<sup>nd</sup> Law for C.V.: R-134a plus wall out to source:

$$\Delta S_{\text{net}} = m(s_2 - s_1) - \frac{Q_H}{T_H}; \quad \text{Check } \Delta S_{\text{net}} \geq 0$$

$$Q_H = {}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 34.2 \text{ kJ}$$

$$\Delta S_{\text{net}} = 0.5(1.7183 - 1.4948) - 34.2/333.15 = 0.0092 \text{ kJ/K},$$

$\Delta S_{\text{net}} > 0$  Process Satisfies 2<sup>nd</sup> Law

## 8.137

A cylinder with a linear spring-loaded piston contains carbon dioxide gas at 2 MPa with a volume of 50 L. The device is of aluminum and has a mass of 4 kg. Everything (Al and gas) is initially at 200°C. By heat transfer the whole system cools to the ambient temperature of 25°C, at which point the gas pressure is 1.5 MPa. Find the total entropy generation for the process.

$$\text{CO}_2: m = P_1 V_1 / RT_1 = 2000 \times 0.05 / (0.18892 \times 473.2) = 1.1186 \text{ kg}$$

$$V_2 = V_1 (P_1 / P_2) (T_2 / T_1) = 0.05 (2 / 1.5) (298.2 / 473.2) = 0.042 \text{ m}^3$$

$${}_1W_2 \text{CO}_2 = \int P dV = \frac{P_1 + P_2}{2} (V_2 - V_1) = \frac{2000 + 1500}{2} (0.042 - 0.050) = -14.0 \text{ kJ}$$

$${}_1Q_2 \text{CO}_2 = m C_{V0} (T_2 - T_1) + {}_1W_2 = 1.1186 \times 0.6529 (25 - 200) - 14.0 = -141.81 \text{ kJ}$$

$${}_1Q_2 \text{Al} = m C (T_2 - T_1) = 4 \times 0.90 (25 - 200) = -630 \text{ kJ}$$

System: CO<sub>2</sub> + Al

$${}_1Q_2 = -141.81 - 630 = -771.81 \text{ kJ}$$

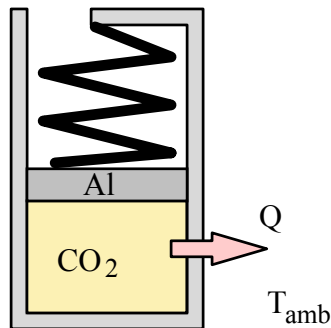
$$\Delta S_{\text{SYST}} = m_{\text{CO}_2} (s_2 - s_1)_{\text{CO}_2} + m_{\text{AL}} (s_2 - s_1)_{\text{AL}}$$

$$= 1.1186 \left[ 0.8418 \ln \frac{298.2}{473.2} - 0.18892 \ln \frac{1.5}{2.0} \right] + 4 \times 0.9 \ln (298.2 / 473.2)$$

$$= -0.37407 - 1.6623 = -2.0364 \text{ kJ/K}$$

$$\Delta S_{\text{SURR}} = -({}_1Q_2 / T_0) = + (771.81 / 298.15) = +2.5887 \text{ kJ/K}$$

$$\Delta S_{\text{NET}} = -2.0364 + 2.5887 = +0.552 \text{ kJ/K}$$



## 8.138

A vertical cylinder/piston contains R-22 at  $-20^{\circ}\text{C}$ , 70% quality, and the volume is 50 L, shown in Fig. P8.138. This cylinder is brought into a  $20^{\circ}\text{C}$  room, and an electric current of 10 A is passed through a resistor inside the cylinder. The voltage drop across the resistor is 12 V. It is claimed that after 30 min the temperature inside the cylinder is  $40^{\circ}\text{C}$ . Is this possible?

C.V. The R-22 out to the surroundings, i.e. include walls.

$$\text{Energy Eq.5.11: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

$$\text{Entropy Eq.8.14: } m(s_2 - s_1) = \int dQ/T + {}_1S_2 \text{ gen} = {}_1Q_2/T_{\text{amb}} + {}_1S_2 \text{ gen}$$

Process: Constant pressure  $P_1 = P_2 = 245 \text{ kPa}$

$$\begin{aligned} \text{State 1: Table B.4.1 } v_1 &= 0.06521 \text{ m}^3/\text{kg}, h_1 = 176 \text{ kJ/kg}, s_1 = 0.6982 \text{ kJ/kg K} \\ m &= V_1/v_1 = 0.05/0.06521 = 0.767 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{State 2: Table B.4.2 Interpolate between 200 and 300 kPa} \\ h_2 &= 282.2 \text{ kJ/kg}, s_2 = 1.1033 \text{ kJ/kg K} \end{aligned}$$

$$\text{Electrical work: } W_{\text{ELEC}} = -Ei \Delta t = -12 \times 10 \times 30 \times 60/1000 = -216 \text{ kJ}$$

$$\text{Total work: } {}_1W_2 = Pm(v_2 - v_1) + W_{\text{ELEC}}$$

Now substitute into energy equation and solve for Q

$$\begin{aligned} {}_1Q_2 &= m(u_2 - u_1) + Pm(v_2 - v_1) + W_{\text{ELEC}} = m(h_2 - h_1) + W_{\text{ELEC}} \\ &= 0.767(282.2 - 176.0) - 216 = -134.5 \text{ kJ} \end{aligned}$$

Solve for the entropy generation from entropy equation

$$\begin{aligned} {}_1S_2 \text{ gen} &= m(s_2 - s_1) - {}_1Q_2/T_{\text{amb}} \\ &= 0.767(1.1033 - 0.6982) + \frac{134.5}{293.15} \\ &= 0.3093 + 0.4587 = +0.768 \text{ kJ/K} \quad \text{Claim is OK.} \end{aligned}$$

## 8.139

A gas in a rigid vessel is at ambient temperature and at a pressure,  $P_1$ , slightly higher than ambient pressure,  $P_0$ . A valve on the vessel is opened, so gas escapes and the pressure drops quickly to ambient pressure. The valve is closed and after a long time the remaining gas returns to ambient temperature at which point the pressure is  $P_2$ . Develop an expression that allows a determination of the ratio of specific heats,  $k$ , in terms of the pressures.

C.V.: air remaining in tank,

First part of the process is an isentropic expansion  $s = \text{constant}$ .

$$P_1, T_0 \rightarrow P_0, T_x \quad T_x/T_0 = (P_0/P_1)^{\frac{k-1}{k}}$$

Second part of the process is a const. vol. heat transfer.  $P_0, T_x \rightarrow P_2, T_0$

$$\frac{P_0}{P_2} = \frac{T_x}{T_0} \Rightarrow \frac{P_0}{P_2} = \left(\frac{P_0}{P_1}\right)^{\frac{k-1}{k}} \rightarrow k = \frac{\ln(P_1/P_0)}{\ln(P_1/P_2)}$$

## Solutions using the Pr and vr functions in Table A.7.2

## 8.88

A piston/cylinder setup contains air at 100 kPa, 400 K which is compressed to a final pressure of 1000 kPa. Consider two different processes (i) a reversible adiabatic process and (ii) a reversible isothermal process. Show both processes in P-v and a T-s diagram. Find the final temperature and the specific work for both processes.

Solution:

C.V. Air, control mass of unknown size and mass.

$$\text{Energy Eq.5.11: } u_2 - u_1 = {}_1q_2 - {}_1w_2$$

$$\text{Entropy Eq.8.14: } s_2 - s_1 = \int dq/T + {}_1s_{2\text{ gen}}$$

$$\text{Process: } \text{Reversible } {}_1s_{2\text{ gen}} = 0$$

$$\text{i) } dq = 0 \text{ so } {}_1q_2 = 0$$

$$\text{ii) } T = C \text{ so } \int dq/T = {}_1q_2/T$$

i) For this process the entropy equation reduces to:

$$s_2 - s_1 = 0 + 0 \text{ so we have constant } s, \text{ an isentropic process.}$$

The relation for air from table A.7.2, constant s becomes

$$P_{r2} = P_{r1} (P_2 / P_1) = 3.06119 \times 10 = 30.6119$$

$$\text{From A.7.2 } \Rightarrow \mathbf{T_2 = 753.6 \text{ K}} \text{ and } u_2 = 555.24 \text{ kJ/kg}$$

From the energy equation we get the work term

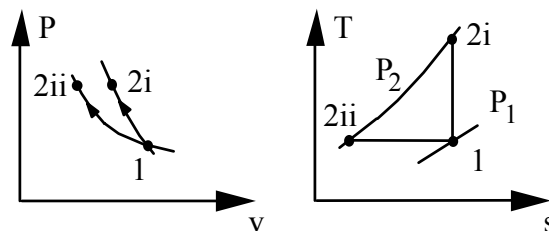
$${}_1w_2 = u_1 - u_2 = 286.5 - 555.2 = \mathbf{-268.7 \text{ kJ/kg}}$$

ii) For this process  $T_2 = T_1$  so since ideal gas we get

$$u_2 = u_1 \text{ also } s_{T2}^o = s_{T1}^o \Rightarrow \text{Energy Eq.: } {}_1w_2 = {}_1q_2$$

Now from the entropy equation we solve for  ${}_1q_2$

$$\begin{aligned} {}_1w_2 = {}_1q_2 &= T(s_2 - s_1) = T[s_{T2}^o - s_{T1}^o - R \ln \frac{P_2}{P_1}] = -RT \ln \frac{P_2}{P_1} \\ &= -0.287 \times 400 \ln 10 = \mathbf{-264 \text{ kJ/kg}} \end{aligned}$$





## 8.95

A piston/cylinder, shown in Fig. P8.95, contains air at 1380 K, 15 MPa, with  $V_1 = 10 \text{ cm}^3$ ,  $A_{\text{cyl}} = 5 \text{ cm}^2$ . The piston is released, and just before the piston exits the end of the cylinder the pressure inside is 200 kPa. If the cylinder is insulated, what is its length? How much work is done by the air inside?

Solution:

C.V. Air, Cylinder is insulated so adiabatic,  $Q = 0$ .

Continuity Eq.:  $m_2 = m_1 = m$ ,

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

Entropy Eq.8.14:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2_{\text{gen}} = 0 + {}_1S_2_{\text{gen}}$

State 1:  $(T_1, P_1)$       State 2:  $(P_2, ?)$

So one piece of information is needed for the ?, assume reversible process.

$${}_1S_2_{\text{gen}} = 0 \Rightarrow s_2 - s_1 = 0$$

State 1: Table A.7.1:  $u_1 = 1095.2 \text{ kJ/kg}$ ,

Table A.7.2:  $P_{r1} = 340.53$ ,  $v_{r1} = 2.7024$

$$m = P_1 V_1 / RT_1 = \frac{15000 \times 10 \times 10^{-6}}{0.287 \times 1380} = 0.000379 \text{ kg}$$

State 2:  $P_2$  and from Entropy eq.:  $s_2 = s_1$

$$\Rightarrow P_{r2} = P_{r1} P_2 / P_1 = 340.53 \times 200 / 15000 = 4.5404$$

Interpolate in A.7.2 to match the  $P_{r2}$  value

$$T_2 = 447 \text{ K}, \quad u_2 = 320.85 \text{ kJ/kg}, \quad v_{r2} = 65.67$$

$$\Rightarrow V_2 = V_1 v_{r2} / v_{r1} = 10 \times 65.67 / 2.7024 = \mathbf{243 \text{ cm}^3}$$

$$\Rightarrow L_2 = V_2 / A_{\text{cyl}} = 243 / 5 = \mathbf{48.6 \text{ cm}}$$

$$\Rightarrow {}_1w_2 = u_1 - u_2 = 774.4 \text{ kJ/kg}, \quad {}_1W_2 = m_1 w_2 = \mathbf{0.2935 \text{ kJ}}$$

We could also have done  $V_2 = V_1 (T_2 P_1 / T_1 P_2)$  from ideal gas law and thus did not need the  $v_r$  function for this problem

**8.107**

A mass of 1 kg of air contained in a cylinder at 1.5 MPa, 1000 K, expands in a reversible adiabatic process to 100 kPa. Calculate the final temperature and the work done during the process, using

- Constant specific heat, value from Table A.5
- The ideal gas tables, Table A.7

Solution:

C.V. Air.

Continuity Eq.:  $m_2 = m_1 = m$  ;

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

Entropy Eq.8.14:  $m(s_2 - s_1) = \int dQ/T + {}_1S_2_{\text{gen}}$

Process:  ${}_1Q_2 = 0$ ,  ${}_1S_2_{\text{gen}} = 0 \Rightarrow s_2 = s_1$

- Using constant  $C_p$  from Table A.5 gives the power relation Eq.8.32.

$$T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 1000\left(\frac{0.1}{1.5}\right)^{0.286} = \mathbf{460.9 \text{ K}}$$

$$\begin{aligned} {}_1W_2 &= -(U_2 - U_1) = mC_{V_o}(T_1 - T_2) \\ &= 1 \times 0.717(1000 - 460.9) = \mathbf{386.5 \text{ kJ}} \end{aligned}$$

- Use the tabulated **reduced pressure function** that includes variable heat capacity from A.7.2

$$P_{r2} = P_{r1} \times P_2/P_1 = 91.65 \times \frac{0.1}{1.5} = 6.11$$

Interpolation gives  $T_2 = \mathbf{486 \text{ K}}$  and  $u_2 = 349.4 \text{ kJ/kg}$

$${}_1W_2 = m(u_1 - u_2) = 1(759.2 - 349.4) = \mathbf{409.8 \text{ kJ}}$$

**8.112**

A piston/cylinder contains air at 300 K, 100 kPa. It is now compressed in a reversible adiabatic process to a volume 7 times as small. Use constant heat capacity and find the final pressure and temperature, the specific work and specific heat transfer for the process.

Solution: Here we use the  $v_r$  function from Table A.7.2

$$\text{Expansion ratio: } v_2/v_1 = 1/7$$

$$\text{Process eq.: Rev. adiabatic and ideal gas gives } Pv^n = C, \text{ with } n = k$$

$$v_{r1} = 179.49 \Rightarrow v_{r2} = v_{r1} v_2/v_1 = 179.49/7 = 25.641$$

Table A.7.2: Interpolate  $T_2 = \mathbf{640.7 \text{ K}}$

$$P_2 = P_1 \times (T_2 / T_1) \times (v_1/v_2) = 100 \times (640.7/300) \times 7 = \mathbf{1495 \text{ kPa}}$$

$$\text{Adiabatic: } {}_1q_2 = \mathbf{0 \text{ kJ/kg}}$$

Polytropic process work term from Eq.8.38

$${}_1w_2 = -(u_2 - u_1) = -(466.37 - 214.36) = \mathbf{-252.0 \text{ kJ/kg}}$$

Notice: Here the solution is done with variable heat capacity..