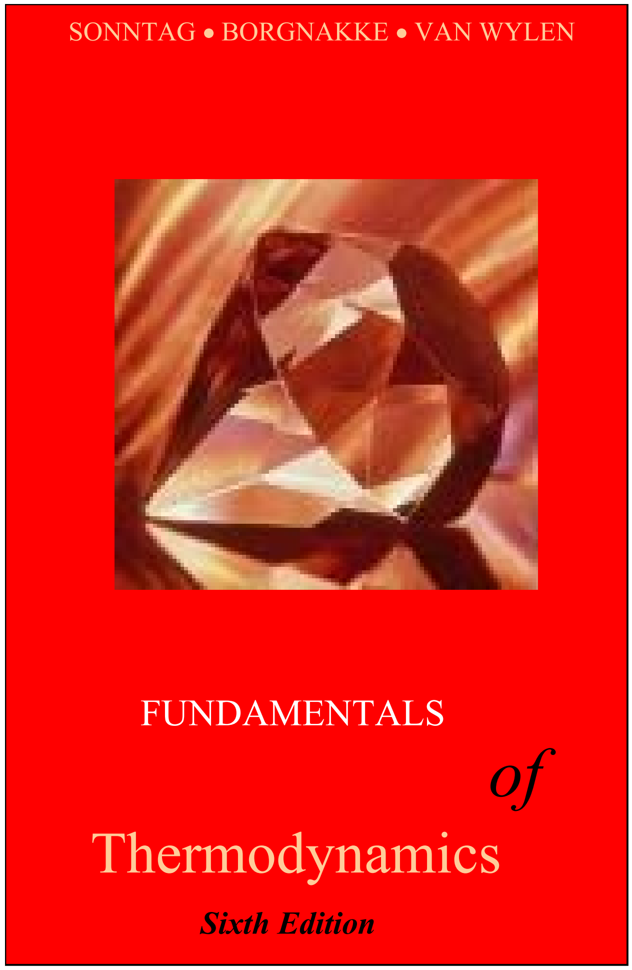
SOLUTION MANUAL
SI UNIT PROBLEMS
CHAPTER 9



CONTENT

Correspondance Table
CHAPTER 9 6th edition

The correspondence between the new problem set and the previous 5th edition chapter 9 problem sets.

New	5th	New	5th	New	5th
21	new	59	18	97	52
22	1	60	23	98	53
23	new	61	new	99	new
24	2	62	new	100	new
25	new	63	new	101	55
26	3	64	new	102	57 mod
27	10	65	26	103	54
28	new	66	30	104	new
29	4	67	new	105	61
30	14	68	new	106	63
31	new	69	31 mod	107	78
32	new	70	new	108	56
33	new	71	33	109	58
34	21	72	new	110	74
35	new	73	27	111	75
36	15	74	29	112	new
37	5	75	new	113	60
38	6	76	40	114	65
39	16	77	38	115	new
40	new	78	41	116	67
41	20	79	39	117	9
42	22 mod	80	42	118	11
43	24	81	new	119	28
44	70 mod	82	43	120	82a
45	73 mod	83	44	121	25
46	80 mod	84	46	122	36
47	8	85	48	123	37
48	17	86	45	124	78
49	new	87	new	125	80
50	new	88	new	126	84
51	new	89	new	127	89
52	12	90	47	128	90
53	new	91	new	129	32
54	50	92	new	130	34 mod
55	new	93	new	131	35
56	19	94	new	132	49
57	13	95	new	133	62
58	new	96	51		

Concept-Study Guide Problems

9.1

In a steady state single flow *s* is either constant or it increases. Is that true?
Solution:

No.

Steady state single flow: $s_e = s_i + \int_i^e \frac{dq}{T} + s_{gen}$

Entropy can only go up or stay constant due to s_{gen}, but it can go up or down due to the heat transfer which can be positive or negative. So if the heat transfer is large enough it can overpower any entropy generation and drive s up or down.

9.2

Which process will make the previous statement true?
Solution:

If the process is said to be adiabatic then:
Steady state adiabatic single flow: $s_e = s_i + s_{gen} \geq s_i$

9.3

A reversible adiabatic flow of liquid water in a pump has increasing P. How about T?
Solution:

Steady state single flow: $s_e = s_i + \int_i^e \frac{dq}{T} + s_{gen} = s_i + 0 + 0$

Adiabatic (dq = 0) means integral vanishes and reversible means $s_{gen} = 0$, so s is constant. Properties for liquid (incompressible) gives Eq.8.19

$$ds = \frac{C}{T}\,dT$$

then constant s gives constant T.

9.4

A reversible adiabatic flow of air in a compressor has increasing P. How about T?

Solution:

Steady state single flow: $s_e = s_i + \int_i^e \frac{dq}{T} + s_{gen} = s_i + 0 + 0$

so s is constant. Properties for an ideal gas gives Eq.8.23 and for constant specific heat we get Eq.8.29. A higher P means a higher T, which is also the case for a variable specific heat, recall Eq.8.28 for the standard entropy.

9.5

An irreversible adiabatic flow of liquid water in a pump has higher P. How about T?

Solution:

Steady state single flow: $s_e = s_i + \int_i^e \frac{dq}{T} + s_{gen} = s_i + 0 + s_{gen}$

so s is increasing. Properties for liquid (incompressible) gives Eq.8.19 where an increase in s gives an increasse in T.

9.6

A compressor receives R-134a at -10^{o}C, 200 kPa with an exit of 1200 kPa, 50^{o}C. What can you say about the process?

Solution:

Properties for R-134a are found in Table B.5

Inlet state: $s_i = 1.7328$ kJ/kg K

Exit state: $s_e = 1.7237$ kJ/kg K

Steady state single flow: $s_e = s_i + \int_i^e \frac{dq}{T} + s_{gen}$

Since s decreases slightly and the generation term can only be positive, it must be that the heat transfer is negative (out) so the integral gives a contribution that is smaller than $-s_{gen}$.

9.7

An air compressor has a significant heat transfer out. See Example 9.4 for how high T becomes if no heat transfer. Is that good or should it be insulated?

Solution:

A lower T at a given pressure P means the specific volume is smaller,

Ideal gas: $Pv = RT$;

Shaft work: $w = -\int v\, dP$

This gives a smaller work input which is good.

9.8

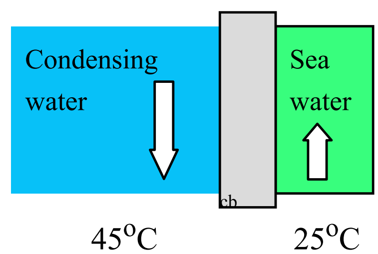
A large condenser in a steam power plant dumps 15 MW at 45°C with an ambient at 25°C. What is the entropy generation rate?

Solution:

This process transfers heat over a finite temperature difference between the water inside the condenser and the outside ambient (cooling water from the sea, lake or river or atmospheric air)

C.V. The wall that separates the inside 45°C water from the ambient at 25°C.

Entropy Eq. 9.1 for steady state operation:



$$\frac{dS}{dt} = 0 = \sum \frac{\dot{Q}}{T} + \dot{S}_{gen} = \frac{\dot{Q}}{T_{45}} - \frac{\dot{Q}}{T_{25}} + \dot{S}_{gen}$$

$$\dot{S}_{gen} = \frac{15}{25 + 273}\frac{MW}{K} - \frac{15}{45 + 273}\frac{MW}{K} = \mathbf{3.17}\ \frac{\mathbf{kW}}{\mathbf{K}}$$

9.9

Air at 1000 kPa, 300 K is throttled to 500 kPa. What is the specific entropy generation?

Solution:

C.V. Throttle, single flow, steady state. We neglect kinetic and potential energies and there are no heat transfer and shaft work terms.

Energy Eq. 6.13: $h_i = h_e \quad \Rightarrow \quad T_i = T_e$ (ideal gas)

Entropy Eq. 9.9: $s_e = s_i + \int_i^e \frac{dq}{T} + s_{gen} = s_i + s_{gen}$

Change in s Eq.8.24: $s_e - s_i = \int_i^e C_p \frac{dT}{T} - R \ln \frac{P_e}{P_i} = - R \ln \frac{P_e}{P_i}$

$$s_{gen} = s_e - s_i = - 0.287 \ln \left(\frac{500}{1000}\right) = \mathbf{0.2} \ \mathbf{\frac{kJ}{kg\ K}}$$

9.10

Friction in a pipe flow causes a slight pressure decrease and a slight temperature increase. How does that affect entropy?

Solution:

The friction converts flow work (P drops) into internal energy (T up if single phase). This is an irreversible process and s increases.

If liquid: Eq. 8.19: $ds = \frac{C}{T} dT$ so s follows T

If ideal gas Eq. 8.23: $ds = C_p \frac{dT}{T} - R \frac{dP}{P}$ (both terms increase)

9.11

A flow of water at some velocity out of a nozzle is used to wash a car. The water then falls to the ground. What happens to the water state in terms of **V**, T and s?

let us follow the water flow. It starts out with kinetic and potential energy of some magnitude at a compressed liquid state P, T. As the water splashes onto the car it looses its kinetic energy (it turns in to internal energy so T goes up by a very small amount). As it drops to the ground it then looses all the potential energy which goes into internal energy. Both of theses processes are irreversible so s goes up.

If the water has a temperature different from the ambient then there will also be some heat transfer to or from the water which will affect both T and s.

9.12

The shaft work in a pump to increase the pressure is small compared to the shaft work in an air compressor for the same pressure increase. Why?

The reversible work is given by Eq. 9.14 or 9.18 if no kinetic or potential energy changes

$$w = -\int v\, dP$$

The liquid has a very small value for v compared to a large value for a gas.

9.13

If the pressure in a flow is constant, can you have shaft work?

The reversible work is given by Eq.9.14

$$w = -\int v\, dP + (\mathbf{V}_i^2 - \mathbf{V}_e^2) + g\,(Z_i - Z_e)$$

For a constant pressure the first term drops out but the other two remains. Kinetic energy changes can give work out (windmill) and potential energy changes can give work out (a dam).

9.14

A pump has a 2 kW motor. How much liquid water at 15°C can I pump to 250 kPa from 100 kPa?

Incompressible flow (liquid water) and we assume reversible. Then the shaftwork is from Eq.9.18

$$w = -\int v\, dP = -v\, \Delta P = -0.001\ \mathrm{m^3/kg}\ (250 - 100)\ \mathrm{kPa}$$
$$= -\ 0.15\ \mathrm{kJ/kg}$$

$$\dot{m} = \frac{\dot{W}}{-w} = \frac{2}{0.15} = \mathbf{13.3\ kg/s}$$

9.15

Liquid water is sprayed into the hot gases before they enter the turbine section of a large gasturbine power plant. It is claimed that the larger mass flow rate produces more work. Is that the reason?

No. More mass through the turbine does give more work, but the added mass is only a few percent. As the liquid vaporises the specific volume increases dramatically which gives a much larger volume flow throught the turbine and that gives more work output.

$$\dot{W} = \dot{m}w = -\dot{m}\int v\, dP = -\int \dot{m}v\, dP = -\int \dot{V}\, dP$$

This should be seen relative to the small work required to bring the liquid water up to the higher turbine inlet pressure from the source of water (presumably atmospheric pressure).

9.16

A polytropic flow process with $n = 0$ might be which device?

As the polytropic process is $Pv^n = C$, then $n = 0$ is a constant pressure process. This can be a pipe flow, a heat exchanger flow (heater or cooler) or a boiler.

9.17

A steam turbine inlet is at 1200 kPa, 500°C. The exit is at 200 kPa. What is the lowest possible exit temperature? Which efficiency does that correspond to?

We would expect the lowest possible exit temperature when the maximum amount of work is taken out. This happens in a reversible process so if we assume it is adiabatic this becomes an isentropic process.

Exit: 200 kPa, $s = s_{in} = 7.6758$ kJ/kg K $\Rightarrow$ **$T = 241.9^oC$**

The efficiency from Eq.9.27 measures the turbine relative to an isentropic turbine, so the **efficiency** will be **100%**.

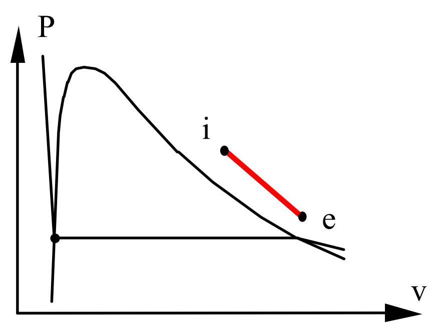
9.18

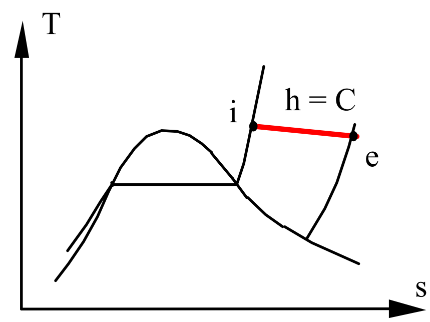
A steam turbine inlet is at 1200 kPa, 500°C. The exit is at 200 kPa. What is the highest possible exit temperature? Which efficiency does that correspond to?

The highest possible exit temperature would be if we did not get any work out, i.e. the turbine broke down. Now we have a throttle process with constant h assuming we do not have a significant exit velocity.

Exit: 200 kPa, $h = h_{in} = 3476.28$ kJ/kg $\Rightarrow$ $\mathbf{T = 495^oC}$

Efficiency: $\eta = \frac{w}{w_s} = \mathbf{0}$





Remark: Since process is irreversible there is no area under curve in T-s diagram that correspond to a q, nor is there any area in the P-v diagram corresponding to a shaft work.

9.19

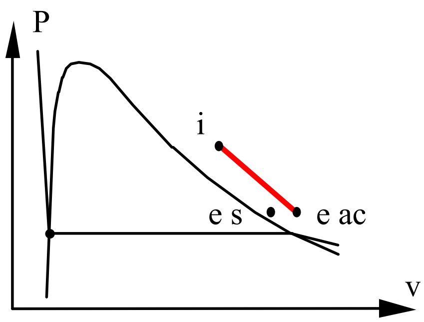
A steam turbine inlet is at 1200 kPa, 500°C. The exit is at 200 kPa, 275°C. What is the isentropic efficiency?

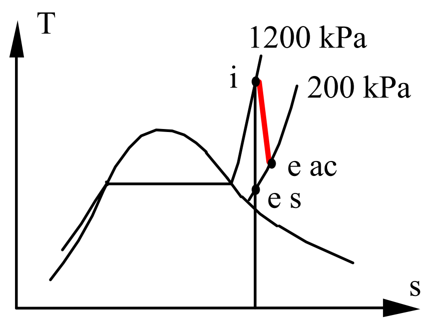
Inlet: h_{in} = 3476.28 kJ/kg, s_{in} = 7.6758 kJ/kg K

Exit: h_{ex} = 3021.4 kJ/kg, s_{ex} = 7.8006 kJ/kg K

Ideal Exit: 200 kPa, $s = s_{in}$ = 7.6758 kJ/kg K $\Rightarrow$ h_s = 2954.7 kJ/kg

$$w_{ac} = h_{in} - h_{ex} = 3476.28 - 3021.4 = 454.9 \text{ kJ/kg}$$
$$w_s = h_{in} - h_s = 3476.28 - 2954.7 = 521.6 \text{ kJ/kg}$$
$$\eta = \frac{w_{ac}}{w_s} = \frac{454.9}{521.6} = \mathbf{0.872}$$





9.20

The exit velocity of a nozzle is 500 m/s. If η_{nozzle} = 0.88 what is the ideal exit velocity?

The nozzle efficiency is given by Eq. 9.30 and since we have the actual exit velocity we get

$$\mathbf{V}_{e\,s}^2 = \mathbf{V}_{ac}^2/\eta_{nozzle} \quad \Rightarrow$$
$$\mathbf{V}_{e\,s} = \mathbf{V}_{ac}/\sqrt{\eta_{nozzle}} = 500 / \sqrt{0.88} = \mathbf{533\ m/s}$$

Steady state reversible processes single flow

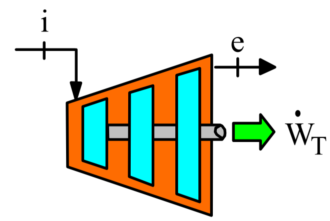
9.21

A first stage in a turbine receives steam at 10 MPa, 800°C with an exit pressure of 800 kPa. Assume the stage is adiabatic and negelect kinetic energies. Find the exit temperature and the specific work.

Solution:

C.V. Stage 1 of turbine.

The stage is adiabatic so $q = 0$ and we will assume reversible so $s_{gen} = 0$



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

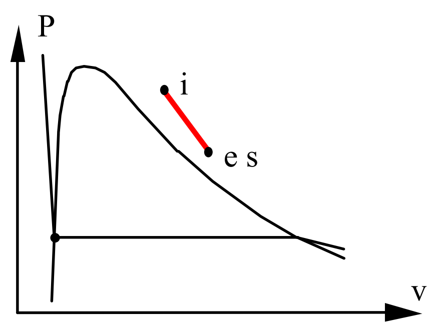
Entropy Eq.9.8: $s_e = s_i + \int dq/T + s_{gen} = s_i + 0 + 0$

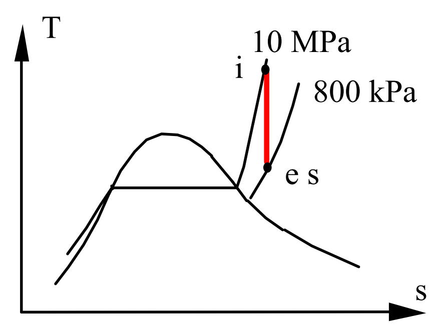
Inlet state: B.1.3: $h_i = 4114.9$ kJ/kg, $s_i = 7.4077$ kJ/kg K

Exit state: 800 kPa, $s = s_i$

Table B.1.3 $\Rightarrow$ $T \cong$ **349.7°C,** $h_e = 3161$ kJ/kg

$w_T = 4114.9 - 3161 =$ **953.9 kJ/kg**





9.22

Steam enters a turbine at 3 MPa, 450°C, expands in a reversible adiabatic process and exhausts at 10 kPa. Changes in kinetic and potential energies between the inlet and the exit of the turbine are small. The power output of the turbine is 800 kW. What is the mass flow rate of steam through the turbine?

Solution:

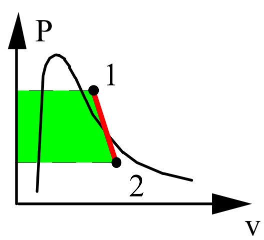
C.V. Turbine, Steady single inlet and exit flows. Adiabatic: $\dot{Q} = 0$.

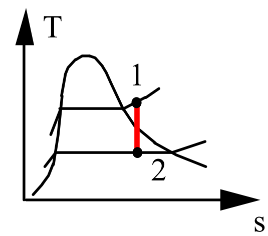
Continuity Eq.6.11: $\dot{m}_i = \dot{m}_e = \dot{m}$,

Energy Eq.6.12: $\dot{m}h_i = \dot{m}h_e + \dot{W}_T$,

Entropy Eq.9.8: $\dot{m}s_i + \emptyset = \dot{m}s_e$ (Reversible $\dot{S}_{gen} = 0$)

Explanation for the work term is in Sect. 9.3, Eq.9.18





Inlet state: Table B.1.3 $h_i = 3344$ kJ/kg, $s_i = 7.0833$ kJ/kg K

Exit state: P_e , $s_e = s_i$ $\Rightarrow$ Table B.1.2 saturated as $s_e < s_g$

$x_e = (7.0833 - 0.6492)/7.501 = 0.8578$,

$h_e = 191.81 + 0.8578 \times 2392.82 = 2244.4$ kJ/kg

$\dot{m} = \dot{W}_T/w_T = \dot{W}_T/(h_i - h_e) = 800/(3344 - 2244.4) = \mathbf{0.728\ kg/s}$

9.23

A reversible adiabatic compressor receives 0.05 kg/s saturated vapor R-22 at 200 kPa and has an exit presure of 800 kPa. Neglect kinetic energies and find the exit temperature and the minimum power needed to drive the unit.

Solution:

C.V. Compressor, Steady single inlet and exit flows. Adiabatic: $\dot{Q} = 0$.

Continuity Eq.6.11: $\dot{m}_i = \dot{m}_e = \dot{m}$,

Energy Eq.6.12: $\dot{m}h_i = \dot{m}h_e + \dot{W}_C$,

Entropy Eq.9.8: $\dot{m}s_i + \emptyset = \dot{m}s_e$ (Reversible $\dot{S}_{gen} = 0$)

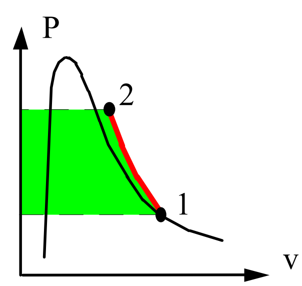
Inlet state: B 4.2.: $h_i = 239.87$ kJ/kg, $s_i = 0.9688$ kJ/kg K

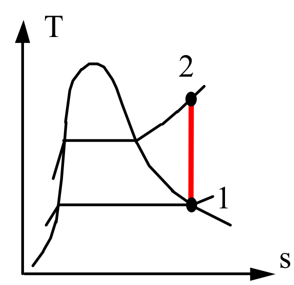
Exit state: P_e , $s_e = s_i$ $\Rightarrow$ Table B.4.2 $h_e = 274.24$ kJ/kg, $\mathbf{T_e \cong 40°C}$

$-w_c = h_e - h_i = 274.24 - 239.87 = 34.37$ kJ/kg

$-\dot{W}_c = \text{Power In} = -w_c\dot{m} = 34.37 \times 0.05 = \mathbf{1.72\ kW}$

Explanation for the work term is in Sect. 9.3, Eq.9.18





9.24

In a heat pump that uses R-134a as the working fluid, the R-134a enters the compressor at 150 kPa, −10°C at a rate of 0.1 kg/s. In the compressor the R-134a is compressed in an adiabatic process to 1 MPa. Calculate the power input required to the compressor, assuming the process to be reversible.

Solution:

C.V. Compressor, Steady single inlet and exit flows. Adiabatic: $\dot{Q} = 0$.

Continuity Eq.6.11: $\dot{m}_1 = \dot{m}_2 = \dot{m}$,

Energy Eq.6.12: $\dot{m}h_1 = \dot{m}h_2 + \dot{W}_C$,

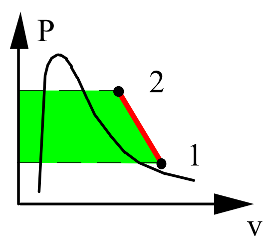
Entropy Eq.9.8: $\dot{m}s_1 + \emptyset = \dot{m}s_2$ (Reversible $\dot{S}_{gen} = 0$)

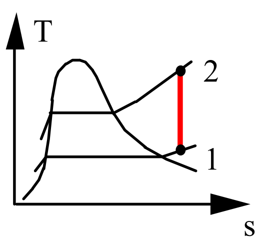
Inlet state: Table B.5.2 $h_1 = 393.84$ kJ/kg, $s_1 = 1.7606$ kJ/kg K

Exit state: $P_2 = 1$ MPa & $s_2 = s_1$ $\Rightarrow$ $h_2 = 434.9$ kJ/kg

$$\dot{W}_c = \dot{m}w_c = \dot{m}(h_1 - h_2) = 0.1 \times (393.84 - 434.9) = \mathbf{-4.1\ kW}$$

Explanation for the work term is in Sect. 9.3 Eq.9.18





9.25

A boiler section boils 3 kg/s saturated liquid water at 2000 kPa to saturated vapor in a reversible constant pressure process. Assume you do not know that there is no work. Prove that there is no shaftwork using the first and second laws of thermodynamics.

Solution:

C.V. Boiler. Steady, single inlet and single exit flows.

Energy Eq.6.13: $h_i + q = w + h_e$;

Entropy Eq.9.8: $s_i + q/T = s_e$

States: Table B.1.2, $T = T_{sat} = 212.42°C = 485.57$ K

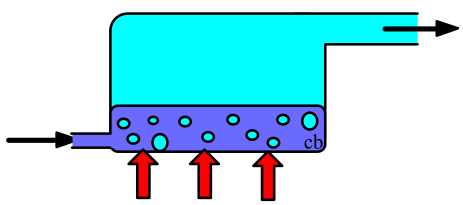
$h_i = h_f = 908.77$ kJ/kg, $s_i = 2.4473$ kJ/kg K

$h_e = h_g = 2799.51$ kJ/kg, $s_e = 6.3408$ kJ/kg K

$q = T(s_e - s_i) = 485.57(6.3408 - 2.4473) =$ **1890.6 kJ/kg**

$w = h_i + q - h_e = 908.77 + 1890.6 - 2799.51 =$ **-0.1 kJ/kg**

It should be zero (non-zero due to round off in values of s, h and T_{sat}).



Often it is a long pipe and not a chamber

9.26

Consider the design of a nozzle in which nitrogen gas flowing in a pipe at 500 kPa, 200°C, and at a velocity of 10 m/s, is to be expanded to produce a velocity of 300 m/s. Determine the exit pressure and cross-sectional area of the nozzle if the mass flow rate is 0.15 kg/s, and the expansion is reversible and adiabatic.

Solution:

C.V. Nozzle. Steady flow, no work out and no heat transfer.

Energy Eq.6.13: $h_i + \mathbf{V}_i^2/2 = h_e + \mathbf{V}_e^2/2$

Entropy Eq.9.8: $s_i + \int dq/T + s_{gen} = s_i + 0 + 0 = s_e$

Properties Ideal gas Table A.5:

$$C_{Po} = 1.042 \frac{\text{kJ}}{\text{kg K}},\ \ R = 0.2968 \frac{\text{kJ}}{\text{kg K}},\ \ k = 1.40$$

$h_e - h_i = C_{Po}(T_e - T_i) = 1.042(T_e - 473.2) = (10^2 - 300^2)/(2\times1000)$

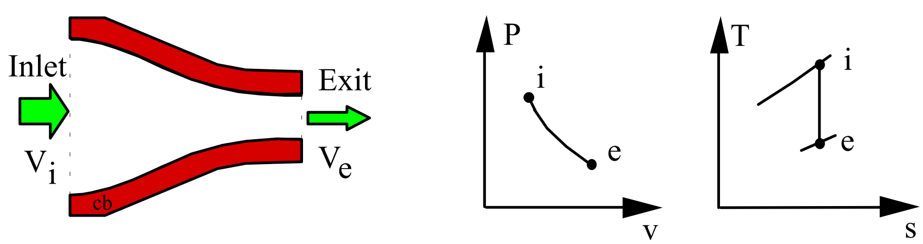
Solving for exit T: $T_e = 430$ K,

Process: $s_i = s_e$ => For ideal gas expressed in Eq.8.32

$$P_e = P_i(T_e/T_i)^{\frac{k}{k-1}} = 500\left(\frac{430}{473.2}\right)^{3.5} = \mathbf{357.6\ kPa}$$

$v_e = RT_e/P_e = (0.2968 \times 430)/357.6 = 0.35689\ \text{m}^3/\text{kg}$

$$A_e = \dot{m}v_e/\mathbf{V}_e = \frac{0.15 \times 0.35689}{300} = \mathbf{1.78 \times 10^{-4}\ m^2}$$



9.27

Atmospheric air at -45°C, 60 kPa enters the front diffuser of a jet engine with a velocity of 900 km/h and frontal area of 1 m^2. After the adiabatic diffuser the velocity is 20 m/s. Find the diffuser exit temperature and the maximum pressure possible.

Solution:

C.V. Diffuser, Steady single inlet and exit flow, no work or heat transfer.

Energy Eq.6.13: $h_i + \mathbf{V}_i^2/2 = h_e + \mathbf{V}_e^2/2$, and $h_e - h_i = C_p(T_e - T_i)$

Entropy Eq.9.8: $s_i + \int dq/T + s_{gen} = s_i + 0 + 0 = s_e$ (Reversible, adiabatic)

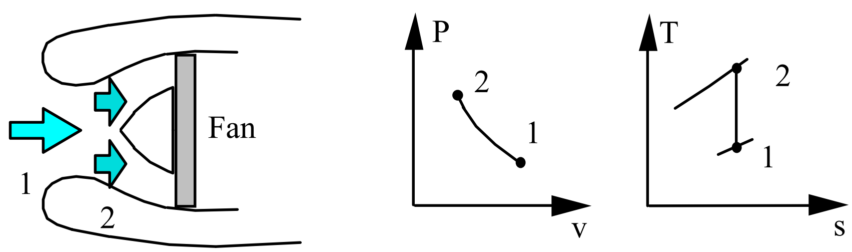
Heat capacity and ratio of specific heats from Table A.5: $C_{Po} = 1.004 \frac{kJ}{kg\ K}$, $k = 1.4$, the energy equation then gives:

$$1.004[\ T_e - (-45)] = 0.5[(900\times1000/3600)^2 - 20^2\ ]/1000 = 31.05\ kJ/kg$$

$$\Rightarrow \quad T_e = -14.05\ °C = \mathbf{259.1\ K}$$

Constant s for an ideal gas is expressed in Eq.8.32:

$$P_e = P_i\ (T_e/T_i)^{\frac{k}{k-1}} = 60\ (259.1/228.1)^{3.5} = \mathbf{93.6\ kPa}$$



9.28

A compressor receives air at 290 K, 100 kPa and a shaft work of 5.5 kW from a gasoline engine. It should deliver a mass flow rate of 0.01 kg/s air to a pipeline. Find the maximum possible exit pressure of the compressor.

Solution:

C.V. Compressor, Steady single inlet and exit flows. Adiabatic: $\dot{Q} = 0$.

Continuity Eq.6.11: $\dot{m}_i = \dot{m}_e = \dot{m}$,

Energy Eq.6.12: $\dot{m}h_i = \dot{m}h_e + \dot{W}_C$,

Entropy Eq.9.8: $\dot{m}s_i + \dot{S}_{gen} = \dot{m}s_e$ (Reversible $\dot{S}_{gen} = 0$)

$$\dot{W}_c = \dot{m}w_c \;\;\Rightarrow\;\; -w_c = -\dot{W}/\dot{m} = 5.5/0.01 = 550 \text{ kJ/kg}$$

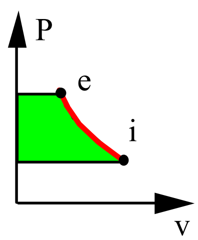
Use constant specific heat from Table A.5, $C_{Po} = 1.004$, $k = 1.4$

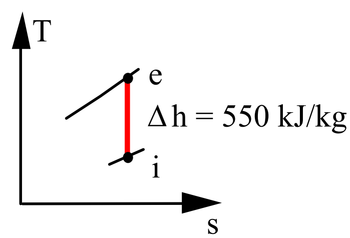
$$h_e = h_i + 550 \;\;\Rightarrow\;\; T_e = T_i + 550/1.004$$

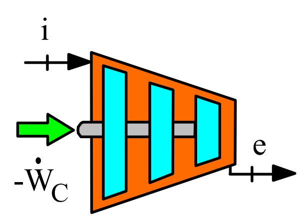
$$T_e = 290 + 550/1.004 = 837.81 \text{ K}$$

$$s_i = s_e \;\;\Rightarrow\;\; P_e = P_i\,(T_e/T_i)^{\frac{k}{k-1}} \qquad \text{Eq.8.32}$$

$$P_e = 100 \times (837.81/290)^{3.5} = \mathbf{4098\ kPa}$$







9.29

A compressor is surrounded by cold R-134a so it works as an isothermal compressor. The inlet state is 0°C, 100 kPa and the exit state is saturated vapor. Find the specific heat transfer and specific work.

Solution:

C.V. Compressor. Steady, single inlet and single exit flows.

Energy Eq.6.13: $h_i + q = w + h_e$;

Entropy Eq.9.8: $s_i + q/T = s_e$

Inlet state: Table B.5.2, $h_i = 403.4$ kJ/kg, $s_i = 1.8281$ kJ/kg K

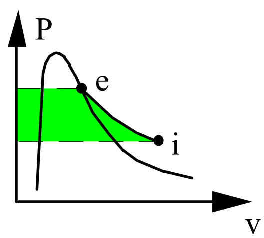
Exit state: Table B.5.1, $h_e = 398.36$ kJ/kg, $s_e = 1.7262$ kJ/kg K

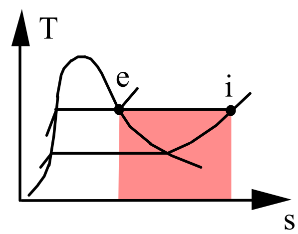
$q = T(s_e - s_i) = 273.15(1.7262 - 1.8281) =$ **- 27.83 kJ/kg**

$w = 403.4 + (-27.83) - 398.36 =$ **-22.8 kJ/kg**

Explanation for the work term is in Sect. 9.3

Eqs. 9.16 and 9.18





9.30

A diffuser is a steady-state device in which a fluid flowing at high velocity is decelerated such that the pressure increases in the process. Air at 120 kPa, 30°C enters a diffuser with velocity 200 m/s and exits with a velocity of 20 m/s. Assuming the process is reversible and adiabatic what are the exit pressure and temperature of the air?

Solution:

C.V. Diffuser, Steady single inlet and exit flow, no work or heat transfer.

Energy Eq.6.13: $h_i + \mathbf{V}_i^2/2 = h_e + \mathbf{V}_e^2/2, \quad \Rightarrow \quad h_e - h_i = C_{Po}(T_e - T_i)$

Entropy Eq.9.8: $s_i + \int dq/T + s_{gen} = s_i + 0 + 0 = s_e$ (Reversible, adiabatic)

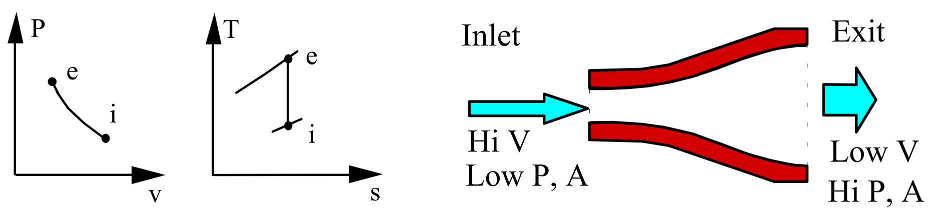
Use constant specific heat from Table A.5, $C_{Po} = 1.004 \frac{kJ}{kg\,K}$, $k = 1.4$

Energy equation then gives:

$C_{Po}(T_e - T_i) = 1.004(T_e - 303.2) = (200^2 - 20^2)/(2\times1000) \quad \Rightarrow \quad T_e = \mathbf{322.9\ K}$

The isentropic process ($s_e = s_i$) gives Eq.8.32

$$P_e = P_i(T_e/T_i)^{\frac{k}{k-1}} = 120(322.9/303.2)^{3.5} = \mathbf{149.6\ kPa}$$



9.31

The exit nozzle in a jet engine receives air at 1200 K, 150 kPa with neglible kinetic energy. The exit pressure is 80 kPa and the process is reversible and adiabatic. Use constant heat capacity at 300 K to find the exit velocity.

Solution:

C.V. Nozzle, Steady single inlet and exit flow, no work or heat transfer.

Energy Eq.6.13: $h_i = h_e + \mathbf{V}_e^2/2 \quad (Z_i = Z_e)$

Entropy Eq.9.8: $s_e = s_i + \int dq/T + s_{gen} = s_i + 0 + 0$

Use constant specific heat from Table A.5, $C_{Po} = 1.004 \frac{kJ}{kg\ K}$, $k = 1.4$

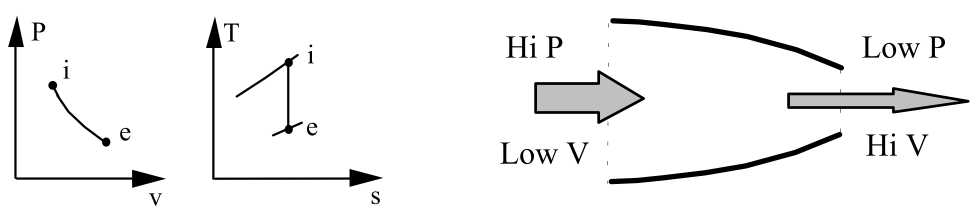
The isentropic process ($s_e = s_i$) gives Eq.8.32

$$=> \qquad T_e = T_i(P_e/P_i)^{\frac{k-1}{k}} = 1200\ (80/150)^{0.2857} = 1002.7\ K$$

The energy equation becomes

$$\mathbf{V}_e^2/2 = h_i - h_e \cong C_P(T_i - T_e)$$

$$\mathbf{V}_e = \sqrt{2\ C_P(T_i - T_e)} = \sqrt{2 \times 1.004(1200\text{-}1002.7) \times 1000} = \mathbf{629.4\ m/s}$$



9.32

Do the previous problem using the air tables in A.7
The exit nozzle in a jet engine receives air at 1200 K, 150 kPa with neglible kinetic energy. The exit pressure is 80 kPa and the process is reversible and adiabatic. Use constant heat capacity at 300 K to find the exit velocity.

Solution:
C.V. Nozzle, Steady single inlet and exit flow, no work or heat transfer.

Energy Eq.6.13: $h_i = h_e + \mathbf{V}_e^2/2 \quad (Z_i = Z_e)$

Entropy Eq.9.8: $s_e = s_i + \int dq/T + s_{gen} = s_i + 0 + 0$

Process: $q = 0, \quad s_{gen} = 0$ as used above leads to $s_e = s_i$

Inlet state: $h_i = 1277.8$ kJ/kg, $s^o_{Ti} = 8.3460$ kJ/kg K

The constant s is rewritten from Eq.8.28 as

$$s^o_{Te} = s^o_{Ti} + R \ln(P_e / P_i) = 8.3460 + 0.287 \ln (80/150) = 8.1656$$

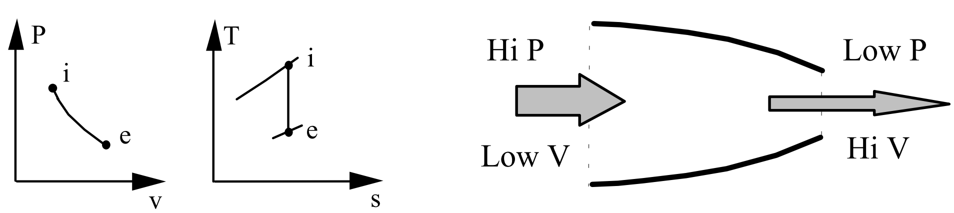
Interpolate in A.7 =>

$$T_e = 1000 + 50 \frac{8.1656 - 8.1349}{8.1908 - 8.1349} = 1027.46 \text{ K}$$

$$h_e = 1046.2 + (1103.5 - 1046.3) \times \frac{8.1656 - 8.1349}{8.1908 - 8.1349} = 1077.7$$

From the energy equation we have $\mathbf{V}_e^2/2 = h_i - h_e$, so then

$$\mathbf{V}_e = \sqrt{2\ (h_i - h_e)} = \sqrt{2(1277.8 - 1077.7) \times 1000} = \mathbf{632.6\ m/s}$$



9.33

An expander receives 0.5 kg/s air at 2000 kPa, 300 K with an exit state of 400 kPa, 300 K. Assume the process is reversible and isothermal. Find the rates of heat transfer and work neglecting kinetic and potential energy changes.

Solution:

C.V. Expander, single steady flow.

Energy Eq.: $\dot{m}h_i + \dot{Q} = \dot{m}h_e + \dot{W}$

Entropy Eq.: $\dot{m}s_i + \dot{Q}/T + \dot{m}s_{gen} = \dot{m}s_e$

Process: T is constant and $s_{gen} = 0$

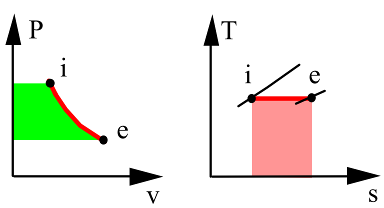
Ideal gas and isothermal gives a change in entropy by Eq. 8.24, so we can solve for the heat transfer

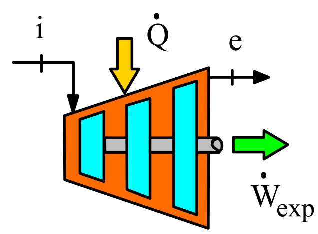
$$\dot{Q} = T\dot{m}(s_e - s_i) = -\dot{m}RT \ln \frac{P_e}{P_i}$$

$$= - 0.5 \times 300 \times 0.287 \times \ln \frac{400}{2000} = \mathbf{69.3\ kW}$$

From the energy equation we get

$$\dot{W} = \dot{m}(h_i - h_e) + \dot{Q} = \dot{Q} = \mathbf{69.3\ kW}$$





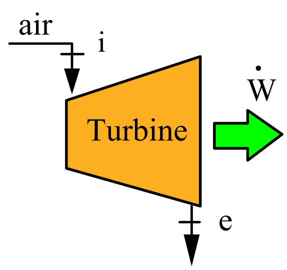
9.34

Air enters a turbine at 800 kPa, 1200 K, and expands in a reversible adiabatic process to 100 kPa. Calculate the exit temperature and the work output per kilogram of air, using

a. The ideal gas tables, Table A.7

b. Constant specific heat, value at 300 K from table A.5

Solution:



C.V. Air turbine.

Adiabatic: $q = 0$, reversible: $s_{gen} = 0$

Energy Eq.6.13: $w_T = h_i - h_e$,

Entropy Eq.9.8: $s_e = s_i$

a) Table A.7: $h_i = 1277.8$ kJ/kg, $s^o_{Ti} = 8.34596$ kJ/kg K

The constant s process is written from Eq.8.28 as

$$\Rightarrow s^o_{Te} = s^o_{Ti} + R \ln(\frac{P_e}{P_i}) = 8.34596 + 0.287 \ln\left(\frac{100}{800}\right) = 7.7492 \text{ kJ/kg K}$$

Interpolate in A.7.1 $\Rightarrow T_e = \mathbf{706\ K}$, $h_e = 719.9$ kJ/kg

$$w = h_i - h_e = \mathbf{557.9\ kJ/kg}$$

b) Table A.5: $C_{Po} = 1.004$ kJ/kg K, $R = 0.287$ kJ/kg K, $k = 1.4$, then from Eq.8.32

$$T_e = T_i\,(P_e/P_i)^{\frac{k-1}{k}} = 1200\left(\frac{100}{800}\right)^{0.286} = \mathbf{662.1\ K}$$

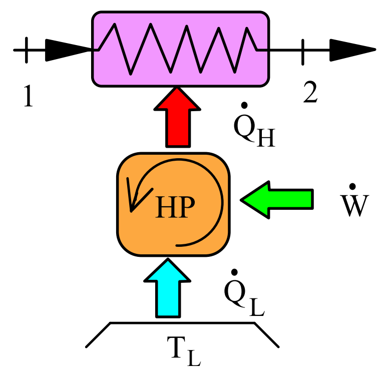
$$w = C_{Po}(T_i - T_e) = 1.004(1200 - 662.1) = \mathbf{539.8\ kJ/kg}$$

9.35

A flow of 2 kg/s saturated vapor R-22 at 500 kPa is heated at constant pressure to 60^{o}C. The heat is supplied by a heat pump that receives heat from the ambient at 300 K and work input, shown in Fig. P9.35. Assume everything is reversible and find the rate of work input.

Solution:

C.V. Heat exchanger



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

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

Table B.4.2:

$h_1 = 250$ kJ/kg, $s_1 = 0.9267$ kJ/kg K

$h_2 = 293.22$ kJ/kg, $s_2 = 1.0696$ kJ/kg K

Notice we can find $\dot{Q}_H$ but the temperature T_H is not constant making it difficult to evaluate the COP of the heat pump.

C.V. Total setup and assume everything is reversible and steady state.

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

Entropy Eq.: $\dot{m}_1 s_1 + \dot{Q}_L / T_L + 0 = \dot{m}_1 s_2$ (T_L is constant, $s_{gen} = 0$)

$$\dot{Q}_L = \dot{m}_1 T_L [s_2 - s_1] = 2 \times 300\ [1.0696 - 0.9267] = 85.74 \text{ kW}$$

$$\dot{W} = \dot{m}_1 [h_2 - h_1] - \dot{Q}_L = 2\ (293.22 - 250) - 85.74 = \mathbf{0.7\ kW}$$

9.36

A reversible steady state device receives a flow of 1 kg/s air at 400 K, 450 kPa and the air leaves at 600 K, 100 kPa. Heat transfer of 800 kW is added from a 1000 K reservoir, 100 kW rejected at 350 K and some heat transfer takes place at 500 K. Find the heat transferred at 500 K and the rate of work produced.

Solution:

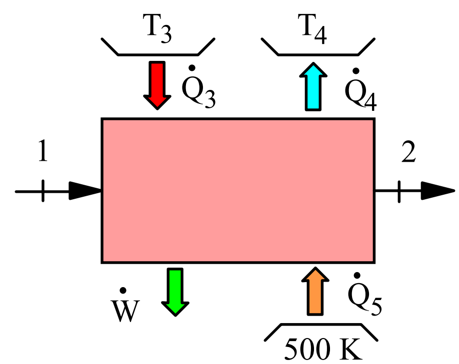
C.V. Device, single inlet and exit flows.

Energy equation, Eq.6.12:

$$\dot{m}h_1 + \dot{Q}_3 - \dot{Q}_4 + \dot{Q}_5 = \dot{m}h_2 + \dot{W}$$

Entropy equation with zero generation, Eq.9.8:

$$\dot{m}s_1 + \dot{Q}_3/T_3 - \dot{Q}_4/T_4 + \dot{Q}_5/T_5 = \dot{m}s_2$$



Solve for the unknown heat transfer using Table A.7.1 and Eq. 8.28 for change in s

$$\dot{Q}_5 = T_5 \ [s_2 - s_1]\dot{m} + \frac{T_5}{T_4}\dot{Q}_4 - \frac{T_5}{T_3}\dot{Q}_3$$

$$= 500 \times 1 \left(7.5764 - 7.1593 - 0.287 \ln \frac{100}{450}\right) + \frac{500}{350} \times 100 - \frac{500}{1000} \times 800$$

$$= 424.4 + 142.8 - 400 = 167.2 \text{ kW}$$

Now the work from the energy equation is

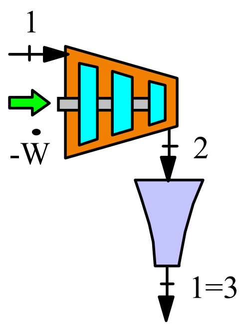
$$\dot{W} = 1 \times (401.3 - 607.3) + 800 - 100 + 167.2 = \mathbf{661.2\ kW}$$

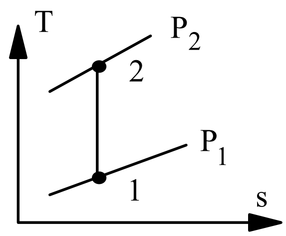
Steady state processes multiple devices and cycles

9.37

Air at 100 kPa, 17°C is compressed to 400 kPa after which it is expanded through a nozzle back to the atmosphere. The compressor and the nozzle are both reversible and adiabatic and kinetic energy in and out of the compressor can be neglected. Find the compressor work and its exit temperature and find the nozzle exit velocity.

Solution:





Separate control volumes around compressor and nozzle. For ideal compressor we have inlet : 1 and exit : 2

Adiabatic : $q = 0$.
Reversible: $s_{gen} = 0$

Energy Eq.6.13: $h_1 + 0 = w_C + h_2$;

Entropy Eq.9.8: $s_1 + 0/T + 0 = s_2$

$$- w_C = h_2 - h_1 , \quad s_2 = s_1$$

Properties Table A.5 air: $C_{Po} = 1.004$ kJ/kg K, $R = 0.287$ kJ/kg K, $k = 1.4$

Process gives constant s (isentropic) which with constant C_{Po} gives Eq.8.32

$$=> \quad T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 290 \ (400/100)^{\ 0.2857} = \mathbf{430.9\ K}$$

$$\Rightarrow \quad -w_C = C_{Po}(T_2 - T_1) = 1.004\ (430.9 - 290) = \mathbf{141.46\ kJ/kg}$$

The ideal nozzle then expands back down to P_1 (constant s) so state 3 equals state 1. The energy equation has no work but kinetic energy and gives:

$$\tfrac{1}{2}\mathbf{V}^2 = h_2 - h_1 = -w_C = 141\ 460 \text{ J/kg} \quad \text{(remember conversion to J)}$$

$$\Rightarrow \quad \mathbf{V}_3 = \sqrt{2\times141460} = \mathbf{531.9\ m/s}$$

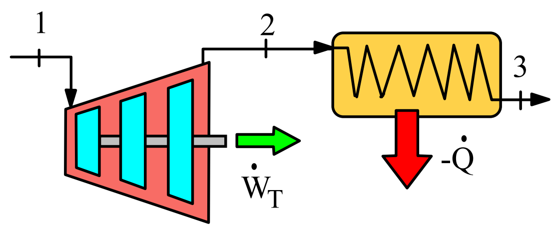
9.38

A small turbine delivers 150 kW and is supplied with steam at 700°C, 2 MPa. The exhaust passes through a heat exchanger where the pressure is 10 kPa and exits as saturated liquid. The turbine is reversible and adiabatic. Find the specific turbine work, and the heat transfer in the heat exchanger.

Solution:

Continuity Eq.6.11: Steady

$\dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}$



Turbine: Energy Eq.6.13: $w_T = h_1 - h_2$

Entropy Eq.9.8: $s_2 = s_1 + s_{T\ gen}$

Inlet state: Table B.1.3 $h_1 = 3917.45$ kJ/kg, $s_1 = 7.9487$ kJ/kg K

Ideal turbine $s_{T\ gen} = 0$, $s_2 = s_1 = 7.9487 = s_{f2} + x\ s_{fg2}$

State 3: P = 10 kPa, $s_2 < s_g$ => saturated 2-phase in Table B.1.2

$\Rightarrow\ x_{2,s} = (s_1 - s_{f2})/s_{fg2} = (7.9487 - 0.6492)/7.501 = 0.9731$

$\Rightarrow\ h_{2,s} = h_{f2} + x\ h_{fg2} = 191.8 + 0.9731 \times 2392.8 = 2520.35$ kJ/kg

$w_{T,s} = h_1 - h_{2,s} =$ **1397.05 kJ/kg**

$\dot{m} = \dot{W} / w_{T,s} = 150 / 1397 = 0.1074$ kg/s

Heat exchanger:

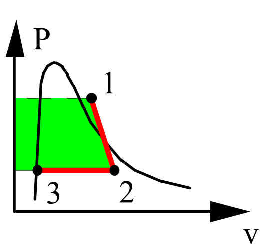
Energy Eq.6.13: $q = h_3 - h_2$,

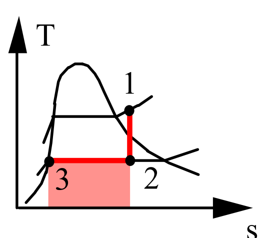
Entropy Eq.9.8: $s_3 = s_2 + \int dq/T + s_{He\ gen}$

$q = h_3 - h_{2,s} = 191.83 - 2520.35 =$ **-2328.5 kJ/kg**

$\dot{Q} = \dot{m}\ q = 0.1074 \times (-2328.5) =$ **- 250 kW**

Explanation for the work term is in Sect. 9.3, Eq.9.18





9.39

One technique for operating a steam turbine in part-load power output is to throttle the steam to a lower pressure before it enters the turbine, as shown in Fig. P9.39. The steamline conditions are 2 MPa, 400°C, and the turbine exhaust pressure is fixed at 10 kPa. Assuming the expansion inside the turbine to be reversible and adiabatic, determine

a. The full-load specific work output of the turbine

b. The pressure the steam must be throttled to for 80% of full-load output

c. Show both processes in a *T–s* diagram.

Solution:

a) C.V Turbine. Full load reversible and adiabatic

Entropy Eq.9.8 reduces to constant s so from Table B.1.3 and B.1.2

$$s_3 = s_1 = 7.1271 = 0.6493 + x_{3a} \times 7.5009$$

$$=> \quad x_{3a} = 0.8636$$

$$h_{3a} = 191.83 + 0.8636 \times 2392.8 = 2258.3 \text{ kJ/kg}$$

Energy Eq.6.13 for turbine

$${}_1w_{3a} = h_1 - h_{3a} = 3247.6 - 2258.3 = \mathbf{989.3\ kJ/kg}$$

b) The energy equation for the part load operation and notice that we have constant h in the throttle process.

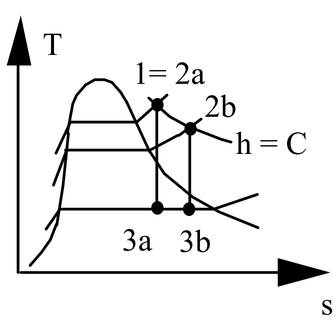
$$w_T = 0.80 \times 989.3 = 791.4 = 3247.6 - h_{3b}$$

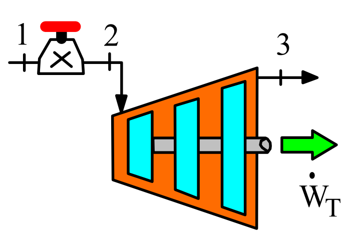
$$h_{3b} = 2456.2 = 191.83 + x_{3b} \times 2392.8 \quad => \quad x_{3b} = 0.9463$$

$$s_{3b} = 0.6492 + 0.9463 \times 7.501 = 7.7474 \text{ kJ/kg}$$

$$\left.\begin{array}{l} s_{2b} = s_{3b} = 7.7474 \\ h_{2b} = h_1 = 3247.6 \end{array}\right\} \rightarrow \begin{array}{l} P_{2b} = \mathbf{510\ kPa} \\ \&\ T_{2b} = 388.4°C \end{array}$$

c)

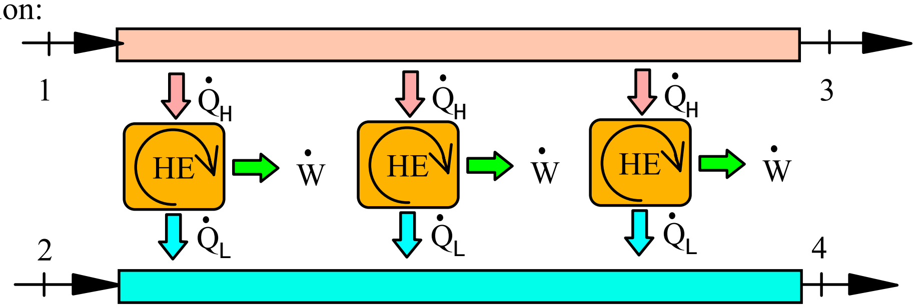




9.40

Two flows of air both at 200 kPa, one has 1 kg/s at 400 K and the other has 2 kg/s at 290 K. The two lines exchange energy through a number of ideal heat engines taking energy from the hot line and rejecting it to the colder line. The two flows then leave at the same temperature. Assume the whole setup is reversible and find the exit temperature and the total power out of the heat engines.

Solution:



C.V. Total setup

Energy Eq.6.10: $\dot m_1 h_1 + \dot m_2 h_2 = \dot m_1 h_3 + \dot m_2 h_4 + \dot W_{TOT}$

Entropy Eq.9.7: $\dot m_1 s_1 + \dot m_2 s_2 + \dot S_{gen} + \int d\dot Q/T = \dot m_1 s_3 + \dot m_2 s_4$

Process: Reversible $\dot S_{gen} = 0$ Adiabatic $\dot Q = 0$

Assume the exit flow has the same pressure as the inlet flow then the pressure part of the entropy cancels out and we have

Exit same T, P => $h_3 = h_4 = h_e$; $s_3 = s_4 = s_e$

$$\dot m_1 h_1 + \dot m_2 h_2 = \dot m_{TOT} h_e + \dot W_{TOT}$$

$$\dot m_1 s_1 + \dot m_2 s_2 = \dot m_{TOT} s_e$$

$$s_e = \frac{\dot m_1}{\dot m_{TOT}} s_1 + \frac{\dot m_2}{\dot m_{TOT}} s_2 = \frac{1}{3} \times 7.1593 + \frac{2}{3} \times 6.8352 = 6.9432$$

Table A.7: => $T_e \cong 323$ K; $h_e = 323.6$

$$\dot W_{TOT} = \dot m_1 (h_1 - h_e) + \dot m_2 (h_2 - h_e)$$
$$= 1(401.3 - 323.6) + 2(290.43 - 323.6) = \mathbf{11.36\ kW}$$

Note: The solution using constant heat capacity writes the entropy equation using Eq.8.25, the pressure terms cancel out so we get

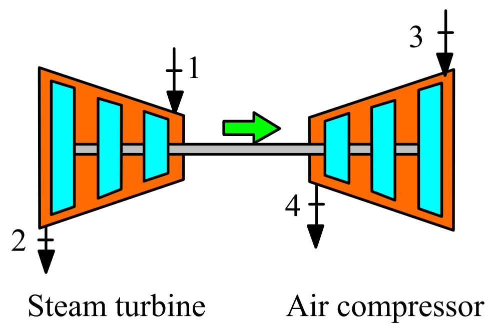
$$\tfrac{1}{3} C_p \ln(T_e/T_1) + \tfrac{2}{3} C_p \ln(T_e/T_2) = 0 \quad => \ln T_e = (\ln T_1 + 2 \ln T_2)/3$$

9.41

A certain industrial process requires a steady supply of saturated vapor steam at 200 kPa, at a rate of 0.5 kg/s. Also required is a steady supply of compressed air at 500 kPa, at a rate of 0.1 kg/s. Both are to be supplied by the process shown in Fig. P9.41. Steam is expanded in a turbine to supply the power needed to drive the air compressor, and the exhaust steam exits the turbine at the desired state. Air into the compressor is at the ambient conditions, 100 kPa, 20°C. Give the required steam inlet pressure and temperature, assuming that both the turbine and the compressor are reversible and adiabatic.

Solution:

C.V. Each device. Steady flow. Both adiabatic ($q = 0$) and reversible ($s_{gen} = 0$).



Compressor: $s_4 = s_3 \quad => \quad T_4 = T_3(P_4/P_3)^{\frac{k-1}{k}} = 293.2\left(\frac{500}{100}\right)^{0.286} = 464.6 \text{ K}$

$\dot{W}_C = \dot{m}_3(h_3 - h_4) = 0.1 \times 1.004(293.2 - 464.6) = -17.2 \text{ kW}$

Turbine: Energy: $\dot{W}_T = +17.2 \text{ kW} = \dot{m}_1(h_1 - h_2)$; Entropy: $s_2 = s_1$

Table B.1.2: $P_2 = 200 \text{ kPa}, x_2 = 1 \quad => \quad h_2 = 2706.6 \text{ kJ/kg}, \ s_2 = 7.1271$

$h_1 = 2706.6 + 17.2/0.5 = 2741.0 \text{ kJ/kg}$

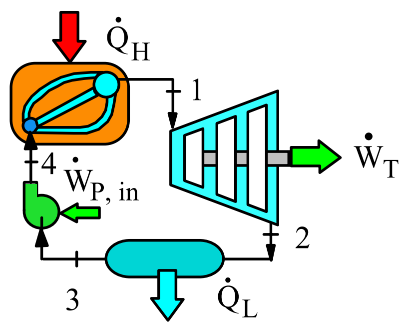
$s_1 = s_2 = 7.1271 \text{ kJ/kg K} \qquad \text{At } h_1, s_1 \rightarrow \begin{array}{l} P_1 = \mathbf{242 \text{ kPa}} \\ T_1 = \mathbf{138.3°C} \end{array}$

9.42

Consider a steam turbine power plant operating near critical pressure, as shown in Fig. P9.42. As a first approximation, it may be assumed that the turbine and the pump processes are reversible and adiabatic. Neglecting any changes in kinetic and potential energies, calculate

a. The specific turbine work output and the turbine exit state
b. The pump work input and enthalpy at the pump exit state
c. The thermal efficiency of the cycle

Solution:



$P_1 = P_4 = 20$ MPa
$T_1 = 700$ °C
$P_2 = P_3 = 20$ kPa
$T_3 = 40$ °C

a) State 1: (P, T) Table B.1.3 $h_1 = 3809.1$ kJ/kg, $s_1 = 6.7993$ kJ/kg K

C.V. Turbine.

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

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

$h_2 = 251.4 + 0.8433 \times 2358.33 = \mathbf{2240.1}$

Energy Eq.6.13: $w_T = h_1 - h_2 = \mathbf{1569\ kJ/kg}$

b)

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

$h_3 = 167.5$ kJ/kg, $v_3 = 0.001008$ m^3/kg

Property relation in Eq.9.13 gives work from Eq.9.18 as

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

$h_4 = h_3 - w_P = 167.5 + 20.1 = \mathbf{187.6\ kJ/kg}$

c) The heat transfer in the boiler is from energy Eq.6.13

$q_{boiler} = h_1 - h_4 = 3809.1 – 187.6 = 3621.5$ kJ/kg

$w_{net} = 1569 – 20.1 = \mathbf{1548.9\ kJ/kg}$

$$\eta_{TH} = w_{net}/q_{boiler} = \frac{1548.9}{3621.5} = \mathbf{0.428}$$

9.43

A turbo charger boosts the inlet air pressure to an automobile engine. It consists of an exhaust gas driven turbine directly connected to an air compressor, as shown in Fig. P9.43. For a certain engine load the conditions are given in the figure. Assume that both the turbine and the compressor are reversible and adiabatic having also the same mass flow rate. Calculate the turbine exit temperature and power output. Find also the compressor exit pressure and temperature.

Solution:

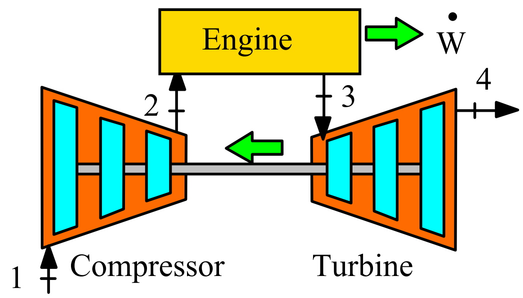
CV: Turbine, Steady single inlet and exit flows,

Process: adiabatic: $q = 0$,

reversible: $s_{gen} = 0$

EnergyEq.6.13: $w_T = h_3 - h_4$,

Entropy Eq.9.8: $s_4 = s_3$



The property relation for ideal gas gives Eq.8.32, k from Table A.5

$$s_4 = s_3 \;\rightarrow\; T_4 = T_3(P_4/P_3)^{\frac{k-1}{k}} = 923.2 \left(\frac{100}{170}\right)^{0.286} = \mathbf{793.2\ K}$$

The energy equation is evaluated with specific heat from Table A.5

$$w_T = h_3 - h_4 = C_{P0}(T_3 - T_4) = 1.004(923.2 - 793.2) = 130.5 \text{ kJ/kg}$$

$$\dot{W}_T = \dot{m}w_T = \mathbf{13.05\ kW}$$

C.V. Compressor, steady 1 inlet and 1 exit, same flow rate as turbine.

Energy Eq.6.13: $-w_C = h_2 - h_1$,

Entropy Eq.9.8: $s_2 = s_1$

Express the energy equation for the shaft and compressor having the turbine power as input with the same mass flow rate so we get

$$-w_C = w_T = 130.5 = C_{P0}(T_2 - T_1) = 1.004(T_2 - 303.2)$$

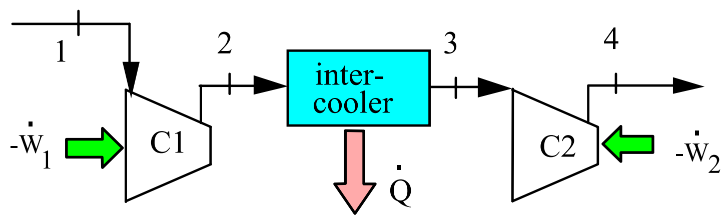
$$T_2 = \mathbf{433.2\ K}$$

The property relation for $s_2 = s_1$ is Eq.8.32 and inverted as

$$P_2 = P_1(T_2/T_1)^{\frac{k}{k-1}} = 100\left(\frac{433.2}{303.2}\right)^{3.5} = \mathbf{348.7\ kPa}$$

9.44

A two-stage compressor having an interstage cooler takes in air, 300 K, 100 kPa, and compresses it to 2 MPa, as shown in Fig. P9.44. The cooler then cools the air to 340 K, after which it enters the second stage, which has an exit pressure of 15.74 MPa. Both stages are adiabatic, and reversible. Find q in the cooler, total specific work, and compare this to the work required with no intercooler.
Solution:



C.V.: Stage 1 air, Steady flow

Process: adibatic: $q = 0$, reversible: $s_{gen} = 0$

Energy Eq.6.13: $-w_{C1} = h_2 - h_1$, Entropy Eq.9.8: $s_2 = s_1$

Assume constant $C_{P0} = 1.004$ from A.5 and isentropic leads to Eq.8.32

$$T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 300(2000/100)^{0.286} = 706.7 \text{ K}$$

$$w_{C1} = h_1 - h_2 = C_{P0}(T_1 - T_2) = 1.004(300 - 706.7) = \mathbf{-408.3 \ kJ/kg}$$

C.V. Intercooler, no work and no changes in kinetic or potential energy.

$$q_{23} = h_3 - h_2 = C_{P0}(T_3 - T_2) = 1.004(340 - 706.7) = \mathbf{-368.2 \ kJ/kg}$$

C.V. Stage 2. Analysis the same as stage 1. So from Eq.8.32

$$T_4 = T_3(P_4/P_3)^{\frac{k-1}{k}} = 340(15.74/2)^{0.286} = 613.4 \text{ K}$$

$$w_{C2} = h_3 - h_4 = C_{P0}(T_3 - T_4) = 1.004(340 - 613.4) = \mathbf{-274.5 \ kJ/kg}$$

Same flow rate through both stages so the total work is the sum of the two

$$w_{comp} = w_{C1} + w_{C2} = -408.3 - 274.5 = \mathbf{-682.8 \ kJ/kg}$$

For no intercooler (P_2 = 15.74 MPa) same analysis as stage 1. So Eq.8.32

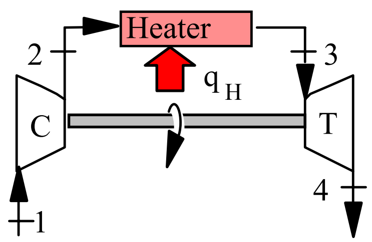
$$T_2 = 300(15740/100)^{0.286} = 1274.9 \text{ K}$$

$$w_{comp} = 1.004(300 - 1274.9) = \mathbf{-978.8 \ kJ/kg}$$

9.45

A heat-powered portable air compressor consists of three components: (a) an adiabatic compressor; (b) a constant pressure heater (heat supplied from an outside source); and (c) an adiabatic turbine. Ambient air enters the compressor at 100 kPa, 300 K, and is compressed to 600 kPa. All of the power from the turbine goes into the compressor, and the turbine exhaust is the supply of compressed air. If this pressure is required to be 200 kPa, what must the temperature be at the exit of the heater?

Solution:



$P_2 = 600$ kPa, $P_4 = 200$ kPa

Adiabatic and reversible compressor:

Process: $q = 0$ and $s_{gen} = 0$

Energy Eq.6.13: $h - w_c = h_2$

Entropy Eq.9.8: $s_2 = s_1$

For constant specific heat the isentropic relation becomes Eq.8.32

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 300(6)^{0.2857} = 500.8 \text{ K}$$

$$-w_c = C_{P0}(T_2 - T_1) = 1.004(500.8 - 300) = 201.5 \text{ kJ/kg}$$

Adiabatic and reversible turbine: $q = 0$ and $s_{gen} = 0$

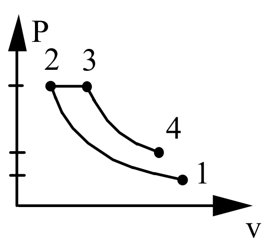
Energy Eq.6.13: $h_3 = w_T + h_4$; Entropy Eq.9.8: $s_4 = s_3$

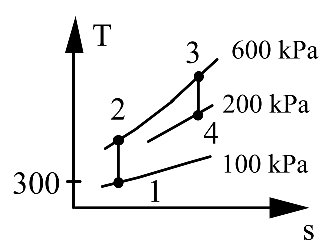
For constant specific heat the isentropic relation becomes Eq.8.32

$$T_4 = T_3(P_4/P_3)^{\frac{k-1}{k}} = T_3(200/600)^{0.2857} = 0.7304\ T_3$$

Energy Eq. for shaft: $-w_c = w_T = C_{P0}(T_3 - T_4)$

$$201.5 = 1.004\ T_3(1 - 0.7304) \quad => \quad T_3 = \mathbf{744.4\ K}$$





9.46

A certain industrial process requires a steady 0.5 kg/s supply of compressed air at 500 kPa, at a maximum temperature of 30°C. This air is to be supplied by installing a compressor and aftercooler. Local ambient conditions are 100 kPa, 20°C. Using an reversible compressor, determine the power required to drive the compressor and the rate of heat rejection in the aftercooler.

Solution:

Air Table A.5: $R = 0.287$ kJ/kg-K, $C_p = 1.004$ kJ/kg K, $k = 1.4$

State 1: $T_1 = T_o = 20^oC$, $P_1 = P_o = 100$ kPa, $\dot{m} = 0.5$ kg/s

State 2: $P_2 = P_3 = 500$ kPa

State 3: $T_3 = 30^oC$, $P_3 = 500$ kPa

Compressor: Assume Isentropic (adiabatic $q = 0$ and reversible $s_{gen} = 0$)
From entropy equation Eq.9.8 this gives constant s which is expressed for an ideal gas in Eq.8.32

$$T_2 = T_1\,(P_2/P_1)^{\frac{k-1}{k}} = 293.15\,(500/100)^{0.2857} = 464.6 \text{ K}$$

1^{st} Law Eq.6.13: $q_c + h_1 = h_2 + w_c$; $q_c = 0$,

assume constant specific heat from Table A.5

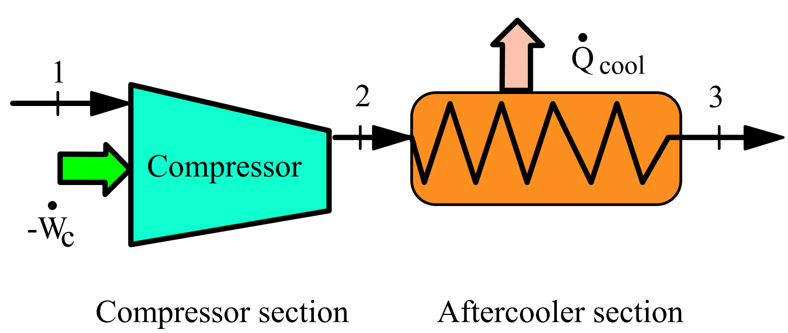
$$w_c = C_p(T_1 - T_2) = -172.0 \text{ kJ/kg}$$

$$\dot{W}_C = \dot{m}w_C = \mathbf{-86\ kW}$$

Aftercooler Energy Eq.6.13: $q + h_2 = h_3 + w$; $w = 0$,

assume constant specific heat

$$q = C_p(T_3 - T_2) = -205 \text{ kJ/kg}, \quad \dot{Q} = \dot{m}q = \mathbf{-102.5\ kW}$$



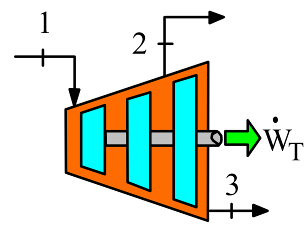
Steady state irreversible processes

9.47

Analyze the steam turbine described in Problem 6.78. Is it possible?

Solution:

C.V. Turbine. Steady flow and adiabatic.



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

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

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

States from Table B.1.3: $s_1 = 6.6775$, $s_2 = 6.9562$, $s_3 = 7.14413$ kJ/kg K

$$\dot{S}_{gen} = 20\times6.9562 + 80\times7.14413 - 100\times6.6775 = \mathbf{42.9\ kW/K} \quad \mathbf{> 0}$$

Since it is positive => **possible.**

Notice the entropy is increasing through turbine: $s_1 < s_2 < s_3$

9.48

Carbon dioxide at 300 K, 200 kPa is brought through a steady device where it is heated to 500 K by a 600 K reservoir in a constant pressure process. Find the specific work, specific heat transfer and specific entropy generation.

Solution:

C.V. Heater and walls out to the source. Steady single inlet and exit flows.

Since the pressure is constant and there are no changes in kinetic or potential energy between the inlet and exit flows the work is zero. **w = 0**

Continuity Eq.6.11: $\dot{m}_i = \dot{m}_e = \dot{m}$

Energy Eq.6.13: $h_i + q = h_e$

Entropy Eq.9.8, 9.23: $s_i + \int dq/T + s_{gen} = s_e = s_i + q/T_{source} + s_{gen}$

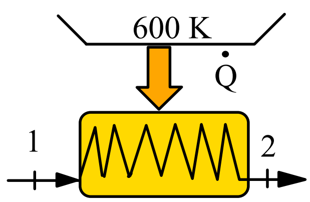
Properties are from Table A.8 so the energy equation gives

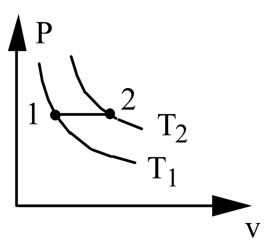
$q = h_e - h_i = 401.52 - 214.38 =$ **187.1 kJ/kg**

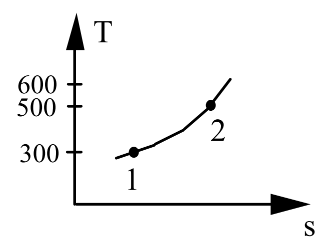
From the entropy equation

$s_{gen} = s_e - s_i - q/T_{source} = (5.3375 - 4.8631) - 187.1/600$

$= 0.4744 - 0.3118 =$ **0.1626 kJ/kg K**







9.49

Consider the steam turbine in Example 6.6. Is this a reversible process?

Solution:

At the given states

Table B.1.3: $s_i = 6.9552$ kJ/kg K; $s_e = 7.3593$ kJ/kg K

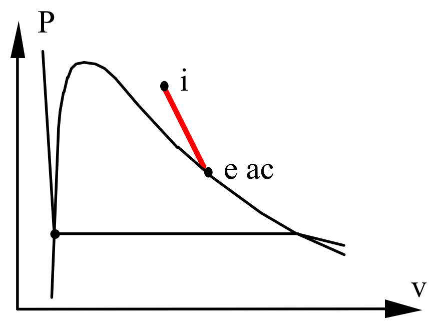
Do the second law for the turbine, Eq.9.8

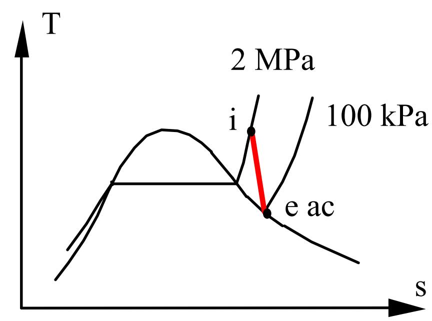
$$\dot{m}_e s_e = \dot{m}_i s_i + \int d\dot{Q}/T + \dot{S}_{gen}$$

$$s_e = s_i + \int dq/T + s_{gen}$$

$$s_{gen} = s_e - s_i - \int dq/T = 7.3593 - 6.9552 - (\text{negative}) > 0$$

Entropy goes up even if q goes out. **This is an irreversible process**.





9.50

The throttle process described in Example 6.5 is an irreversible process. Find the entropy generation per kg ammonia in the throttling process.

Solution:

The process is adiabatic and irreversible. The consideration with the energy given in the example resulted in a constant h and two-phase exit flow.

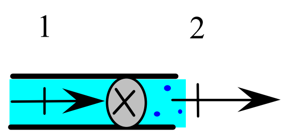
Table B.2.1: $s_i = 1.2792$ kJ/kg K

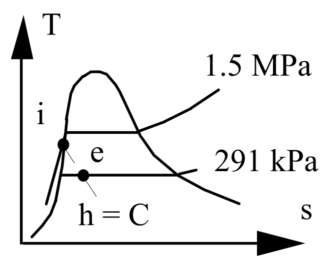
Table B.2.1: $s_e = s_f + x_e\, s_{fg} = 0.5408 + 0.1638 \times 4.9265$

$= 1.34776$ kJ/kg K

We assumed no heat transfer so the entropy equation Eq.9.8 gives

$s_{gen} = s_e - s_i - \int dq/T = 1.34776 - 1.2792 - 0 =$ **0.0686 kJ/kg K**





9.51

A geothermal supply of hot water at 500 kPa, 150°C is fed to an insulated flash evaporator at the rate of 1.5 kg/s. A stream of saturated liquid at 200 kPa is drained from the bottom of the chamber and a stream of saturated vapor at 200 kPa is drawn from the top and fed to a turbine. Find the rate of entropy generation in the flash evaporator.

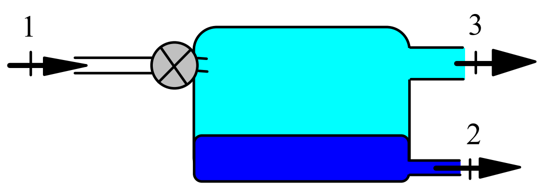
Solution:

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

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

Entropy Eq.9.7: $\dot{m}_1 s_1 + \dot{S}_{gen} + \int d\dot{Q}/T \;\; = \dot{m}_2 s_2 + \dot{m}_3 s_3$

Process: $\dot{Q} = 0$, irreversible (throttle)



Two-phase out of the valve. The liquid drops to the bottom.

B.1.1 $h_1 = 632.18$ kJ/kg, $s_1 = 1.8417$ kJ/kg K

B.1.2 $h_3 = 2706.63$ kJ/kg, $s_3 = 7.1271$ kJ/kg K,

$h_2 = 504.68$ kJ/kg, $s_2 = 1.53$ kJ/kg K

From the energy equation we solve for the flow rate

$$\dot{m}_3 = \dot{m}_1(h_1 - h_2)/(h_3 - h_2) = 1.5 \times 0.0579 = 0.08685 \text{ kg/s}$$

Continuity equation gives

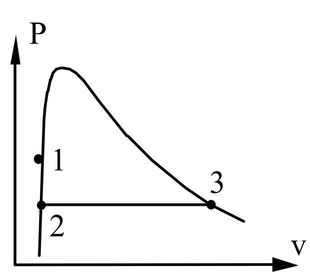
$$\dot{m}_2 = \dot{m}_1 - \dot{m}_2 = 1.41315 \text{ kg/s}$$

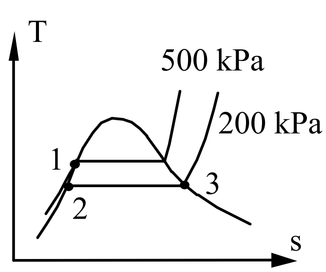
Entropy equation now leads to

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

$$= 1.41315 \times 1.53 + 0.08685 \times 7.127 - 1.5 \times 1.8417$$

$$= \mathbf{0.017 \text{ kW/K}}$$





9.52

Two flowstreams of water, one at 0.6 MPa, saturated vapor, and the other at 0.6 MPa, 600°C, mix adiabatically in a steady flow process to produce a single flow out at 0.6 MPa, 400°C. Find the total entropy generation for this process.

Solution:

1: B.1.2 $h_1 = 2756.8$ kJ/kg, $s_1 = 6.760$ kJ/kg K
2: B.1.3 $h_2 = 3700.9$ kJ/kg, $s_2 = 8.2674$ kJ/kg K
3: B.1.3 $h_3 = 3270.3$ kJ/kg, $s_3 = 7.7078$ kJ/kg K

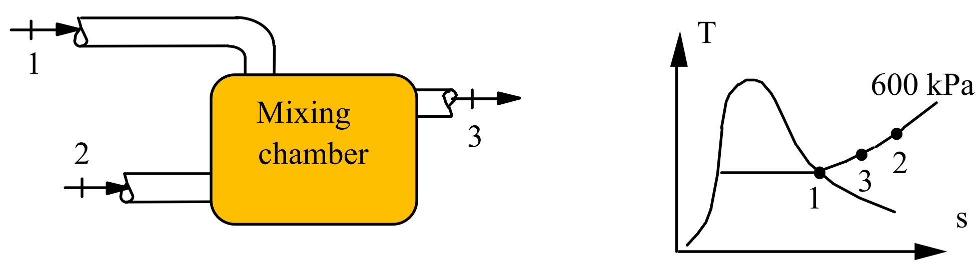
Continuity Eq.6.9: $\dot{m}_3 = \dot{m}_1 + \dot{m}_2,$

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

$$=> \quad \dot{m}_1/\dot{m}_3 = (h_3 - h_2) / (h_1 - h_2) = 0.456$$

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

$$\dot{S}_{gen}/\dot{m}_3 = s_3 - (\dot{m}_1/\dot{m}_3)\, s_1 - (\dot{m}_2/\dot{m}_3)\, s_2$$
$$= 7.7078 - 0.456 \times 6.760 - 0.544 \times 8.2674 = \mathbf{0.128\ kJ/kg\ K}$$



The mixing process generates entropy. The two inlet flows could have exchanged energy (they have different T) through some heat engines and produced work, the process failed to do that, thus irreversible.

9.53

A condenser in a power plant receives 5 kg/s steam at 15 kPa, quality 90% and rejects the heat to cooling water with an average temperature of 17°C. Find the power given to the cooling water in this constant pressure process and the total rate of enropy generation when condenser exit is saturated liquid.

Solution:

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

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

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

Properties are from Table B.1.2

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

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

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

$\dot{S}_{gen} = \dot{m}\,(s_e - s_i) + \dot{Q}_{out}/T$

$= 5(0.7548 - 7.283) + 10679/(273 + 17)$

$= -32.641 + 36.824 = \mathbf{4.183\ kW/K}$

9.54

A mixing chamber receives 5 kg/min ammonia as saturated liquid at −20°C from one line and ammonia at 40°C, 250 kPa from another line through a valve. The chamber also receives 325 kJ/min energy as heat transferred from a 40°C reservoir. This should produce saturated ammonia vapor at −20°C in the exit line. What is the mass flow rate in the second line and what is the total entropy generation in the process?

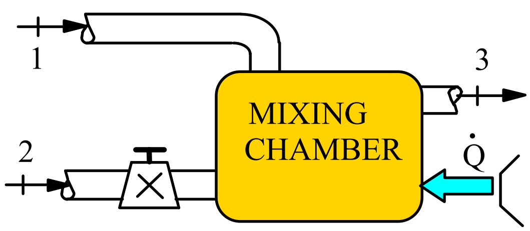
Solution:

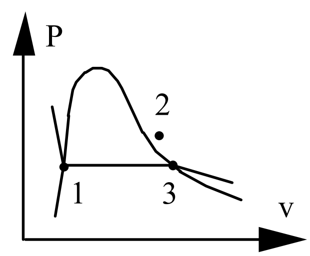
CV: Mixing chamber out to reservoir

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

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

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





From the energy equation:

$$\dot{m}_2 = \left[(\dot{m}_1(h_1 - h_3) + \dot{Q}\right]/(h_3 - h_2)$$

$$= \left[5 \times (89.05 - 1418.05) + 325\right] / (1418.05 - 1551.7)$$

$$= \mathbf{47.288\ kg/min} \quad \Rightarrow \quad \dot{m}_3 = 52.288 \text{ kg/min}$$

$$\dot{S}_{gen} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2 - \dot{Q}/T_{res}$$

$$= 52.288 \times 5.6158 - 5 \times 0.3657 - 47.288 \times 5.9599 - 325/313.15$$

$$= \mathbf{8.94\ kJ/K\ min}$$

9.55

A heat exchanger that follows a compressor receives 0.1 kg/s air at 1000 kPa, 500 K and cools it in a constant pressure process to 320 K. The heat is absorbed by ambient ait at 300 K. Find the total rate of entropy generation.

Solution:

C.V. Heat exchanger to ambient, steady constant pressure so no work.

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

Entropy Eq.9.8, 9.23: $\dot{m}s_i + \dot{S}_{gen} = \dot{m}s_e + \dot{Q}_{out}/T$

Using Table A.5 and Eq.8.25 for change in s

$$\dot{Q}_{out} = \dot{m}(h_i - h_e) = \dot{m}C_{Po}(T_i - T_e) = 0.1 \times 1.004(500 - 320) = 18.07 \text{ kW}$$

$$\dot{S}_{gen} = \dot{m}(s_e - s_i) + \dot{Q}_{out}/T = \dot{m}C_{Po} \ln(T_e/T_i) + \dot{Q}_{out}/T$$
$$= 0.1 \times 1.004 \ln(320/500) + 18.07/300$$
$$= \mathbf{0.0154\ kW/K}$$

Using Table A.7.1 and Eq. 8.28 for change in entropy

$h_{500} = 503.36$ kJ/kg, $h_{320} = 320.58$ kJ/kg;

$s_{T500} = 7.38692$ kJ/kg K, $s_{T320} = 6.93413$ kJ/kg K

$$\dot{Q}_{out} = \dot{m}(h_i - h_e) = 0.1\ (503.36 - 320.58) = 18.28 \text{ kW}$$

$$\dot{S}_{gen} = \dot{m}(s_e - s_i) + \dot{Q}_{out}/T$$
$$= 0.1(6.93413 - 7.38692) + 18.28/300$$
$$= \mathbf{0.0156\ kW/K}$$

9.56

Air at 327°C, 400 kPa with a volume flow 1 m^3/s runs through an adiabatic turbine with exhaust pressure of 100 kPa. Neglect kinetic energies and use constant specific heats. Find the lowest and highest possible exit temperature. For each case find also the rate of work and the rate of entropy generation.

Solution:

C.V Turbine. Steady single inlet and exit flows, q = 0.

Inlet state: (T, P) $\quad v_i = RT_i/P_i = 0.287 \times 600/400 = 0.4305\ m^3/kg$

$$\dot{m} = \dot{V}/v_i = 1/0.4305 = 2.323\ kg/s$$

The lowest exit T is for maximum work out i.e. reversible case

Process: Reversible and adiabatic => constant s from Eq.9.8

Eq.8.32: $\quad T_e = T_i(P_e/P_i)^{\frac{k-1}{k}} = 600 \times (100/400)^{0.2857} = \mathbf{403.8\ K}$

$\Rightarrow \quad w = h_i - h_e = C_{Po}(T_i - T_e) = 1.004 \times (600 - 403.8) = 197\ kJ/kg$

$\dot{W}_T = \dot{m}w = 2.323 \times 197 = \mathbf{457.6\ kW}$ and $\dot{\mathbf{S}}_{\mathbf{gen}} = \mathbf{0}$

Highest exit T occurs when there is no work out, throttling

$q = \varnothing;\ \ \mathbf{w = \varnothing} \quad \Rightarrow \quad h_i - h_e = 0 \quad \Rightarrow \quad T_e = T_i = \mathbf{600\ K}$

$$\dot{S}_{gen} = \dot{m}(s_e - s_i) = -\dot{m}R \ln \frac{P_e}{P_i} = -2.323 \times 0.287 \ln \frac{100}{400} = \mathbf{0.924\ kW/K}$$

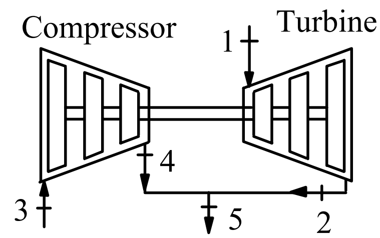
9.57

In a heat-driven refrigerator with ammonia as the working fluid, a turbine with inlet conditions of 2.0 MPa, 70°C is used to drive a compressor with inlet saturated vapor at –20°C. The exhausts, both at 1.2 MPa, are then mixed together. The ratio of the mass flow rate to the turbine to the total exit flow was measured to be 0.62. Can this be true?

Solution:

Assume the compressor and the turbine are both adiabatic.

C.V. Total:



Continuity Eq.6.11: $\dot{m}_5 = \dot{m}_1 + \dot{m}_3$

Energy Eq.6.10: $\dot{m}_5 h_5 = \dot{m}_1 h_1 + \dot{m}_3 h_3$

Entropy: $\dot{m}_5 s_5 = \dot{m}_1 s_1 + \dot{m}_3 s_3 + \dot{S}_{C.V.,gen}$

$$s_5 = y s_1 + (1\text{-}y) s_3 + \dot{S}_{C.V.,gen}/\dot{m}_5$$

Assume $y = \dot{m}_1/\dot{m}_5 = 0.62$

State 1: Table B.2.2 $h_1 = 1542.7$ kJ/kg, $s_1 = 4.982$ kJ/kg K,

State 3: Table B.2.1 $h_3 = 1418.1$ kJ/kg, $s_3 = 5.616$ kJ/kg K

Solve for exit state 5 in the energy equation

$$h_5 = y h_1 + (1\text{-}y) h_3 = 0.62 \times 1542.7 + (1 - 0.62)1418.1 = 1495.4 \text{ kJ/kg}$$

State 5: $h_5 = 1495.4$ kJ/kg, $P_5 = 1200$ kPa $\Rightarrow$ $s_5 = 5.056$ kJ/kg K

Now check the 2nd law, entropy generation

$$\Rightarrow \dot{S}_{C.V.,gen}/\dot{m}_5 = s_5 - y s_1 - (1\text{-}y) s_3 = \mathbf{-0.1669\ Impossible}$$

The problem could also have been solved assuming a reversible process and then find the needed flow rate ratio y. Then y would have been found larger than 0.62 so the stated process can not be true.

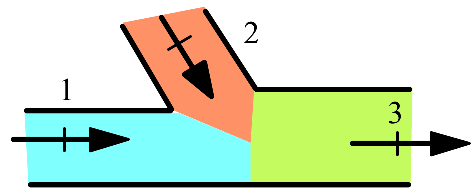
9.58

Two flows of air both at 200 kPa; one has 1 kg/s at 400 K and the other has 2 kg/s at 290 K. The two flows are mixed together in an insulated box to produce a single exit flow at 200 kPa. Find the exit temperature and the total rate of entropy generation.

Solution:

Continuity Eq.6.9:

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 = 1 + 2 = 3 \text{ kg/s}$$



Energy Eq.6.10:

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

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

Using constant specific heats from A.5 and Eq.8.25 for s change.

Divide the energy equation with $\dot{m}_3 C_{Po}$

$$T_3 = (\dot{m}_1/\dot{m}_3)T_1 + (\dot{m}_2/\dot{m}_3)T_2 = \frac{1}{3} \times 400 + \frac{2}{3} \times 290 = 326.67 \text{ K}$$

$$\dot{S}_{gen} = \dot{m}_1(s_3 - s_1) + \dot{m}_2(s_3 - s_2)$$
$$= 1 \times 1.004 \ln (326.67/400) + 2 \times 1.004 \ln (326.67/290)$$
$$= \mathbf{0.0358 \text{ kW/K}}$$

Using A.7.1 and Eq.8.28 for change in s.

$$h_3 = (\dot{m}_1/\dot{m}_3)h_1 + (\dot{m}_2/\dot{m}_3)h_2 = \frac{1}{3} \times 401.3 + \frac{2}{3} \times 290.43 = 327.39 \text{ kJ/kg}$$

From A.7.1: $T_3 = 326.77$ K $\quad s_{T_3} = 6.9548$ kJ/kg K

$$\dot{S}_{gen} = 1(6.9548 - 7.15926) + 2(6.9548 - 6.83521)$$
$$= \mathbf{0.0347 \text{ kW/K}}$$

The pressure correction part of the entropy terms cancel out as all three states have the same pressure.

9.59

One type of feedwater heater for preheating the water before entering a boiler operates on the principle of mixing the water with steam that has been bled from the turbine. For the states as shown in Fig. P9.59, calculate the rate of net entropy increase for the process, assuming the process to be steady flow and adiabatic.

Solution:

CV: Feedwater heater, Steady flow, no external heat transfer.

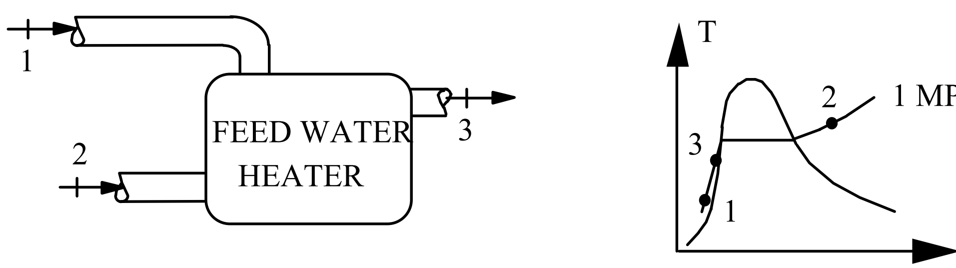
Continuity Eq.6.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

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

Properties: All states are given by (P,T) table B.1.1 and B.1.3

$h_1 = 168.42$, $h_2 = 2828$, $h_3 = 675.8$ all kJ/kg

$s_1 = 0.572$, $s_2 = 6.694$, $s_3 = 1.9422$ all kJ/kg K



Solve for the flow rate from the energy equation

$$\dot{m}_1 = \frac{\dot{m}_3(h_3 - h_2)}{(h_1 - h_2)} = \frac{4(675.8 - 2828)}{(168.42 - 2828)} = 3.237 \text{ kg/s}$$

$$\Rightarrow \quad \dot{m}_2 = 4 - 3.237 = 0.763 \text{ kg/s}$$

The second law for steady flow, $\dot{S}_{CV} = 0$, and no heat transfer, Eq.9.7:

$$\dot{S}_{C.V.,gen} = \dot{S}_{SURR} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2$$

$$= 4(1.9422) - 3.237(0.572) - 0.763(6.694) = \mathbf{0.8097 \text{ kJ/K s}}$$

9.60

A supply of 5 kg/s ammonia at 500 kPa, 20°C is needed. Two sources are available one is saturated liquid at 20°C and the other is at 500 kPa and 140°C. Flows from the two sources are fed through valves to an insulated mixing chamber, which then produces the desired output state. Find the two source mass flow rates and the total rate of entropy generation by this setup.

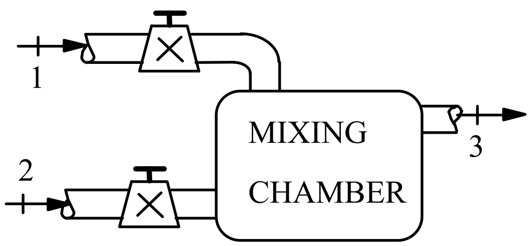
Solution:

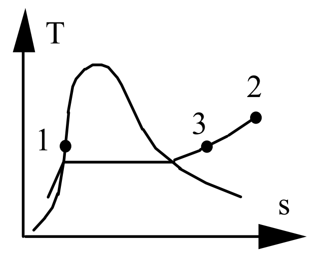
C.V. mixing chamber + valve. Steady, no heat transfer, no work.

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

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

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





State 1: Table B.2.1 $h_1 = 273.4$ kJ/kg, $s_1 = 1.0408$ kJ/kg K

State 2: Table B.2.2 $h_2 = 1773.8$ kJ/kg, $s_2 = 6.2422$ kJ/kg K

State 3: Table B.2.2 $h_3 = 1488.3$ kJ/kg, $s_3 = 5.4244$ kJ/kg K

As all states are known the energy equation establishes the ratio of mass flow rates and the entropy equation provides the entropy generation.

$$\dot{m}_1 h_1 + (\dot{m}_3 - \dot{m}_2) h_2 = \dot{m}_3 h_3 \quad => \quad \dot{m}_1 = \dot{m}_3 \frac{h_3 - h_2}{h_1 - h_2} = 0.952 \text{ kg/s}$$

$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1 = 4.05 \text{ kg/s}$$

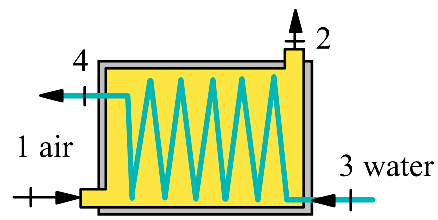
$$\dot{S}_{gen} = 5 \times 5.4244 - 0.95 \times 1.0408 - 4.05 \times 6.2422 = \mathbf{0.852\ kW/K}$$

9.61

A counter flowing heat exchanger has one line with 2 kg/s at 125 kPa, 1000 K entering and the air is leaving at 100 kPa, 400 K. The other line has 0.5 kg/s water coming in at 200 kPa, 20°C and leaving at 200 kPa. What is the exit temperature of the water and the total rate of entropy generation?

Solution:

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



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

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

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

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

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

$T_4 = T_{sat} = 120.23°C$,

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

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

From entropy Eq.9.7

$\dot{S}_{gen} = \dot{m}_{H2O}\,(s_4 - s_3) + \dot{m}_{AIR}(s_2 - s_1)$

$= 0.5(7.01786 - 0.2966) + 2(7.1593 - 8.1349 - 0.287 \ln (100/125))$

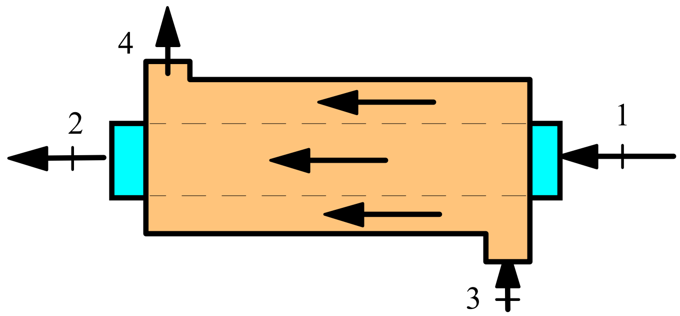
$= 3.3606 - 1.823 =$ **1.54 kW/K**

9.62

A coflowing (same direction) heat exchanger has one line with 0.25 kg/s oxygen at 17°C, 200 kPa entering and the other line has 0.6 kg/s nitrogen at 150 kPa, 500 K entering. The heat exchanger is very long so the two flows exit at the same temperature. Use constant heat capacities and find the exit temperature and the total rate of entropy generation.

Solution:

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



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

Same exit temperature so $T_4 = T_2$ with values from Table A.5

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

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

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

Entropy Eq.9.7 gives for the generation

$$\dot{S}_{gen} = \dot{m}_{O2}(s_2 - s_1) + \dot{m}_{N2}(s_4 - s_3)$$

$$= \dot{m}_{O2}C_P \ln (T_2/T_1) + \dot{m}_{N2}C_P \ln (T_4/T_3)$$

$$= 0.25 \times 0.922 \ln (443.4/290) + 0.6 \times 1.042 \ln (443.4/500)$$

$$= 0.0979 - 0.0751 = \mathbf{0.0228\ kW/K}$$

Transient processes

9.63

Calculate the specific entropy generated in the filling process given in Example 6.11.

Solution:

C.V. Cannister filling process where: ${}_1Q_2 = 0$; ${}_1W_2 = 0$; $m_1 = 0$

Continuity Eq.6.15: $m_2 - 0 = m_{in}$;

Energy Eq.6.16: $m_2u_2 - 0 = m_{in}h_{line} + 0 + 0 \quad \Rightarrow \quad u_2 = h_{line}$

Entropy Eq.9.12: $m_2s_2 - 0 = m_{in}s_{line} + 0 + {}_1S_{2\ gen}$

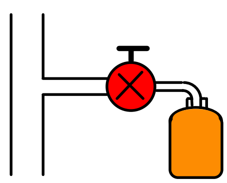
Inlet state : 1.4 MPa, 300°C, $h_i = 3040.4$ kJ/kg, $s_i = 6.9533$ kJ/kg K

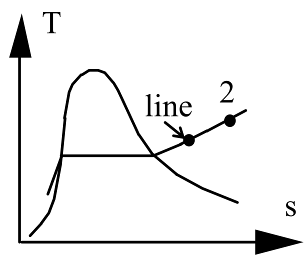
final state: 1.4 MPa, $u_2 = h_i = 3040.4$ kJ/kg

=> $T_2 = 452°C$, $s_2 = 7.45896$ kJ/kg K

${}_1S_{2\ gen} = m_2(s_2 - s_i)$

${}_1s_{2\ gen} = s_2 - s_i = 7.45896 – 6.9533 =$ **0.506 kJ/kg K**





9.64

Calculate the total entropy generated in the filling process given in Example 6.12.

Solution:

Since the solution to the problem is done in the example we will just add the second law analysis to that.

Initial state: Table B.1.2: $s_1 = 6.9404$ kJ/kg K

Final state: Table B.1.3: $s_2 = 6.9533 + \frac{42}{50} \times (7.1359 - 6.9533) = 7.1067 \frac{\text{kJ}}{\text{kg K}}$

Inlet state: Table B.1.3: $s_i = 6.9533$ kJ/kg K

Entropy Eq.9.12: $m_2 s_2 - m_1 s_1 = m_i s_i + {}_1S_{2\ gen}$

Now solve for the generation

$${}_1S_{2\ gen} = m_2 s_2 - m_1 s_1 - m_i s_i$$

$$= 2.026 \times 7.1067 - 0.763 \times 6.9404 - 1.263 \times 6.9533$$

$$= \mathbf{0.32\ kJ/K} \quad > 0$$

9.65

An initially empty 0.1 m^3 cannister is filled with R-12 from a line flowing saturated liquid at −5°C. This is done quickly such that the process is adiabatic. Find the final mass, liquid and vapor volumes, if any, in the cannister. Is the process reversible?

Solution:

C.V. Cannister filling process where: $_1Q_2 = \emptyset$; $_1W_2 = \emptyset$; $m_1 = \emptyset$

Continuity Eq.6.15: $m_2 - \emptyset = m_{in}$;

Energy Eq.6.16: $m_2u_2 - \emptyset = m_{in}h_{line} + \emptyset + \emptyset \quad \Rightarrow \quad u_2 = h_{line}$

2: $P_2 = P_L$; $u_2 = h_L \Rightarrow$ 2 phase $u_2 > u_f$; $u_2 = u_f + x_2u_{fg}$

Table B.3.1: $u_f = 31.26$; $u_{fg} = 137.16$; $h_f = 31.45$ all kJ/kg

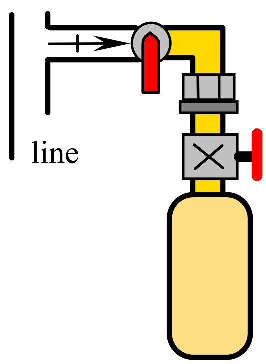
$x_2 = (31.45 - 31.26)/137.16 = 0.001385$

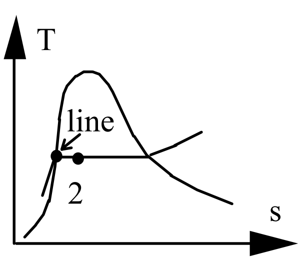
$\Rightarrow v_2 = v_f + x_2v_{fg} = 0.000708 + 0.001385 \times 0.06426 = 0.000797 \text{ m}^3\text{/kg}$

$\Rightarrow m_2 = V/v_2 =$ **125.47 kg** ; $m_f = 125.296$ kg; $m_g = 0.174$ kg

$V_f = m_fv_f =$ **0.0887** m^3; $V_g = m_gv_g =$ **0.0113 m^3**

Process is irreversible (throttling) $s_2 > s_f$





9.66

A 1-m^3 rigid tank contains 100 kg R-22 at ambient temperature, 15°C. A valve on top of the tank is opened, and saturated vapor is throttled to ambient pressure, 100 kPa, and flows to a collector system. During the process the temperature inside the tank remains at 15°C. The valve is closed when no more liquid remains inside. Calculate the heat transfer to the tank and total entropy generation in the process.

Solution:

C.V. Tank out to surroundings. Rigid tank so no work term.

Continuity Eq.6.15: $m_2 - m_1 = -\, m_e$;

Energy Eq.6.16: $m_2u_2 - m_1u_1 = Q_{CV} - m_eh_e$

Entropy Eq.9.12: $m_2s_2 - m_1s_1 = Q_{CV}/T_{SUR} - m_es_e + S_{gen}$

State 1: Table B.3.1, $v_1 = V_1/m_1 = 1/100 = 0.000812 + x_1\ 0.02918$

$x_1 = 0.3149$, $u_1 = 61.88 + 0.3149 \times 169.47 = 115.25$ kJ/kg

$s_1 = 0.2382 + 0.3149 \times 0.668 = 0.44855$; $h_e = h_g = 255.0$ kJ/kg

State 2: $v_2 = v_g = 0.02999$, $u_2 = u_g = 231.35$, $s_2 = 0.9062$ kJ/kg K

Exit state: $h_e = 255.0$, $P_e = 100$ kPa $\rightarrow$ $T_e = -4.7$°C, $s_e = 1.0917$

$m_2 = 1/0.02999 = 33.34$ kg; $m_e = 100 - 33.34 = 66.66$ kg

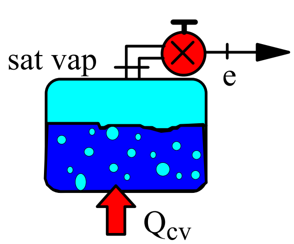
$Q_{CV} = m_2u_2 - m_1u_1 + m_eh_e$

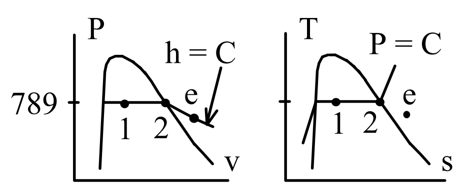
$= 33.34 \times 231.35 - 100 \times 115.25 + 66.66 \times 255 =$ **13 186 kJ**

$\Delta S_{CV} = m_2s_2 - m_1s_1 = 33.34(0.9062) - 100(0.44855) = -14.642$

$\Delta S_{SUR} = -\, Q_{CV}/T_{SUR} + m_es_e = -13186/288.2 + 66.66(1.0917) = +27.012$

$S_{gen} = \Delta S_{NET} = -14.642 + 27.012 =$ **+12.37 kJ/K**





9.67

Air in a tank is at 300 kPa, 400 K with a volume of 2 m^3. A valve on the tank is opened to let some air escape to the ambient to a final pressure inside of 200 kPa. Find the final temperature and mass assuming a reversible adiabatic process for the air remaining inside the tank.

Solution:

C.V. Total tank.

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

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

Entropy Eq.9.12: $m_2s_2 - m_1s_1 = -m_{ex}s_{ex} + \int dQ/T + {}_1S_{2\ gen}$

Process: Adiabatic ${}_1Q_2 = 0$; rigid tank ${}_1W_2 = 0$

This has too many unknowns (we do not know state 2).

C.V. m_2 the mass that remains in the tank. This is a control mass.

Energy Eq.5.11: $m_2(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.8.14: $m_2(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen}$

Process: Adiabatic ${}_1Q_2 = 0$; Reversible ${}_1S_{2\ gen} = 0$

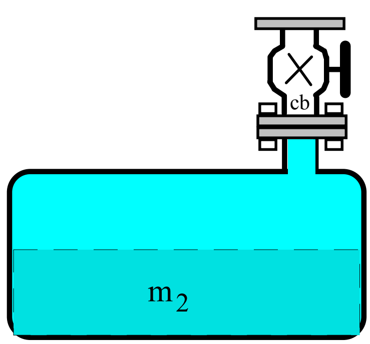
$\Rightarrow \quad s_2 = s_1$

Ideal gas and process Eq.8.32

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 400(200/300)^{0.2857} = \mathbf{356.25\ K}$$

$$m_2 = \frac{P_2V}{RT_2} = \frac{200 \times 2}{0.287 \times 356.25} = \mathbf{3.912\ kg}$$

Notice that the work term is not zero for mass m_2. The work goes into pushing the mass m_{ex} out.



9.68

An empty cannister of 0.002 m^3 is filled with R-134a from a line flowing saturated liquid R-134a at 0°C. The filling is done quickly so it is adiabatic. Find the final mass in the cannister and the total entropy generation.

Solution:

C.V. Cannister filling process where: ${}_1Q_2 = \emptyset$; ${}_1W_2 = \emptyset$; $m_1 = \emptyset$

Continuity Eq.6.15: $m_2 - \emptyset = m_{in}$;

Energy Eq.6.16: $m_2u_2 - \emptyset = m_{in}h_{line} + \emptyset + \emptyset \quad \Rightarrow \quad u_2 = h_{line}$

Entropy Eq.9.12: $m_2s_2 - \emptyset = m_{in}s_{line} + \emptyset + {}_1S_{2\ gen}$

Inlet state: Table B.5.1 $\quad h_{line} = 200$ kJ/kg, $\quad s_{line} = 1.0$ kJ/kg K

State 2: $\quad P_2 = P_{line}$ and $u_2 = h_{line} = 200 \text{ kJ/kg} > u_f$

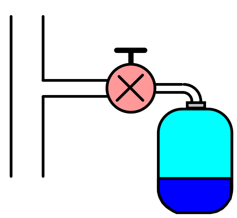
$x_2 = (200 – 199.77) / 178.24 = 0.00129$

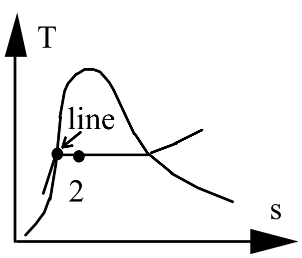
$v_2 = 0.000773 + x_2\ 0.06842 = 0.000861\ m^3/kg$

$s_2 = 1.0 + x_2\ 0.7262 = 1.000937$ kJ/kg K

$m_2 = V / v_2 = 0.002/0.000861 = \mathbf{2.323\ kg}$

${}_1S_{2\ gen} = m_2(s_2 - s_{line}) = 2.323\ (1.00094 – 1) = \mathbf{0.0109\ kJ/K}$





9.69

An old abandoned saltmine, 100 000 m^3 in volume, contains air at 290 K, 100 kPa. The mine is used for energy storage so the local power plant pumps it up to 2.1 MPa using outside air at 290 K, 100 kPa. Assume the pump is ideal and the process is adiabatic. Find the final mass and temperature of the air and the required pump work.

Solution:

C.V. The mine volume and the pump

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

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

Entropy Eq.9.12: $m_2s_2 - m_1s_1 = \int dQ/T + {}_1S_{2\,gen} + m_{in}s_{in}$

Process: Adiabatic ${}_1Q_2 = 0$, Process ideal ${}_1S_{2\,gen} = 0$, $s_1 = s_{in}$

$\Rightarrow\; m_2s_2 = m_1s_1 + m_{in}s_{in} = (m_1 + m_{in})s_1 = m_2s_1 \;\Rightarrow\; s_2 = s_1$

Constant s $\Rightarrow$ Eq.8.28 $s^o_{T2} = s^o_{Ti} + R\ln(P_2 / P_{in})$

$$s^o_{T2} = 6.83521 + 0.287 \ln(21) = 7.7090 \text{ kJ/kg K}$$

A.7 $\Rightarrow$ $T_2 =$ **680 K** , $u_2 = 496.94$ kJ/kg

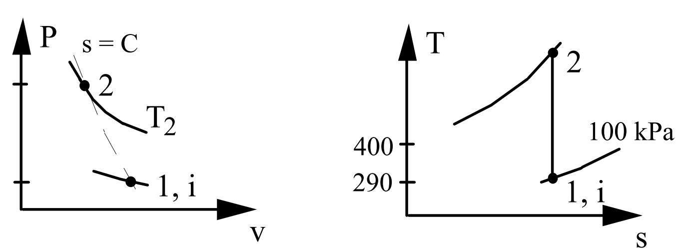
$m_1 = P_1V_1/RT_1 = 100\times10^5/(0.287 \times 290) = 1.20149 \times 10^5$ kg

$m_2 = P_2V_2/RT_2 = 100 \times 21\times10^5/(0.287 \times 680) = \mathbf{10.760 \times 10^5}$ **kg**

$\Rightarrow$ $m_{in} = 9.5585\times10^5$ kg

${}_1W_2 = m_{in}h_{in} + m_1u_1 - m_2u_2$

$= m_{in}(290.43) + m_1(207.19) - m_2(496.94) = \mathbf{-2.322 \times 10^8}$ **kJ**



9.70

Air in a tank is at 300 kPa, 400 K with a volume of 2 m^3. A valve on the tank is opened to let some air escape to the ambient to a final pressure inside of 200 kPa. At the same time the tank is heated so the air remaining has a constant temperature. What is the mass average value of the s leaving assuming this is an internally reversible process?

Solution:

C.V. Tank, emptying process with heat transfer.

Continuity Eq.6.15: $m_2 - m_1 = -m_e$

Energy Eq.6.16: $m_2u_2 - m_1u_1 = -m_eh_e + {}_1Q_2$

Entropy Eq.9.12: $m_2s_2 - m_1s_1 = -m_es_e + {}_1Q_2/T + 0$

Process: $T_2 = T_1$ => ${}_1Q_2$ in at 400 K

Reversible ${}_1S_{2\ gen} = 0$

State 1: Ideal gas $m_1 = P_1V/RT_1 = 300 \times 2/0.287 \times 400 = 5.2265$ kg

State 2: 200 kPa, 400 K

$m_2 = P_2V/RT_2 = 200 \times 2/0.287 \times 400 = 3.4843$ kg

=> $m_e = 1.7422$ kg

From the energy equation:

$${}_1Q_2 = m_2u_2 - m_1u_1 + m_eh_e$$
$$= 3.4843 \times 286.49 – 5.2265 \times 286.49 + 1.7422 \times 401.3$$
$$= 1.7422(401.3 – 286.49) = 200 \text{ kJ}$$

$$m_es_e = m_1s_1 - m_2s_2 + {}_1Q_2/T$$
$$= 5.2265[7.15926 – 0.287 \ln (300/100)] – 3.4843[7.15926 – 0.287 \ln (200/100)] + (200/400)$$
$$m_es_e = 35.770 – 24.252 + 0.5 = 12.018 \text{ kJ/K}$$
$$s_e = 12.018/1.7422 = 6.89817 = \mathbf{6.8982\ kJ/kg\ K}$$

Note that the exit state e in this process is for the air before it is throttled across the discharge valve. The throttling process from the tank pressure to ambient pressure is a highly irreversible process.

9.71

An insulated 2 m^3 tank is to be charged with R-134a from a line flowing the refrigerant at 3 MPa. The tank is initially evacuated, and the valve is closed when the pressure inside the tank reaches 3 MPa. The line is supplied by an insulated compressor that takes in R-134a at 5°C, quality of 96.5 %, and compresses it to 3 MPa in a reversible process. Calculate the total work input to the compressor to charge the tank.

Solution:

C.V.: Compressor, R-134a. Steady 1 inlet and 1 exit flow, no heat transfer.

1^{st} Law Eq.6.13: $\quad q_c + h_1 = h_1 = h_2 + w_c$

Entropy Eq.9.8: $\quad s_1 + \int dq/T + s_{gen} = s_1 + 0 = s_2$

inlet: $T_1 = 5^oC$, $x_1 = 0.965$ use Table B.5.1

$s_1 = s_f + x_1 s_{fg} = 1.0243 + 0.965{\times}0.6995 = 1.6993$ kJ/kg K,

$h_1 = h_f + x_1 h_{fg} = 206.8 + 0.965{\times}194.6 = 394.6$ kJ/kg

exit: $P_2 = 3$ MPa

From the entropy eq.: $\quad s_2 = s_1 = 1.6993$ kJ/kg K;

$T_2 = 90^oC, \quad h_2 = 436.2$ kJ/kg

$w_c = h_1 - h_2 = -41.6$ kJ/kg

C.V.: Tank; $V_T = 2\ m^3$, $P_T = 3$ MPa

1^{st} Law Eq.6.16: $\quad Q + m_i h_i = m_2 u_2 - m_1 u_1 + m_e h_e + W;$

Process and states have: $\quad Q = 0,\ W = 0,\ m_e = 0,\ m_1 = 0,\ m_2 = m_i$

$u_2 = h_i = 436.2$ kJ/kg

Final state: $\quad P_T = 3$ MPa, $u_2 = 436.2$ kJ/kg

$\rightarrow T_T = 101.9^oC$, $v_T = 0.006783\ m^3/kg$

$m_T = V_T/v_T = 294.84$ kg;

The work term is from the specific compressor work and the total mass

$-W_c = m_T(-w_c) =$ **12 295 kJ**

9.72

An 0.2 m^3 initially empty container is filled with water from a line at 500 kPa, 200°C until there is no more flow. Assume the process is adiabatic and find the final mass, final temperature and the total entropy generation.

Solution:

C.V. The container volume and any valve out to line.

Continuity Eq.6.15: $m_2 - m_1 = m_2 = m_i$

Energy Eq.6.16: $m_2u_2 - m_1u_1 = m_2u_2 = {}_1Q_2 - {}_1W_2 + m_ih_i = m_ih_i$

Entropy Eq.9.12: $m_2s_2 - m_1s_1 = m_2s_2 = \int dQ/T + {}_1S_{2\ gen} + m_is_i$

Process: Adiabatic ${}_1Q_2 = 0$, Rigid ${}_1W_2 = 0$ Flow stops $P_2 = P_{line}$

State i: $h_i = 2855.37$ kJ/kg; $s_i = 7.0592$ kJ/kg K

State 2: 500 kPa, $u_2 = h_i = 2855.37$ kJ/kg => Table B.1.3

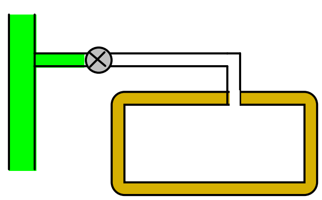
$T_2 \cong 332.9°C$, $s_2 = 7.5737$ kJ/kg, $v_2 = 0.55387\ m^3/kg$

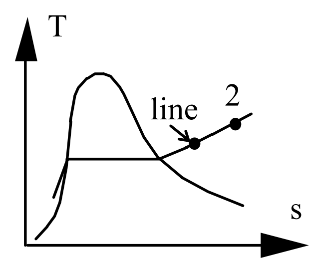
$m_2 = V/v_2 = 0.2/0.55387 = 0.361$ kg

From the entropy equation

$${}_1S_{2\ gen} = m_2s_2 - m_2s_i$$

$$= 0.361(7.5737 - 7.0592) = \mathbf{0.186\ kJ/K}$$





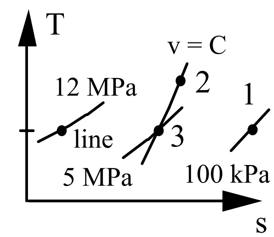
9.73

Air from a line at 12 MPa, 15°C, flows into a 500-L rigid tank that initially contained air at ambient conditions, 100 kPa, 15°C. The process occurs rapidly and is essentially adiabatic. The valve is closed when the pressure inside reaches some value, P_2. The tank eventually cools to room temperature, at which time the pressure inside is 5 MPa. What is the pressure P_2? What is the net entropy change for the overall process?

Solution:

CV: Tank. Mass flows in, so this is transient. Find the mass first

$$m_1 = P_1V/RT_1 = \frac{100 \times 0.5}{0.287 \times 288.2} = 0.604 \text{ kg}$$



Fill to P_2, then cool to $T_3 = 15°C$, $P_3 = 5$ MPa

$$m_3 = m_2 = P_3V/RT_3$$

$$= \frac{5000 \times 0.5}{0.287 \times 288.2} = 30.225 \text{ kg}$$

Mass: $m_i = m_2 - m_1 = 30.225 - 0.604 = 29.621$ kg

In the process 1-2 heat transfer = 0

1st law Eq.6.16: $m_ih_i = m_2u_2 - m_1u_1$; $m_iC_{P0}T_i = m_2C_{V0}T_2 - m_1C_{V0}T_1$

$$T_2 = \frac{(29.621 \times 1.004 + 0.604 \times 0.717) \times 288.2}{30.225 \times 0.717} = 401.2 \text{ K}$$

$$P_2 = m_2RT_2/V = (30.225 \times 0.287 \times 401.2)/0.5 = \mathbf{6.960\ MPa}$$

Consider now the total process from the start to the finish at state 3.

Energy Eq.6.16: $Q_{CV} + m_ih_i = m_2u_3 - m_1u_1 = m_2h_3 - m_1h_1 - (P_3 - P_1)V$

But, since $T_i = T_3 = T_1$, $m_ih_i = m_2h_3 - m_1h_1$

$\Rightarrow Q_{CV} = -(P_3 - P_1)V = -(5000 - 100)0.5 = -2450$ kJ

From Eqs.9.24-9.26

$$\Delta S_{NET} = m_3s_3 - m_1s_1 - m_is_i - Q_{CV}/T_0 = m_3(s_3 - s_i) - m_1(s_1 - s_i) - Q_{CV}/T_0$$

$$= 30.225\left[0\text{-}0.287 \ln\frac{5}{12}\right] - 0.604\left[0\text{-}0.287 \ln\frac{0.1}{12}\right] + (2450 / 288.2)$$

$$= \mathbf{15.265\ kJ/K}$$

9.74

An initially empty canister of volume 0.2 m^3 is filled with carbon dioxide from a line at 1000 kPa, 500 K. Assume the process is adiabatic and the flow continues until it stops by itself. Use constant heat capacity to solve for the final mass and temperature of the carbon dioxide in the canister and the total entropy generated by the process.

Solution:

C.V. Cannister + valve out to line. No boundary/shaft work, $m_1 = 0$; $Q = 0$.

Continuity Eq.6.15: $m_2 - 0 = m_i$

Energy Eq.6.16: $m_2 u_2 - 0 = m_i h_i$

Entropy Eq.9.12: $m_2 s_2 - 0 = m_i s_i + {}_1S_{2\,gen}$

State 2: $P_2 = P_i$ and $u_2 = h_i = h_{line} = h_2 - RT_2$ (ideal gas)

To reduce or eliminate guess use: $h_2 - h_{line} = C_{Po}(T_2 - T_{line})$

Energy Eq. becomes: $C_{Po}(T_2 - T_{line}) - RT_2 = 0$

$$T_2 = T_{line}\, C_{Po}/(C_{Po} - R) = T_{line}\, C_{Po}/C_{Vo} = k\, T_{line}$$

Use A.5: $C_P = 0.842 \frac{kJ}{kg\,K}$, $k = 1.289$ => $T_2 = 1.289 \times 500 =$ **644.5 K**

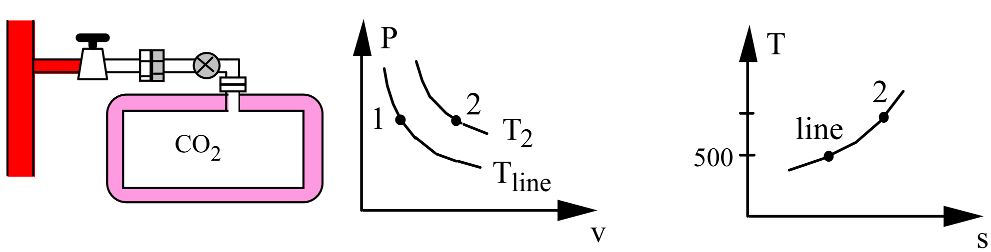
$m_2 = P_2V/RT_2 = 1000 \times 0.2/(0.1889 \times 644.5) =$ **1.643 kg**

${}_1S_{2\,gen} = m_2 (s_2 - s_i) = m_2[\, C_P \ln(T_2 / T_{line}) - R \ln(P_2 / P_{line})]$

$= 1.644[0.842 \times \ln(1.289) - 0] =$ **0.351 kJ/K**

If we use A.8 at 550 K: $C_P = 1.045 \frac{kJ}{kg\,K}$, $k = 1.22$

=> $T_2 = 610$ K, $m_2 = 1.735$ kg



9.75

A cook filled a pressure cooker with 3 kg water at 20°C and a small amount of air and forgot about it. The pressure cooker has a vent valve so if P > 200 kPa steam escapes to maintain a pressure of 200 kPa. How much entropy was generated in the throttling of the steam through the vent to 100 kPa when half the original mass has escaped?

Solution:

The pressure cooker goes through a transient process as it heats water up to the boiling temperature at 200 kPa then heats more as saturated vapor at 200 kPa escapes. The throttling process is steady state as it flows from saturated vapor at 200 kPa to 100 kPa which we assume is a constant h process.

C.V. Pressure cooker, no work.

Continuity Eq.6.15: $m_2 - m_1 = -m_e$

Energy Eq.6.16: $m_2 u_2 - m_1 u_1 = -m_e h_e + {}_1Q_2$

Entropy Eq.9.12: $m_2 s_2 - m_1 s_1 = -m_e s_e + \int dQ/T + {}_1S_{2\ gen}$

State 1: $v_1 = v_f = 0.001002\ m^3/kg$ $V = m_1 v_1 = 0.003006\ m^3$

State 2: $m_2 = m_1/2 = 1.5$ kg, $v_2 = V/m_2 = 2v_1$, $P_2 = 200$ kPa

Exit: $h_e = h_g = 2706.63$ kJ/kg, $s_e = s_g = 7.1271$ kJ/kg K

So we can find the needed heat transfer and entropy generation if we know the C.V. surface temperature T. If we assume T for water then ${}_1S_{2\ gen} = 0$, which is an internally reversible externally irreversible process, there is a ΔT between the water and the source.

C.V. Valve, steady flow from state e (200 kPa) to state 3 (at 100 kPa).

Energy Eq.: $h_3 = h_e$

Entropy Eq.: $s_3 = s_e + {}_es_{3\ gen}$ generation in valve (throttle)

State 3: 100 kPa, $h_3 = 2706.63$ kJ/kg Table B.1.3 $\Rightarrow$

$$T_3 = 99.62 + (150\text{-}99.62)\,\frac{2706.63 - 2675.46}{2776.38 - 2675.46} = 115.2°C$$

$$s_3 = 7.3593 + (7.6133 - 7.3593)\ 0.30886 = 7.4378\ \text{kJ/kg K}$$

$${}_eS_{3\ gen} = m_e(s_3 - s_e) = 1.5\ (7.4378 - 7.1271) = \mathbf{0.466\ kJ/K}$$

Reversible shaft work, Bernoulli equation

9.76

A large storage tank contains saturated liquid nitrogen at ambient pressure, 100 kPa; it is to be pumped to 500 kPa and fed to a pipeline at the rate of 0.5 kg/s. How much power input is required for the pump, assuming it to be reversible?

Solution:

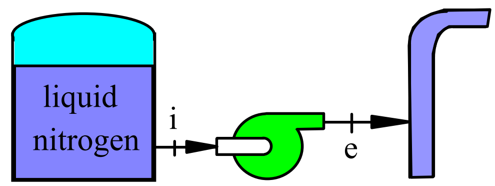
C.V. Pump, liquid is assumed to be incompressible.

Table B.6.1 at P_i = 101.3 kPa , v_{Fi} = 0.00124 m^3/kg

Eq.9.18

$w_{PUMP} = - w_{cv} = \int v dP \approx v_{Fi}(P_e - P_i)$

$= 0.00124(500 - 101) = 0.494$ kJ/kg



$\dot{W}_{PUMP} = \dot{m} w_{PUMP}$ = 0.5 kg/s (0.494 kJ/kg) = **0.247 kW**

9.77

Liquid water at ambient conditions, 100 kPa, 25°C, enters a pump at the rate of 0.5 kg/s. Power input to the pump is 3 kW. Assuming the pump process to be reversible, determine the pump exit pressure and temperature.

Solution:

C.V. Pump. Steady single inlet and exit flow with no heat transfer.

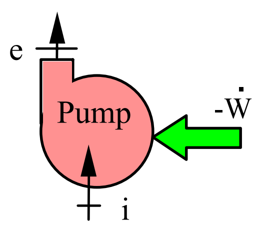
Energy Eq.6.13: $w = h_i - h_e = \dot{W}/\dot{m} = -3/0.5 = -\,6.0$ kJ/kg

Using also incompressible media we can use Eq.9.18

$$w = -\int v\,dP \approx -v_i(P_e - P_i) = -0.001003(P_e - 100)$$

from which we can solve for the exit pressure

$$P_e = 100 + 6.0/0.001003 = 6082 \text{ kPa} = \mathbf{6.082\ MPa}$$



$-\dot{W} = 3$ kW, $P_i = 100$ kPa

$T_i = 25°C$, $\dot{m} = 0.5$ kg/s

Energy Eq.: $h_e = h_i - w = 104.87 - (-6) = 110.87$ kJ/kg

Use Table B.1.4 at 5 MPa => $\mathbf{T_e = 25.3°C}$

Remark:

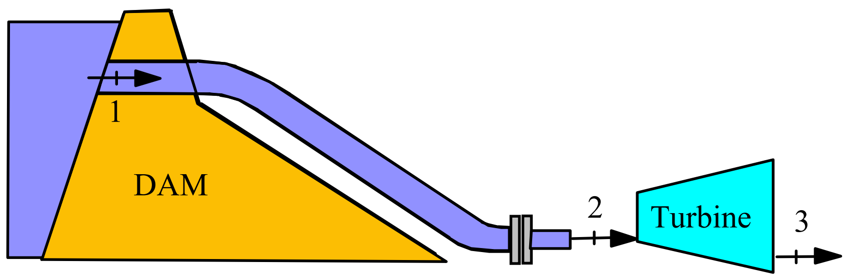
If we use the software we get: $\left.\begin{array}{l} s_i = 0.36736 = s_e \\ \text{At } s_e \,\&\, P_e \end{array}\right\} \rightarrow T_e = \mathbf{25.1°C}$

9.78

A small dam has a pipe carrying liquid water at 150 kPa, 20°C with a flow rate of 2000 kg/s in a 0.5 m diameter pipe. The pipe runs to the bottom of the dam 15 m lower into a turbine with pipe diameter 0.35 m. Assume no friction or heat transfer in the pipe and find the pressure of the turbine inlet. If the turbine exhausts to 100 kPa with negligible kinetic energy what is the rate of work?

Solution:

C.V. Pipe. Steady flow no work, no heat transfer.



States: compressed liquid B.1.1 $\quad v_2 \approx v_1 \approx v_f = 0.001002 \text{ m}^3/\text{kg}$

Continuity Eq.6.3: $\quad \dot{m} = \rho A\mathbf{V} = A\mathbf{V}/v$

$$\mathbf{V}_1 = \dot{m}v_1/A_1 = 2000 \times 0.001002 / (\tfrac{\pi}{4}0.5^2) = 10.2 \text{ m s}^{-1}$$

$$\mathbf{V}_2 = \dot{m}v_2/A_2 = 2000 \times 0.001002 / (\tfrac{\pi}{4}0.35^2) = 20.83 \text{ m s}^{-1}$$

From Bernoulli Eq.9.17 for the pipe (incompressible substance):

$$v(P_2 - P_1) + \tfrac{1}{2}(\mathbf{V}_2^2 - \mathbf{V}_1^2) + g(Z_2 - Z_1) = \varnothing \Rightarrow$$

$$P_2 = P_1 + \left[\tfrac{1}{2}(\mathbf{V}_1^2 - \mathbf{V}_2^2) + g(Z_1 - Z_2)\right]/v$$

$$= 150 + [\tfrac{1}{2}\times 10.2^2 - \tfrac{1}{2}\times 20.83^2 + 9.80665 \times 15]/(1000 \times 0.001002)$$

$$= 150 - 17.8 = \mathbf{132.2 \text{ kPa}}$$

Note that the pressure at the bottom should be higher due to the elevation difference but lower due to the acceleration.

Now apply the energy equation Eq.9.14 for the total control volume

$$w = -\int v\, dP + \tfrac{1}{2}(\mathbf{V}_1^2 - \mathbf{V}_3^2) + g(Z_1 - Z_3)$$

$$= -\,0.001002\,(100 - 150) + [\tfrac{1}{2}\times 10.2^2 + 9.80665 \times 15]/1000 = 0.25 \text{ kJ/kg}$$

$$\dot{W} = \dot{m}w = 2000 \times 0.25 = \mathbf{500 \text{ kW}}$$

9.79

A firefighter on a ladder 25 m above ground should be able to spray water an additional 10 m up with the hose nozzle of exit diameter 2.5 cm. Assume a water pump on the ground and a reversible flow (hose, nozzle included) and find the minimum required power.

Solution:

C.V.: pump + hose + water column, total height difference 35 m. Here **V** is velocity, not volume.

Continuity Eq.6.3, 6.11: $\dot{m}_{in} = \dot{m}_{ex} = (\rho A \mathbf{V})_{nozzle}$

Energy Eq.6.12: $\dot{m}(-w_p) + \dot{m}(h + \mathbf{V}^2/2 + gz)_{in} = \dot{m}(h + \mathbf{V}^2/2 + gz)_{ex}$

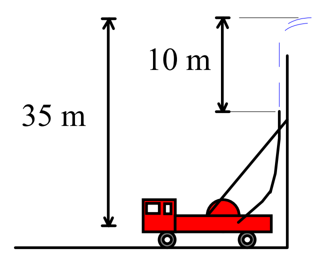
Process: $h_{in} \cong h_{ex}$, $\mathbf{V}_{in} \cong \mathbf{V}_{ex} = 0$, $z_{ex} - z_{in} = 35$ m, $\rho = 1/v \cong 1/v_f$

$$-w_p = g(z_{ex} - z_{in}) = 9.81 \times (35 - 0) = 343.2 \text{ J/kg}$$

The velocity in the exit nozzle is such that it can rise 10 m. Make that column a C.V. for which Bernoulli Eq.9.17 is:

$$gz_{noz} + \frac{1}{2}\mathbf{V}^2_{noz} = gz_{ex} + 0$$

$$\mathbf{V}_{noz} = \sqrt{2g(z_{ex} - z_{noz})} = \sqrt{2 \times 9.81 \times 10} = 14 \text{ m/s}$$



$$\dot{m} = \frac{\pi}{v_f}\left(\frac{D}{2}\right)^2 \mathbf{V}_{noz} = (\pi/4)\ 0.025^2 \times 14 / 0.001 = 6.873 \text{ kg/s}$$

$$-\dot{W}_p = -\dot{m}w_p = 6.873 \text{ kg/s} \times 343.2 \text{ J/kg} = \mathbf{2.36\ kW}$$

9.80

A small pump is driven by a 2 kW motor with liquid water at 150 kPa, 10°C entering. Find the maximum water flow rate you can get with an exit pressure of 1 MPa and negligible kinetic energies. The exit flow goes through a small hole in a spray nozzle out to the atmosphere at 100 kPa. Find the spray velocity.

Solution:

C.V. Pump. Liquid water is incompressible so work from Eq.9.18

$$\dot{W} = \dot{m}w = -\dot{m}v(P_e - P_i) \Rightarrow$$

$$\dot{m} = \dot{W} / [-v(P_e - P_i)] = -2/[-0.001003\ (1000 - 150)] = 2.35 \text{ kg/s}$$

C.V Nozzle. No work, no heat transfer, $v \approx$ constant => Bernoulli Eq.9.17

$$\frac{1}{2}\mathbf{V}_{ex}^2 = v\Delta P = 0.001\ (1000 - 100) = 0.9 \text{ kJ/kg} = 900 \text{ J/kg}$$

$$\mathbf{V}_{ex} = \sqrt{2 \times 900 \text{ J/kg}} = \mathbf{42.4\ m\ s^{-1}}$$

9.81

A garden water hose has liquid water at 200 kPa, 15°C. How high a velocity can be generated in a small ideal nozzle? If you direct the water spray straight up how high will it go?

Solution:

Liquid water is incompressible and we will assume process is reversible.

Bernoulli's Eq. across the nozzle Eq.9.17: $v\Delta P = \Delta(\frac{1}{2}\mathbf{V}^2)$

$\mathbf{V} = \sqrt{2v\Delta P} = \sqrt{2\times 0.001001 \times (200\text{-}101) \times 1000} =$ **14.08 m/s**

Bernoulli's Eq.9.17 for the column: $\Delta(\frac{1}{2}\mathbf{V}^2) = \Delta gZ$

$\Delta Z = \Delta(\frac{1}{2}\mathbf{V}^2)/g = v\Delta P/g = 0.001001 \times (200 - 101) \times 1000/9.807 =$ **10.1 m**

9.82

Saturated R-134a at -10°C is pumped/compressed to a pressure of 1.0 MPa at the rate of 0.5 kg/s in a reversible adiabatic process. Calculate the power required and the exit temperature for the two cases of inlet state of the R-134a:

a) quality of 100 %.

b) quality of 0 %.

Solution:

C.V.: Pump/Compressor, $\dot{m} = 0.5$ kg/s, R-134a

a) State 1: Table B.5.1, $T_1 = -10^oC$, $x_1 = 1.0$ Saturated vapor

$P_1 = P_g = 202$ kPa, $h_1 = h_g = 392.3$ kJ/kg, $s_1 = s_g = 1.7319$ kJ/kg K

Assume Compressor is isentropic, $s_2 = s_1 = 1.7319$ kJ/kg-K

$h_2 = 425.7$ kJ/kg, $\mathbf{T_2 = 45^oC}$

1^{st} Law Eq.6.13: $q_c + h_1 = h_2 + w_c$; $q_c = 0$

$w_{cs} = h_1 - h_2 = -33.4$ kJ/kg; => $\dot{W}_C = \dot{m}w_C = \mathbf{-16.7\ kW}$

b) State 1: $T_1 = -10^oC$, $x_1 = 0$ Saturated liquid. This is a pump.

$P_1 = 202$ kPa, $h_1 = h_f = 186.72$ kJ/kg, $v_1 = v_f = 0.000755$ m^3/kg

1^{st} Law Eq.6.13: $q_p + h_1 = h_2 + w_p$; $q_p = 0$

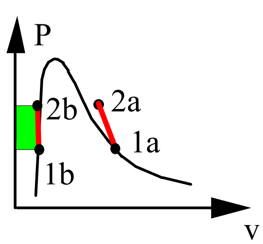
Assume Pump is isentropic and the liquid is incompressible, Eq.9.18:

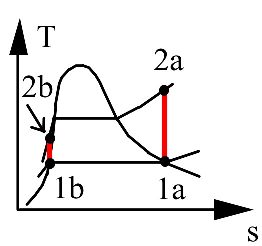
$w_{ps} = - \int v\, dP = -v_1(P_2 - P_1) = -0.6$ kJ/kg

$h_2 = h_1 - w_p = 186.72 - (- 0.6) = 187.3$ kJ/kg, $P_2 = 1$ MPa

Assume State 2 is approximately a saturated liquid => $\mathbf{T_2 \cong -9.6^oC}$

$\dot{W}_P = \dot{m}w_P = \mathbf{-0.3\ kW}$

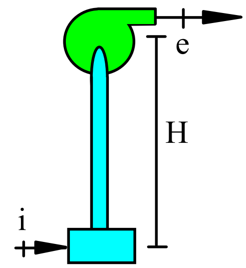




9.83

A small water pump on ground level has an inlet pipe down into a well at a depth H with the water at 100 kPa, 15°C. The pump delivers water at 400 kPa to a building. The absolute pressure of the water must be at least twice the saturation pressure to avoid cavitation. What is the maximum depth this setup will allow?

Solution:



C.V. Pipe in well, no work, no heat transfer

From Table B.1.1

$$P_{\text{inlet pump}} \geq 2\ P_{\text{sat, 15C}} = 2\times1.705 = 3.41 \text{ kPa}$$

Process:

Assume Δ KE $\approx \varnothing$, $\quad$ v $\approx$ constant. =>

Bernoulli Eq.9.17:

$$v\ \Delta P + g\ H = 0 \ \ =>$$

$$1000 \times 0.001001\ (3.41 - 100) + 9.80665 \times H = 0$$

$$\Rightarrow \quad \mathbf{H = 9.86\ m}$$

Since flow has some kinetic energy and there are losses in the pipe the height is overestimated. Also the start transient would generate a very low inlet pressure (it moves flow by suction)

9.84

A small pump takes in water at 20°C, 100 kPa and pumps it to 2.5 MPa at a flow rate of 100 kg/min. Find the required pump power input.

Solution:

C.V. Pump. Assume reversible pump and incompressible flow.

This leads to the work in Eq.9.18

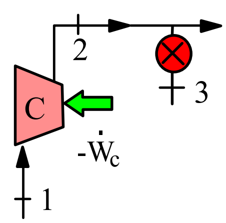
$$w_p = -\int v dP = -v_i(P_e - P_i) = -0.001002(2500 - 100) = -2.4 \text{ kJ/kg}$$

$$\dot{W}_p = \dot{m}w_p = \frac{100}{60}\frac{\text{kg/min}}{\text{sec/min}}(-2.4 \text{ kJ/kg}) = \mathbf{-4.0\ kW}$$

9.85

A pump/compressor pumps a substance from 100 kPa, 10°C to 1 MPa in a reversible adiabatic process. The exit pipe has a small crack, so that a small amount leaks to the atmosphere at 100 kPa. If the substance is (a) water, (b) R-12, find the temperature after compression and the temperature of the leak flow as it enters the atmosphere neglecting kinetic energies.

Solution:



C.V.: Compressor, reversible adiabatic

Eq.6.13: $h_1 - w_c = h_2$; Eq.9.8: $s_1 = s_2$

State 2: P_2, $s_2 = s_1$

C.V.: Crack (Steady throttling process)

Eq.6.13: $h_3 = h_2$; Eq.9.8: $s_3 = s_2 + s_{gen}$

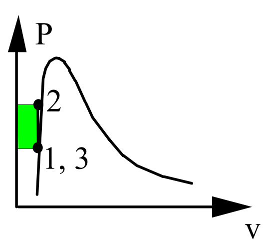
State 3: P_3, $h_3 = h_2$

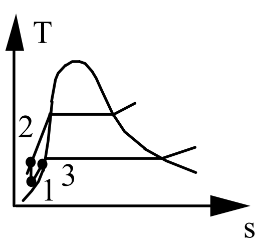
a) Water 1: compressed liquid, Table B.1.1

$$-w_c = +\int v dP = v_{f1}(P_2 - P_1) = 0.001 \times (1000 - 100) = 0.9 \text{ kJ/kg}$$

$h_2 = h_1 - w_c = 41.99 + 0.9 = 42.89$ kJ/kg => $\mathbf{T_2 = 10.2°C}$

P_3 , h_3 $\Rightarrow$ compressed liquid at **~10.2°C**





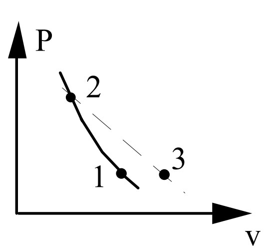
States 1 and 3 are at the same 100 kPa, and same v. You cannot separate them in the P-v fig.

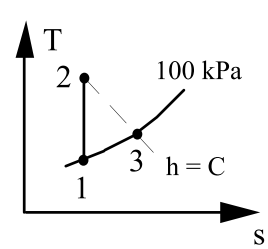
b) R-12 1: superheated vapor, Table B.3.2, $s_1 = 0.8070$ kJ/kg K

$s_2 = s_1$ & P_2 $\Rightarrow$ $\mathbf{T_2 = 98.5°C}$, $h_2 = 246.51$ kJ/kg

$-w_c = h_2 - h_1 = 246.51 - 197.77 = 48.74$ kJ/kg

P_3 , h_3 $\Rightarrow$ $\mathbf{T_3 = 86.8°C}$





9.86

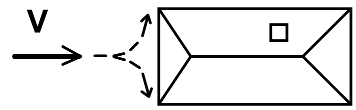
Atmospheric air at 100 kPa, 17°C blows at 60 km/h towards the side of a building. Assume the air is nearly incompressible find the pressure and the temperature at the stagnation point (zero velocity) on the wall.

Solution:

C.V. A stream line of flow from the freestream to the wall.

Eq.9.17:

$$v(P_e - P_i) + \frac{1}{2}(\mathbf{V}_e^2 - \mathbf{V}_i^2) + g(Z_e - Z_i) = 0$$



$$\mathbf{V}_i = 60 \frac{\text{km}}{\text{h}} \times 1000 \frac{\text{m}}{\text{km}} \times \frac{1}{3600} \frac{\text{h}}{\text{s}} = 16.667 \text{ m/s}$$

$$v = \frac{RT_i}{P_i} = \frac{0.287 \times 290.15}{100} = 0.8323 \frac{\text{m}^3}{\text{kg}}$$

$$\Delta P = \frac{1}{2v} \mathbf{V}_i^2 = \frac{16.667^2}{0.8323 \times 2000} = 0.17 \text{ kPa}$$

$$P_e = P_i + \Delta P = 100.17 \text{ kPa}$$

Then Eq.8.32 for an isentropic process:

$$T_e = T_i (P_e/P_i)^{0.286} = 290.15 \times 1.0005 = \mathbf{290.3\ K}$$

Very small effect due to low velocity and air is light (large specific volume)

9.87

You drive on the highway with 120 km/h on a day with 17°C, 100 kPa atmosphere. When you put your hand out of the window flat against the wind you feel the force from the air stagnating, i.e. it comes to relative zero velocity on your skin. Assume the air is nearly incompressible and find the air temperature and pressure right on your hand.

Solution:

Energy Eq.6.13: $\frac{1}{2}\mathbf{V}^2 + h_o = h_{st}$

$$T_{st} = T_o + \frac{1}{2}\mathbf{V}^2/C_p = 17 + \frac{1}{2}[(120\times1000)/3600]^2 \times (1/1004)$$

$$= 17 + 555.5/1004 = \mathbf{17.6°C}$$

$$v = RT_o/P_o = 0.287 \times 290/100 = 0.8323\ m^3/kg$$

From Bernoulli Eq.9.17:

$$v\Delta P = \frac{1}{2}\mathbf{V}^2$$

$$P_{st} = P_o + \frac{1}{2}\mathbf{V}^2/v = 100 + 555.5/(0.8323 \times 1000) = \mathbf{100.67\ kPa}$$

9.88

An air flow at 100 kPa, 290 K, 200 m/s is directed towards a wall. At the wall the flow stagnates (comes to zero velocity) without any heat transfer. Find the stagnation pressure a) assuming incompressible flow b) assume an adiabatic compression. Hint: T comes from the energy equation.

Solution:

Ideal gas: $v = RT_o/P_o = 0.287 \times 290/100 = 0.8323 \text{ m}^3/\text{kg}$

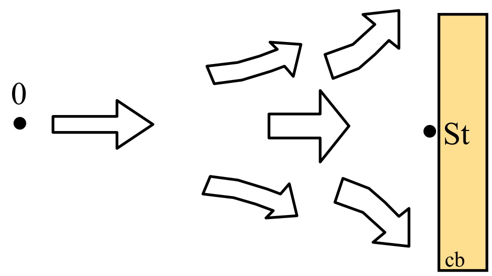
Kinetic energy: $\frac{1}{2}\mathbf{V}^2 = \frac{1}{2}(200^2/1000) = 20 \text{ kJ/kg}$

a) Reversible and incompressible gives Bernoulli Eq.9.17:

$\Delta P = \frac{1}{2}\mathbf{V}^2/v = 20/0.8323$

$= 24 \text{ kPa}$

$P_{st} = P_o + \Delta P = 124 \text{ kPa}$



b) adiabatic compression

Energy Eq.6.13: $\frac{1}{2}\mathbf{V}^2 + h_o = h_{st}$

$h_{st} - h_o = \frac{1}{2}\mathbf{V}^2 = C_p\Delta T$

$\Delta T = \frac{1}{2}\mathbf{V}^2/C_p = 20/1.004 = 19.92°C$

$=> \; T_{st} = 290 + 19.92 = 309.92 \text{ K}$

Entropy Eq.9.8 assume also reversible process:

$s_o + s_{gen} + \int (1/T)\, dq = s_{st}$

as $dq = 0$ and $s_{gen} = 0$ then it follows that $s = \text{constant}$

This relation gives Eq.8.32:

$$P_{st} = P_o\left(\frac{T_{st}}{T_o}\right)^{\frac{k}{k-1}} = 100 \times (309.92/290)^{3.5} = \mathbf{126 \text{ kPa}}$$

9.89

Calculate the air temperature and pressure at the stagnation point right in front of a meteorite entering the atmosphere (-50 °C, 50 kPa) with a velocity of 2000 m/s. Do this assuming air is incompressible at the given state and repeat for air being a compressible substance going through an adiabatic compression.

Solution:

Kinetic energy: $\frac{1}{2}\mathbf{V}^2 = \frac{1}{2}(2000)^2/1000 = 2000$ kJ/kg

Ideal gas: $v_{atm} = RT/P = 0.287 \times 223/50 = 1.28$ m^3/kg

a) incompressible

Energy Eq.6.13: $\Delta h = \frac{1}{2}\mathbf{V}^2 = 2000$ kJ/kg

If A.5 $\Delta T = \Delta h/C_p = 1992$ K unreasonable, too high for that C_p

Use A.7: $h_{st} = h_o + \frac{1}{2}\mathbf{V}^2 = 223.22 + 2000 = 2223.3$ kJ/kg

$T_{st} = 1977$ K

Bernoulli (incompressible) Eq.9.17:

$\Delta P = P_{st} - P_o = \frac{1}{2}\mathbf{V}^2/v = 2000/1.28 = 1562.5$ kPa

$P_{st} = 1562.5 + 50 = 1612.5$ kPa

b) compressible

$T_{st} = 1977$ K the same energy equation.

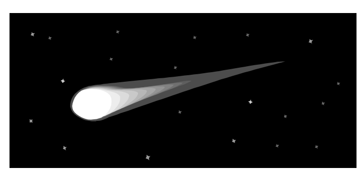
From A.7.1: $s^o_{T\,st} = 8.9517$ kJ/kg K; $s^o_{T\,o} = 6.5712$ kJ/kg K

Eq.8.28:

$$P_{st} = P_o \times e^{(s^o_{T\,st} - s^o_{T\,o})/R}$$

$$= 50 \times \exp\left[\frac{8.9517 - 6.5712}{0.287}\right]$$

$$= \mathbf{200\ 075\ kPa}$$

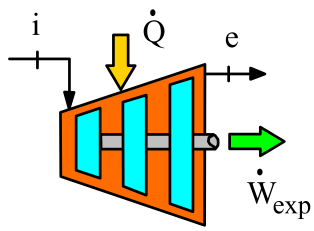


Notice that this is highly compressible, v is not constant.

9.90

Helium gas enters a steady-flow expander at 800 kPa, 300°C, and exits at 120 kPa. The mass flow rate is 0.2 kg/s, and the expansion process can be considered as a reversible polytropic process with exponent, *n* = 1.3. Calculate the power output of the expander.

Solution:



CV: expander, reversible polytropic process.
From Eq.8.37:

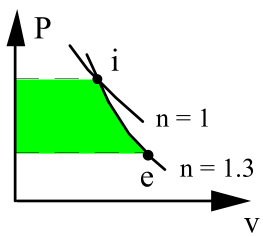
$$T_e = T_i\left(\frac{P_e}{P_i}\right)^{\frac{n-1}{n}} = 573.2\left(\frac{120}{800}\right)^{\frac{0.3}{1.3}} = 370 \text{ K}$$

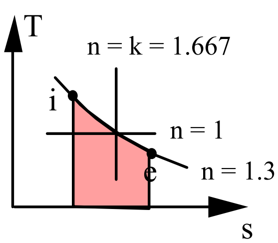
Work evaluated from Eq.9.19

$$w = -\int v dP = -\frac{nR}{n-1}(T_e - T_i) = \frac{-1.3 \times 2.07703}{0.3}(370 - 573.2)$$

$$= 1828.9 \text{ kJ/kg}$$

$\dot{W} = \dot{m}w = 0.2 \times 1828.9 =$ **365.8 kW**





9.91

Air at 100 kPa, 300 K, flows through a device at steady state with the exit at 1000 K during which it went through a polytropic process with n = 1.3. Find the exit pressure, the specific work and heat transfer.

Solution:

C.V. Steady state device, single inlet and single exit flow.

Energy Eq.6.13: $h_1 + q = h_2 + w$ Neglect kinetic, potential energies

Entropy Eq.9.8: $s_1 + \int dq/T + s_{gen} = s_2$

$T_e = 1000$ K; $T_i = 300$ K; $P_i = 100$ kPa

Process Eq.8.37: $P_e = P_i\,(T_e/\,T_i)^{\frac{n}{n-1}} = 100\,(1000/300)^{\frac{1.3}{0.3}} = \mathbf{18\,442\ kPa}$

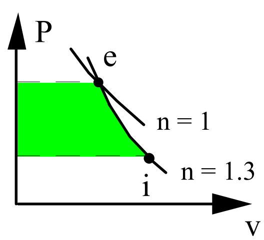
and the process leads to Eq.9.19 for the work term

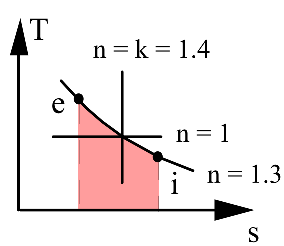
$$w = \frac{n}{n-1}\,R\,(T_e - T_i) = (1.3/-0.3) \times 0.287 \times (1000 - 300)$$

$= \mathbf{-\ 849.3\ kJ/kg}$

$q = h_e - h_i + w = 1046.2 - 300.5 - 849.3$

$= \mathbf{-103.6\ kJ/kg}$





Notice:
dP > 0
so dw <0

ds < 0
so dq < 0

9.92

A flow of 4 kg/s ammonia goes through a device in a polytropic process with an inlet state of 150 kPa, -20°C and an exit state of 400 kPa, 80°C. Find the polytropic exponent n, the specific work and heat transfer.

Solution:

C.V. Steady state device, single inlet and single exit flow.

Energy Eq.6.13: $h_1 + q = h_2 + w$ Neglect kinetic, potential energies

Entropy Eq.9.8: $s_1 + \int dq/T + s_{gen} = s_2$

Process Eq.8.37: $P_1 v_1^n = P_2 v_2^n$:

State 1: Table B.2.2 $v_1 = 0.79774$, $s_1 = 5.7465$ kJ/kg K, $h_1 = 1422.9$ kJ/kg

State 2: Table B.2.2 $v_2 = 0.4216$, $s_2 = 5.9907$ kJ/kg K, $h_2 = 1636.7$ kJ/kg

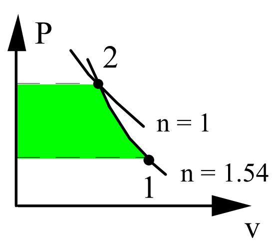
$$\ln (P_2/P_1) = n \ln (v_1/v_2) \quad => \quad 0.98083 = n \times 0.63772$$

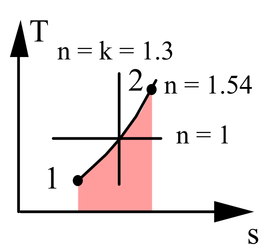
$$n = \ln (P_2/P_1) / \ln (v_1/v_2) = \mathbf{1.538}$$

From the process and the integration of v dP gives Eq.9.19.

$$w_{shaft} = -\frac{n}{n-1} (P_2 v_2 - P_1 v_1) = -2.8587 (168.64 - 119.66) = \mathbf{-140.0\ kJ/kg}$$

$$q = h_2 + w - h_1 = 1636.7 - 1422.9 - 140 = \mathbf{73.8\ kJ/kg}$$





Notice:
dP > 0
so dw <0

ds > 0
so dq > 0

9.93

Carbon dioxide flows through a device entering at 300 K, 200 kPa and leaving at 500 K. The process is steady state polytropic with n = 3.8 and heat transfer comes from a 600 K source. Find the specific work, specific heat transfer and the specific entropy generation due to this process.

Solution:

C.V. Steady state device, single inlet and single exit flow.

Energy Eq.6.13: $h_i + q = h_e + w$ Neglect kinetic, potential energies

Entropy Eq.9.8: $s_i + \int dq/T + s_{gen} = s_e$

Process Eq.8.37:

$$P_e = P_i\,(T_e/\,T_i)^{\frac{n}{n-1}} = 200(500/300)^{\frac{3.8}{2.8}} = 400\text{ kPa}$$

and the process leads to Eq.9.19 for the work term

$$w = -\frac{n}{n-1}\,R\,(T_e - T_i) = -\frac{3.8}{2.8} \times 0.1889 \times (500 - 300) = \mathbf{-51.3\ kJ/kg}$$

Energy equation gives

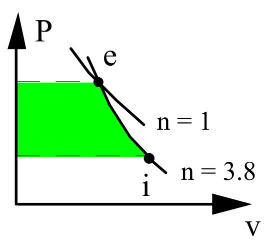
$$q = h_e - h_i + w = 401.52 - 214.38 - 51.3 = \mathbf{135.8\ kJ/kg}$$

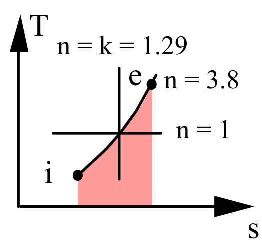
Entropy equation gives (CV out to source)

$$s_{gen} = s_e - s_i - q/T_{source} = s^o_{Te} - s^o_{Ti} - R\,\ln(P_e\,/\,P_i) - q/T_{source}$$

$$= 5.3375 - 4.8631 - 0.1889\,\ln\,(400/200) - (135.8/600)$$

$$= \mathbf{0.117\ kJ/kg\ K}$$





Notice:
dP > 0
so dw <0

ds > 0
so dq > 0

Notice process is externally irreversible, ΔT between source and CO_2

9.94

An expansion in a gas turbine can be approximated with a polytropic process with exponent n = 1.25. The inlet air is at 1200 K, 800 kPa and the exit pressure is 125 kPa with a mass flow rate of 0.75 kg/s. Find the turbine heat transfer and power output.

Solution:

C.V. Steady state device, single inlet and single exit flow.

Energy Eq.6.13: $h_i + q = h_e + w$ Neglect kinetic, potential energies

Entropy Eq.9.8: $s_i + \int dq/T + s_{gen} = s_e$

Process Eq.8.37:

$$T_e = T_i\,(P_e/P_i)^{\frac{n-1}{n}} = 1200\,(125/800)^{\frac{0.25}{1.25}} = 827.84 \text{ K}$$

so the exit enthalpy is from Table A.7.1

$$h_e = 822.2 + \frac{27.84}{50}(877.4 - 822.2) = 852.94 \text{ kJ/kg}$$

The process leads to Eq.9.19 for the work term

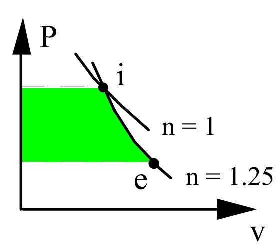
$$\dot{W} = \dot{m}w = -\dot{m}\frac{nR}{n-1}(T_e - T_i) = -0.75\,\frac{1.25 \times 0.287}{0.25} \times (827.84 - 1200)$$

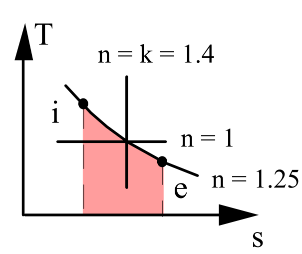
$$= \mathbf{400.5\ kW}$$

Energy equation gives

$$\dot{Q} = \dot{m}q = \dot{m}(h_e - h_i) + \dot{W} = 0.75(852.94 - 1277.81) + 400.5$$

$$= -318.65 + 400.5 = \mathbf{81.9\ kW}$$





Notice:
dP < 0
so dw > 0

ds > 0
so dq > 0

Notice this process has some heat transfer in during expansion which is unusual. The typical process would have n = 1.5 with a heat loss.

Device efficiency

9.95

Find the isentropic efficiency of the R-134a compressor in Example 6.10

Solution:

State 1: Table B.5.2 $h_1 = 387.2$ kJ/kg; $s_1 = 1.7665$ kJ/kg K

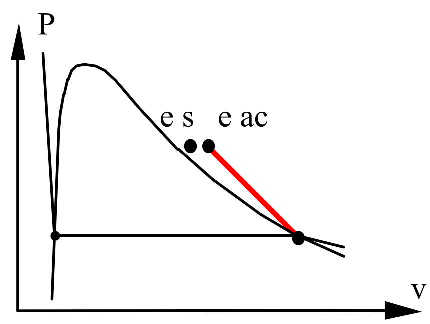
State 2ac: $h_2 = 435.1$ kJ/kg

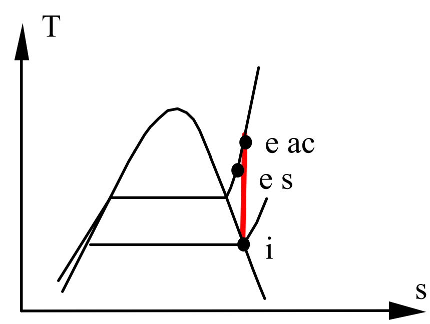
State 2s: s = 1.7665 kJ/kg K, 800 kPa => h = 431.8 kJ/kg; T = 46.8°C

$-w_{c\,s} = h_{2s} - h_1 = 431.8 - 387.2 = 44.6$ kJ/kg

$-w_{ac} = 5/0.1 = 50$ kJ/kg

$\eta = w_{c\,s} / w_{ac} = 44.6/50 =$ **0.89**





9.96

A compressor is used to bring saturated water vapor at 1 MPa up to 17.5 MPa, where the actual exit temperature is 650°C. Find the isentropic compressor efficiency and the entropy generation.

Solution:

C.V. Compressor. Assume adiabatic and neglect kinetic energies.

Energy Eq.6.13: $w = h_1 - h_2$

Entropy Eq.9.8: $s_2 = s_1 + s_{gen}$

We have two different cases, the ideal and the actual compressor.

States: 1: B.1.2 $h_1 = 2778.1$ kJ/kg, $s_1 = 6.5865$ kJ/kg K

2ac: B.1.3 $h_{2,AC} = 3693.9$ kJ/kg, $s_{2,AC} = 6.7357$ kJ/kg K

2s: B.1.3 (P, $s = s_1$) $h_{2,s} = 3560.1$ kJ/kg

IDEAL:

$-w_{c,s} = h_{2,s} - h_1 = 782$ kJ/kg

ACTUAL:

$-w_{C,AC} = h_{2,AC} - h_1 = 915.8$ kJ/kg

Definition Eq.9.28: $\eta_c = w_{c,s}/w_{c,AC} = \mathbf{0.8539 \sim 85\%}$

Entropy Eq.9.8:

$s_{gen} = s_{2\ ac} - s_1 = 6.7357 - 6.5865 =$ **0.1492 kJ/kg K**

9.97

Liquid water enters a pump at 15°C, 100 kPa, and exits at a pressure of 5 MPa. If the isentropic efficiency of the pump is 75%, determine the enthalpy (steam table reference) of the water at the pump exit.

Solution:

CV: pump $\dot{Q}_{CV} \approx 0, \quad \Delta KE \approx 0, \quad \Delta PE \approx 0$

2nd law, reversible (ideal) process: $s_{es} = s_i \;\Rightarrow$

Eq.9.18 for work term.

$$w_s = -\int_i^{es} v\,dP \approx -v_i(P_e - P_i) = -0.001001(5000 - 100) = -4.905 \text{ kJ/kg}$$

Real process Eq.9.28: $w = w_s/\eta_s = -4.905/0.75 = -6.54$ kJ/kg

Energy Eq.6.13: $h_e = h_i - w = 62.99 + 6.54 =$ **69.53 kJ/kg**

9.98

A centrifugal compressor takes in ambient air at 100 kPa, 15°C, and discharges it at 450 kPa. The compressor has an isentropic efficiency of 80%. What is your best estimate for the discharge temperature?

Solution:

C.V. Compressor. Assume adiabatic, no kinetic energy is important.

Energy Eq.6.13: $w = h_1 - h_2$

Entropy Eq.9.8: $s_2 = s_1 + s_{gen}$

We have two different cases, the ideal and the actual compressor.

We will solve using constant specific heat.

State 2 for the ideal, $s_{gen} = 0$ so $s_2 = s_1$ and it becomes:

Eq.8.32: $T_{2s} = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 288.15\ (450 / 100)^{0.2857} = 442.83\ \text{K}$

$w_s = h_1 - h_{2s} = C_p\ (T_1 - T_{2s}) = 1.004\ (288.15 - 442.83) = -155.299$

The actual work from definition Eq.9.28 and then energy equation:

$w_{ac} = -155.299 / 0.8 = -194.12\ \text{kJ/kg} = h_1 - h_2 = C_p(T_1 - T_2)$

$\Rightarrow\ T_2 = T_1 - w_{ac} / C_p$

$= 288.15 + 194.12/1.004 =$ **481.5 K**

Solving using Table A.7.1 instead will give

State 1: Table A.7.1: $s^o_{T1} = 6.82869$ kJ/kg K

Now constant s for the ideal is done with Eq.8.28

$s^o_{T2s} = s^o_{T1} + R \ln(\frac{P_2}{P_1}) = 6.82869 + 0.287 \ln(\frac{450}{100}) = 7.26036\ \text{kJ/kg K}$

From A.7.1: $T_{2s} = 442.1$ K and $h_{2s} = 443.86$ kJ/kg

$w_s = h_1 - h_{2s} = 288.57 - 443.86 = -155.29$ kJ/kg

The actual work from definition Eq.9.28 and then energy equation:

$w_{ac} = -155.29/0.8 = -194.11$ kJ/kg

$\Rightarrow\ h_2 = 194.11 + 288.57 = 482.68$, Table A.7.1: $T_2 =$ **480 K**

9.99

An emergency drain pump should be able to pump 0.1 m^3/s liquid water at 15°C, 10 m vertically up delivering it with a velocity of 20 m/s. It is estimated that the pump, pipe and nozzle have a combined isentropic efficiency expressed for the pump as 60%. How much power is needed to drive the pump?

Solution:

C.V. Pump, pipe and nozzle together. Steady flow, no heat transfer.

Consider the ideal case first (it is the reference for the efficiency).

Energy Eq.6.12: $\dot{m}_i(h_i + \mathbf{V}^2{}_i/2 + gZ_i) + \dot{W}_{in} = \dot{m}_e(h_e + \mathbf{V}^2{}_e/2 + gZ_e)$

Solve for work and use reversible process Eq.9.13

$$\dot{W}_{ins} = \dot{m}\,[h_e - h_i + (\mathbf{V}^2{}_e - \mathbf{V}^2{}_i)/2 + g(Z_e - Z_i)]$$

$$= \dot{m}[(P_e - P_i)v + \mathbf{V}^2{}_e/2 + g\Delta Z]$$

$$\dot{m} = \dot{V}/v = 0.1/0.001001 = 99.9 \text{ kg/s}$$

$$\dot{W}_{ins} = 99.9[0 + (20^2/2) \times (1/1000) + 9.807 \times (10/1000)]$$

$$= 99.9(0.2 + 0.09807) = 29.8 \text{ kW}$$

With the estimated efficiency the actual work, Eq.9.28 is

$$\dot{W}_{inactual} = \dot{W}_{ins}/\eta = 29.8/0.6 = 49.7 \text{ kW} = \mathbf{50\ kW}$$

9.100

A pump receives water at 100 kPa, 15°C and a power input of 1.5 kW. The pump has an isentropic efficiency of 75% and it should flow 1.2 kg/s delivered at 30 m/s exit velocity. How high an exit pressure can the pump produce?

Solution:

CV Pump. We will assume the ideal and actual pumps have same exit pressure, then we can analyse the ideal pump.

Specific work: $w_{ac} = 1.5/1.2 = 1.25$ kJ/kg

Ideal work Eq.9.28: $w_s = \eta\ w_{ac} = 0.75 \times 1.25 = 0.9375$ kJ/kg

As the water is incompressible (liquid) we get

Energy Eq.9.14:

$$w_s = (P_e - P_i)v + \mathbf{V}^2{}_e/2 = (P_e - P_i)0.001001 + (30^2/2)/1000$$

$$= (P_e - P_i)0.001001 + 0.45$$

Solve for the pressure difference

$$P_e - P_i = (w_s – 0.45)/0.001001 = 487 \text{ kPa}$$

$$\mathbf{P_e = 587\ kPa}$$

9.101

A small air turbine with an isentropic efficiency of 80% should produce 270 kJ/kg of work. The inlet temperature is 1000 K and it exhausts to the atmosphere. Find the required inlet pressure and the exhaust temperature.

Solution:

C.V. Turbine actual energy Eq.6.13:

$$w = h_i - h_{e,ac} = 270 \text{ kJ/kg}$$

Table A.7: $h_i = 1046.22 \;\Rightarrow\; h_{e,ac} = 776.22$ kJ/kg, $\mathbf{T_e = 757.9\ K}$

C.V. Ideal turbine, Eq.9.27 and energy Eq.6.13:

$$w_s = w/\eta_s = 270/0.8 = 337.5 = h_i - h_{e,s} \;\Rightarrow\; h_{e,s} = 708.72 \text{ kJ/kg}$$

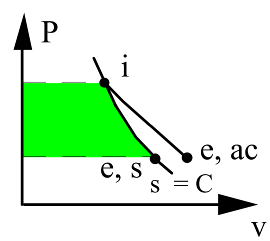
From Table A.7: $T_{e,s} = 695.5$ K

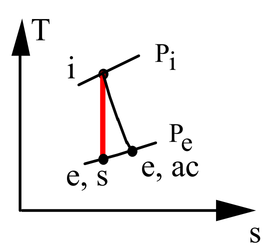
Entropy Eq.9.8: $s_i = s_{e,s}$ adiabatic and reversible

To relate the entropy to the pressure use Eq.8.28 inverted and standard entropy from Table A.7.1:

$$P_e/P_i = \exp[\,(s^o_{Te} - s^o_{Ti}\,)\,/\,R\,] = \exp[(7.733 - 8.13493)/0.287] = 0.2465$$

$$P_i = P_e\,/\,0.2465 = 101.3/0.2465 = \mathbf{411\ kPa}$$





If constant heat capacity were used

$$T_e = T_i - w/C_p = 1000 - 270/1.004 = 731 \text{ K}$$

C.V. Ideal turbine, Eq.9.27 and energy Eq.6.13:

$$w_s = w/\eta_s = 270/0.8 = 337.5 \text{ kJ/kg} = h_i - h_{e,s} = C_p(T_i - T_{e,s})$$

$$T_{e,s} = T_i - w_s/C_p = 1000 - 337.5/1.004 = 663.8 \text{ K}$$

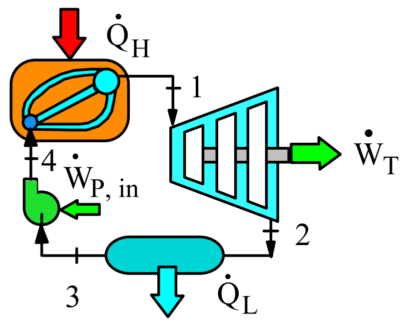
Eq.9.8 (adibatic and reversible) gives constant s and relation is Eq.8.32

$$P_e/P_i = (T_e/T_i)^{k/(k-1)} \;\Rightarrow\; P_i = 101.3\ (1000/663.8)^{3.5} = 425 \text{ kPa}$$

9.102

Repeat Problem 9.42 assuming the turbine and the pump each have an isentropic efficiency of 85%.

Solution:



$P_1 = P_4 = 20$ MPa
$T_1 = 700$ °C
$P_2 = P_3 = 20$ kPa
$T_3 = 40$ °C
$\eta_P = \eta_T = 85\%$

a) State 1: (P, T) Table B.1.3 $h_1 = 3809.1$ kJ/kg, $s_1 = 6.7993$ kJ/kg K

C.V. Turbine. First we do the ideal, then the actual.

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

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

$h_{2\,s} = 251.4 + 0.8433 \times 2358.33 = 2240.1$ kJ/kg

Energy Eq.6.13: $w_{T\,s} = h_1 - h_{2\,s} = 1569$ kJ/kg

$w_{T\,AC} = \eta_T w_{T\,s} = \mathbf{1333.65} = h_1 - h_{2\,AC}$

$h_{2\,AC} = h_1 - w_{T\,AC} = 2475.45$ kJ/kg;

$\mathbf{x_{2,AC}} = (2475.45 - 251.4)/2358.3 = \mathbf{0.943}$ **,** $\mathbf{T_{2,AC} = 60.06°C}$

b)

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

$h_3 = 167.54$ kJ/kg, $v_3 = 0.001008$ m^3/kg

$w_{P\,s} = -\,v_3(P_4 - P_3) = -0.001008(20000 - 20) = -20.1$ kJ/kg

$-w_{P,AC} = -w_{P,s}/\eta_\rho = 20.1/0.85 = \mathbf{23.7} = h_{4,AC} - h_3$

$h_{4,AC} = \mathbf{191.2}$ $T_{4,AC} \cong 45.7°C$

c) The heat transfer in the boiler is from energy Eq.6.13

$q_{boiler} = h_1 - h_4 = 3809.1 - 191.2 = 3617.9$ kJ/kg

$w_{net} = 1333.65 - 23.7 = \mathbf{1310\ kJ/kg}$

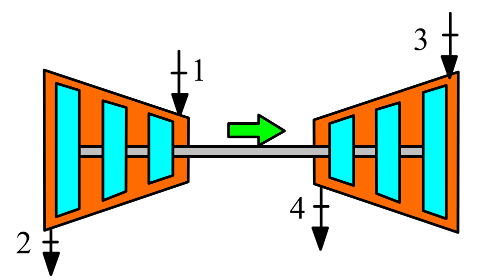
$$\eta_{TH} = w_{net}/q_{boiler} = \frac{1310}{3617.9} = \mathbf{0.362}$$

9.103

Repeat Problem 9.41 assuming the steam turbine and the air compressor each have an isentropic efficiency of 80%.
A certain industrial process requires a steady supply of saturated vapor steam at 200 kPa, at a rate of 0.5 kg/s. Also required is a steady supply of compressed air at 500 kPa, at a rate of 0.1 kg/s. Both are to be supplied by the process shown in Fig. P9.41. Steam is expanded in a turbine to supply the power needed to drive the air compressor, and the exhaust steam exits the turbine at the desired state. Air into the compressor is at the ambient conditions, 100 kPa, 20°C. Give the required steam inlet pressure and temperature, assuming that both the turbine and the compressor are reversible and adiabatic.

Solution:

C.V. Each device. Steady flow. Both adiabatic ($q = 0$) and actual devices ($s_{gen} > 0$) given by η_{sT} and η_{sc}.



Air Eq.8.32, $T_{4s} = T_3(P_4/P_3)^{\frac{k-1}{k}} = 293.2\left(\frac{500}{100}\right)^{0.286} = 464.6 \text{ K}$

$$\dot{W}_{Cs} = \dot{m}_3(h_3 - h_{4s}) = 0.1 \times 1.004(293.2 - 464.6) = -17.21 \text{ kW}$$

$$\dot{W}_{Cs} = \dot{m}_3(h_3 - h_4) = \dot{W}_{Cs} /\eta_{sc} = -17.2/0.80 = -21.5 \text{ kW}$$

Now the actual turbine must supply the actual compressor work. The actual state 2 is given so we must work backwards to state 1.

$$\dot{W}_T = +21.5 \text{ kW} = \dot{m}_1(h_1 - h_2) = 0.5(h_1 - 2706.6)$$

$$\Rightarrow \quad h_1 = 2749.6 \text{ kJ/kg}$$

Also, $\eta_{sT} = 0.80 = (h_1 - h_2)/(h_1 - h_{2s}) = 43/(2749.6 - h_{2s})$

$$\Rightarrow h_{2s} = 2695.8 \text{ kJ/kg}$$

$2695.8 = 504.7 + x_{2s}(2706.6 - 504.7) \quad => \quad x_{2s} = 0.9951$

$s_{2s} = 1.5301 + 0.9951(7.1271 - 1.5301) = 7.0996 \text{ kJ/kg K}$

$(s_1 = s_{2s}, h_1) \rightarrow P_1 =$ **269 kPa**, $T_1 =$ **143.5°C**

9.104

Steam enters a turbine at 300°C, 600 kPa and exhausts as saturated vapor at 20 kPa. What is the isentropic efficiency?

Solution:

C.V. Turbine. Steady single inlet and exit flow.

To get the efficiency we must compare the actual turbine to the ideal one (the reference).

Energy Eq.6.13: $w_T = h_1 - h_2$;

Entropy Eq.9.8: $s_{2s} = s_1 + s_{gen} = s_1$

Process: Ideal $s_{gen} = 0$

State 1: Table B.1.3 $h_1 = 3061.63$ kJ/kg, $s_1 = 7.3723$ kJ/kg K

State 2s: 20 kPa, $s_{2s} = s_1 = 7.3723$ kJ/kg K $< s_g$ so two-phase

$$x_{2s} = \frac{s - s_f}{s_{fg}} = \frac{7.3723 - 0.8319}{7.0766} = 0.92423$$

$$h_{2s} = h_f + x_{2s}\, h_{fg} = 251.38 + x_{2s} \times 2358.33 = 2431.0 \text{ kJ/kg}$$

$$w_{Ts} = h_1 - h_{2s} = 3061.63 - 2431.0 = 630.61 \text{ kJ/kg}$$

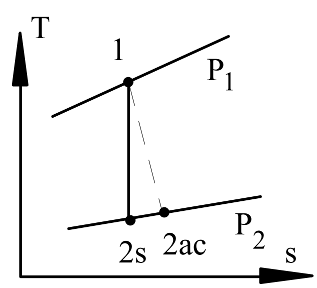
State 2ac: Table B.1.2 $h_{2ac} = 2609.7$ kJ/kg, $s_{2ac} = 7.9085$ kJ/kg K

Now we can consider the actual turbine from energy Eq.6.13:

$$w^T_{ac} = h_1 - h_{2ac} = 3061.63 - 2609.7 = 451.93$$

Then the efficiency from Eq. 9.27

$$\eta_T = w^T_{ac} / w_{Ts} = 451.93/630.61 = \mathbf{0.717}$$



9.105

A turbine receives air at 1500 K, 1000 kPa and expands it to 100 kPa. The turbine has an isentropic efficiency of 85%. Find the actual turbine exit air temperature and the specific entropy increase in the actual turbine.

Solution:

C.V. Turbine. steady single inlet and exit flow.

To analyze the actual turbine we must first do the ideal one (the reference).

Energy Eq.6.13: $w_T = h_1 - h_2$;

Entropy Eq.9.8: $s_2 = s_1 + s_{gen} = s_1$

Entropy change in Eq.8.28 and Table A.7.1:

$$s^o_{T2} = s^o_{T1} + R \ln(P_2/P_1) = 8.61208 + 0.287 \ln(100/1000) = 7.95124$$

Interpolate in A.7 => $T_{2s} = 849.2$, $h_{2s} = 876.56$ =>

$$w_T = 1635.8 - 876.56 = 759.24 \text{ kJ/kg}$$

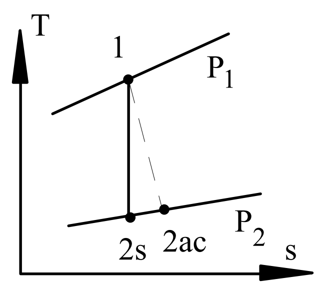
Now we can consider the actual turbine from Eq.9.27 and Eq.6.13:

$$w^T_{ac} = \eta_T\, w_T = 0.85 \times 759.24 = 645.35 = h_1 - h_{2ac}$$

$$\Rightarrow \quad h_{2ac} = h_1 - w^T_{ac} = 990.45 \quad \Rightarrow \quad \mathbf{T_{2ac} = 951\ K}$$

The entropy balance equation is solved for the generation term

$$s_{gen} = s_{2ac} - s_1 = 8.078 - 8.6121 - 0.287 \ln(100/1000) = \mathbf{0.1268\ kJ/kg\ K}$$



9.106

The small turbine in Problem 9.38 was ideal. Assume instead the isentropic turbine efficiency is 88%. Find the actual specific turbine work and the entropy generated in the turbine.

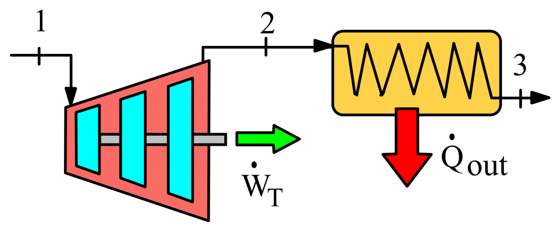
Solution:

Continuity Eq.6.11: (Steady)

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}$$

Turbine: Energy Eq.6.13:

$$w_T = h_1 - h_2$$



Entropy Eq.9.8: $s_2 = s_1 + s_{T\ gen}$

Inlet state: Table B.1.3 $h_1 = 3917.45$ kJ/kg, $s_1 = 7.9487$ kJ/kg K

Ideal turbine $s_{T\ gen} = 0$, $s_2 = s_1 = 7.9487 = s_{f2} + x\ s_{fg2}$

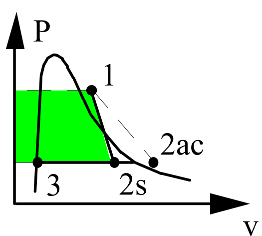
State 2: P = 10 kPa, $s_2 < s_g$ => saturated 2-phase in Table B.1.2

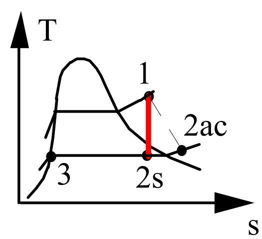
$\Rightarrow\ x_{2,s} = (s_1 - s_{f2})/s_{fg2} = (7.9487 - 0.6492)/7.501 = 0.9731$

$\Rightarrow\ h_{2,s} = h_{f2} + x \times h_{fg2} = 191.8 + 0.9731 \times 2392.8 = 2520.35$ kJ/kg

$w_{T,s} = h_1 - h_{2,s} = 1397.05$ kJ/kg

Explanation for the reversible work term is in sect. 9.3 Eq.9.18





$w_{T,AC} = \eta \times w_{T,s} = \mathbf{1229.9\ kJ/kg}$

$= h_1 - h_{2,AC} \ \Rightarrow\ h_{2,AC} = h_1 - w_{T,AC} = 2687.5$ kJ/kg

$\Rightarrow\ T_{2,AC} = 100°C$, $s_{2,AC} = 8.4479$ kJ/kg-K

$s_{T\ gen} = s_{2,AC} - s_1 = \mathbf{0.4992\ kJ/kg\ K}$

9.107

Air enters an insulated turbine at 50°C, and exits the turbine at - 30°C, 100 kPa. The isentropic turbine efficiency is 70% and the inlet volumetric flow rate is 20 L/s. What is the turbine inlet pressure and the turbine power output?

Solution:

C.V.: Turbine, $\eta_s = 0.7$, Insulated

Air table A.5: $C_p = 1.004$ kJ/kg K, $R = 0.287$ kJ/kg K, $k = 1.4$

Inlet: $T_i = 50^oC$, $\dot{V}_i = 20$ L/s $= 0.02$ m^3/s ;

$$\dot{m} = P\dot{V}/RT = 100 \times 0.02/(0.287 \times 323.15) = 0.099 \text{ kg/s}$$

Exit (actual): $T_e = -30^oC$, $P_e = 100$ kPa

1st Law Steady state Eq.6.13: $q_T + h_i = h_e + w_T$; $q_T = 0$

Assume Constant Specific Heat

$w_T = h_i - h_e = C_p(T_i - T_e) = 80.3$ kJ/kg

$w_{Ts} = w/\eta = 114.7$ kJ/kg, $w_{Ts} = C_p(T_i - T_{es})$

Solve for $T_{es} = 208.9$ K

Isentropic Process Eq.8.32: $P_e = P_i\,(T_e / T_i)^{\frac{k}{k-1}}$ => $\mathbf{P_i = 461\ kPa}$

$\dot{W}_T = \dot{m}w_T = 0.099 \times 80.3 =$ **7.98 kW**

9.108

Carbon dioxide, CO_2, enters an adiabatic compressor at 100 kPa, 300 K, and exits at 1000 kPa, 520 K. Find the compressor efficiency and the entropy generation for the process.

Solution:

C.V. Ideal compressor. We will assume constant heat capacity.

Energy Eq.6.13: $w_c = h_1 - h_2$,

Entropy Eq.9.8, 8.32: $s_2 = s_1$: $T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 300\left(\frac{1000}{100}\right)^{0.2242} = 502.7$ K

$w_{cs} = C_p(T_1 - T_{2s}) = 0.842(300\text{-}502.7) = -170.67$ kJ/kg

C.V. Actual compressor

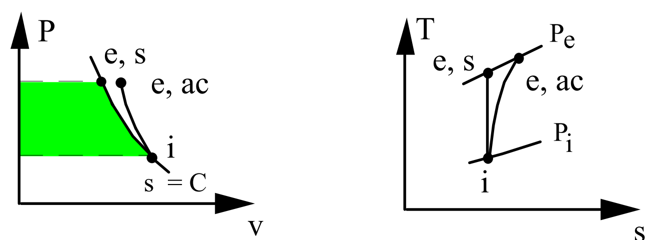
$w_{cac} = C_p(T_1 - T_{2ac}) = 0.842(300 - 520) = -185.2$ kJ/kg

$\eta_c = w_{cs}/w_{cac} = -170.67/(-185.2) = \mathbf{0.92}$

Use Eq.8.25 for the change in entropy

$s_{gen} = s_{2ac} - s_1 = C_p \ln(T_{2ac}/T_1) - R \ln(P_2/P_1)$

$= 0.842 \ln(520 / 300) - 0.1889 \ln(1000 / 100) = \mathbf{0.028\ kJ/kg\ K}$



Constant heat capacity is not the best approximation. It would be more accurate to use Table A.8.

9.109

Air enters an insulated compressor at ambient conditions, 100 kPa, 20°C, at the rate of 0.1 kg/s and exits at 200°C. The isentropic efficiency of the compressor is 70%. What is the exit pressure? How much power is required to drive the compressor? Assume the ideal and actual compressor has the same exit pressure.

Solution:

C.V. Compressor: P_1, T_1, T_e(real), $\eta_{s\ COMP}$ known, assume constant C_{P0}

Energy Eq.6.13 for real: $-w = C_{P0}(T_e - T_i) = 1.004(200 - 20) = 180.72$

Ideal $-w_s = -w \times \eta_s = 180.72 \times 0.70 = 126.5$

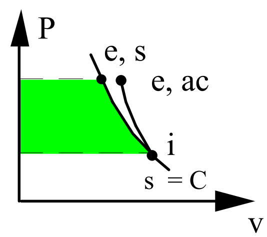
Energy Eq.6.13 for ideal:

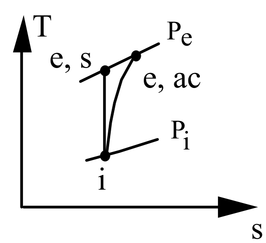
$126.5 = C_{P0}(T_{es} - T_i) = 1.004(T_{es} - 293.2)$, $T_{es} = 419.2$ K

Constant entropy for ideal as in Eq.8.32:

$P_e = P_i(T_{es}/T_i)^{\frac{k}{k-1}} = 100(419.2/293.20)^{3.5} = \mathbf{349\ kPa}$

$-\dot{W}_{REAL} = \dot{m}(-w) = 0.1 \times 180.72 = \mathbf{18.07\ kW}$





9.110

Assume an actual compressor has the same exit pressure and specific heat transfer as the ideal isothermal compressor in Problem 9.8 with an isothermal efficiency of 80%. Find the specific work and exit temperature for the actual compressor.

Solution:

C.V. Compressor. Steady, single inlet and single exit flows.

Energy Eq.6.13: $h_i + q = w + h_e$;

Entropy Eq.9.8: $s_i + q/T = s_e$

Inlet state: Table B.5.2, $h_i = 403.4$ kJ/kg, $s_i = 1.8281$ kJ/kg K

Exit state: Table B.5.1, $h_e = 398.36$ kJ/kg, $s_e = 1.7262$ kJ/kg K

$q = T(s_e - s_i) = 273.15(1.7262 - 1.8281) = - 27.83$ kJ/kg

$w = 403.4 + (-27.83) - 398.36 = -22.8$ kJ/kg

From Eq.9.29 for a cooled compressor

$w_{ac} = w_T / \eta = - 22.8/0.8 =$ **28.5 kJ/kg**

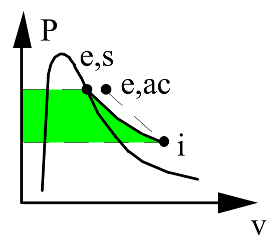
Now the energy equation gives

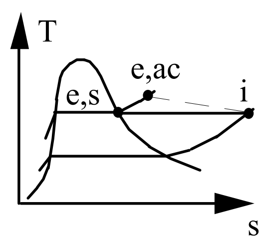
$h_e = h_i + q - w_{ac} = 403.4 + (-27.83) + 28.5 = 404.07$

$T_{e\ ac} \approx$ **6°C** $P_e = 294$ kPa

Explanation for the reversible work term is in Sect. 9.3

Eqs. 9.16 and 9.18





9.111

A water-cooled air compressor takes air in at 20°C, 90 kPa and compresses it to 500 kPa. The isothermal efficiency is 80% and the actual compressor has the same heat transfer as the ideal one. Find the specific compressor work and the exit temperature.

Solution:

Ideal isothermal compressor exit 500 kPa, 20°C

Reversible process: $dq = T\,ds \quad \Rightarrow \quad q = T(s_e - s_i)$

$$q = T(s_e - s_i) = T[s^o_{Te} - s^o_{T1} - R \ln(P_e / P_i)]$$

$$= - RT \ln (P_e / P_i) = - 0.287 \times 293.15 \ln (500/90) = - 144.3 \text{ kJ/kg}$$

As same temperature for the ideal compressor $\quad h_e = h_i \Rightarrow$

$$w = q = -144.3 \text{ kJ/kg} \quad \Rightarrow \quad w_{ac} = w/\eta = \mathbf{- 180.3\ kJ/kg}, \quad q_{ac} = q$$

Now for the actual compressor energy equation becomes

$$q_{ac} + h_i = h_{e\,ac} + w_{ac} \Rightarrow$$

$$h_{e\,ac} - h_i = q_{ac} - w_{ac} = - 144.3 - (-180.3) = 36 \text{ kJ/kg} \approx C_p (T_{e\,ac} - T_i)$$

$$T_{e\,ac} = T_i + 36/1.004 = \mathbf{55.9°C}$$

9.112

A nozzle in a high pressure liquid water sprayer has an area of 0.5 cm^2. It receives water at 250 kPa, 20°C and the exit pressure is 100 kPa. Neglect the inlet kinetic energy and assume a nozzle isentropic efficiency of 85%. Find the ideal nozzle exit velocity and the actual nozzle mass flow rate.

Solution:

C.V. Nozzle. Liquid water is incompressible v ≈ constant, no work, no heat transfer => Bernoulli Eq.9.17

$$\frac{1}{2}\mathbf{V}_{ex}^2 - 0 = v(P_i - P_e) = 0.001002\ (250 - 100) = 0.1503 \text{ kJ/kg}$$

$$\mathbf{V}_{ex} = \sqrt{2 \times 0.1503 \times 1000 \text{ J/kg}} = \mathbf{17.34\ m\ s^{-1}}$$

This was the ideal nozzle now we can do the actual nozzle, Eq. 9.30

$$\frac{1}{2}\mathbf{V}_{ex\ ac}^2 = \eta\ \frac{1}{2}\mathbf{V}_{ex}^2 = 0.85 \times 0.1503 = 0.12776 \text{ kJ/kg}$$

$$\mathbf{V}_{ex\ ac} = \sqrt{2 \times 0.12776 \times 1000 \text{ J/kg}} = 15.99 \text{ m s}^{-1}$$

$$\dot{m} = \rho A\mathbf{V}_{ex\ ac} = A\mathbf{V}_{ex\ ac}/v = 0.5 \times 10^{-4} \times 15.99 / 0.001002 = \mathbf{0.798\ kg/s}$$

9.113

A nozzle is required to produce a flow of air at 200 m/s at 20°C, 100 kPa. It is estimated that the nozzle has an isentropic efficiency of 92%. What nozzle inlet pressure and temperature is required assuming the inlet kinetic energy is negligible?

Solution:

C.V. Air nozzle: P_e, T_e(real), V_e(real), η_s(real)

For the real process: $h_i = h_e + \mathbf{V}_e^2/2$ or

$T_i = T_e + \mathbf{V}_e^2/2C_{P0} = 293.2 + 200^2/2 \times 1000 \times 1.004 = \mathbf{313.1\ K}$

For the ideal process, from Eq.9.30:

$\mathbf{V}_{es}^2/2 = \mathbf{V}_e^2/2\eta_s = 200^2/2 \times 1000 \times 0.92 \quad = 21.74$ kJ/kg

and $h_i = h_{es} + (\mathbf{V}_{es}^2/2)$

$T_{es} = T_i - \mathbf{V}_{es}^2/(2C_{P0}) = 313.1 - 21.74/1.004 = 291.4$ K

The constant s relation in Eq.8.32 gives

$$\Rightarrow \quad P_i = P_e\,(T_i/T_{es})^{\frac{k}{k-1}} = 100\left(\frac{313.1}{291.4}\right)^{3.50} = \mathbf{128.6\ kPa}$$

9.114

Redo Problem 9.79 if the water pump has an isentropic efficiency of 85% (hose, nozzle included).

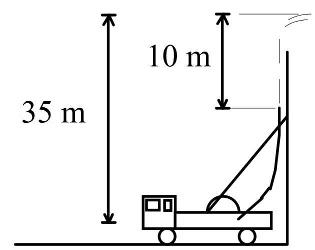
Solution:

C.V.: pump + hose + water column, height difference 35 m. **V** is velocity.

Continuity Eq.6.11: $\dot{m}_{in} = \dot{m}_{ex} = (\rho A\mathbf{V})_{nozzle}$;

Energy Eq.6.12: $\dot{m}(-w_p) + \dot{m}(h + \mathbf{V}^2/2 + gz)_{in} = \dot{m}(h + \mathbf{V}^2/2 + gz)_{ex}$

Process: $h_{in} \cong h_{ex}$, $\mathbf{V}_{in} \cong \mathbf{V}_{ex} = 0$,
$z_{ex} - z_{in} = 35$ m , $\rho = 1/v \cong 1/v_f$



$-w_p = g(z_{ex} - z_{in}) = 9.80665(35 - 0) = 343.2$ J/kg

The velocity in nozzle is such that it can rise 10 m, so make that column C.V.

$$gz_{noz} + \tfrac{1}{2}\mathbf{V}^2{}_{noz} = gz_{ex} + 0$$

$$\Rightarrow \mathbf{V}_{noz} = \sqrt{2g(z_{ex} - z_{noz})} = \sqrt{2 \times 9.81 \times 10} = 14 \text{ m/s}$$

$$\dot{m} = (\pi/v_f)\,(D^2/4)\,\mathbf{V}_{noz} = (\pi/4)\,0.025^2 \times 14 / 0.001 = 6.873 \text{ kg/s} ;$$

$$-\dot{W}_p = \dot{m}(-w_p)/\eta = 6.872 \times 0.343/0.85 = \mathbf{2.77\ kW}$$

9.115

Find the isentropic efficiency of the nozzle in example 6.4.

Solution:

C.V. adiabatic nozzle with known inlet state and velocity.

Inlet state: B.1.3 $h_i = 2850.1$ kJ/kg; $s_i = 6.9665$ kJ/kg K

Process ideal: adiabatic and reversible Eq.9.8 gives constant s

ideal exit, (150 kPa, s) ; $x_{es} = (6.9665 - 1.4335)/5.7897 = 0.9557$

$h_{es} = h_f + x_{es}\, h_{fg} = 2594.9$ kJ/kg

$\mathbf{V}_{es}^2/2 = h_i - h_{es} + \mathbf{V}_i^2/2 = 2850.1 - 2594.9 + (50^2)/2000 = 256.45$ kJ/kg

$\mathbf{V}_{es} = 716.2$ m/s

From Eq.9.30,

$$\eta_{noz.} = (\mathbf{V}_e^2/2)/(\mathbf{V}_{es}^2/2) = 180/256.45 = \mathbf{0.70}$$

9.116

Air flows into an insulated nozzle at 1 MPa, 1200 K with 15 m/s and mass flow rate of 2 kg/s. It expands to 650 kPa and exit temperature is 1100 K. Find the exit velocity, and the nozzle efficiency.

Solution:

C.V. Nozzle. Steady 1 inlet and 1 exit flows, no heat transfer, no work.

Energy Eq.6.13: $h_i + (1/2)\mathbf{V}_i^2 = h_e + (1/2)\mathbf{V}_e^2$

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

Ideal nozzle $s_{gen} = 0$ and assume same exit pressure as actual nozzle. Instead of using the standard entropy from Table A.7 and Eq.8.28 let us use a constant heat capacity at the average T and Eq.8.32. First from A.7.1

$$C_{p\ 1150} = \frac{1277.81 - 1161.18}{1200 - 1100} = 1.166 \text{ kJ/kg K};$$

$$C_v = C_{p\ 1150} - R = 1.166 - 0.287 = 0.8793, \quad k = C_{p\ 1150}/C_v = 1.326$$

Notice how they differ from Table A.5 values.

$$T_{e\ s} = T_i\ (P_e/P_i)^{\frac{k-1}{k}} = 1200 \left(\frac{650}{1000}\right)^{0.24585} = 1079.4 \text{ K}$$

$$\frac{1}{2}\mathbf{V}_{e\ s}^2 = \frac{1}{2}\mathbf{V}_i^2 + C(T_i - T_{e\ s}) = \frac{1}{2}\times 15^2 + 1.166(1200 - 1079.4) \times 1000$$

$$= 112.5 + 140619.6 = 140732 \text{ J/kg} \quad \Rightarrow \quad \mathbf{V}_{e\ s} = 530.5 \text{ m/s}$$

Actual nozzle with given exit temperature

$$\frac{1}{2}\mathbf{V}_{e\ ac}^2 = \frac{1}{2}\mathbf{V}_i^2 + h_i - h_{e\ ac} = 112.5 + 1.166(1200 - 1100) \times 1000$$

$$= 116712.5 \text{ J/kg}$$

$$\Rightarrow \quad \mathbf{V}_{e\ ac} = \mathbf{483\ m/s}$$

$$\eta_{noz} = (\tfrac{1}{2}\mathbf{V}_{e\ ac}^2 - \tfrac{1}{2}\mathbf{V}_i^2) / (\tfrac{1}{2}\mathbf{V}_{e\ s}^2 - \tfrac{1}{2}\mathbf{V}_i^2) =$$

$$= (h_i - h_{e,\ AC})/(h_i - h_{e,\ s}) = \frac{116600}{140619.6} = \mathbf{0.829}$$

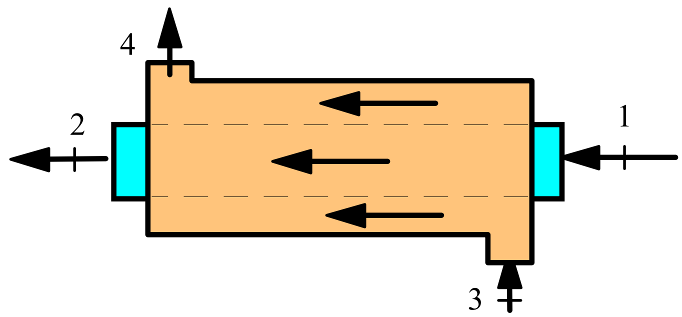
Review Problems

9.117

A coflowing heat exchanger has one line with 2 kg/s saturated water vapor at 100 kPa entering. The other line is 1 kg/s air at 200 kPa, 1200 K. The heat exchanger is very long so the two flows exit at the same temperature. Find the exit temperature by trial and error. Calculate the rate of entropy generation.

Solution:

C.V. Heat exchanger, steady 2 flows in and two flows out.
No W, no external Q



Flows: $\dot{m}_1 = \dot{m}_2 = \dot{m}_{H_2O}$; $\dot{m}_3 = \dot{m}_4 = \dot{m}_{air}$

Energy: $\dot{m}_{H_2O}\,(h_2 - h_1) = \dot{m}_{air}\,(h_3 - h_4)$

State 1: Table B.1.2 $h_1 = 2675.5$ kJ/kg State 2: 100 kPa, T_2

State 3: Table A.7 $h_3 = 1277.8$ kJ/kg, State 4: 200 kPa, T_2

Only one unknown T_2 and one equation the energy equation:

$$2(\,h_2 - 2675.5) = 1(1277.8 - h_4) \quad \Rightarrow \quad 2h_2 + h_4 = 6628.8 \text{ kW}$$

At 500 K: $h_2 = 2902.0$, $h_4 = 503.36$ => LHS = 6307 too small

At 700 K: $h_2 = 3334.8$, $h_4 = 713.56$ => LHS = 7383 too large

Linear interpolation $T_2 = 560$ K, $h_2 = 3048.3$, $h_4 = 565.47$ => LHS = 6662

Final states are with $\mathbf{T_2 = 554.4\ K = 281\ °C}$

H2O: Table B.1.3, $h_2 = 3036.8$ kJ/kg, $s_2 = 8.1473$, $s_1 = 7.3593$ kJ/kg K

AIR: Table A.7, $h_4 = 559.65$ kJ/kg, $s_{T4} = 7.4936$, $s_{T3} = 8.3460$ kJ/kg K

The entropy balance equation, Eq.9.7, is solved for the generation term:

$$\dot{S}_{gen} = \dot{m}_{H_2O}\,(s_2 - s_1) + \dot{m}_{air}\,(s_4 - s_3)$$

$$= 2(8.1473 - 7.3593) + 1\,(7.4936 - 8.3460) = \mathbf{0.724\ kW/K}$$

No pressure correction is needed as the air pressure for 4 and 3 is the same.

9.118

A vortex tube has an air inlet flow at 20°C, 200 kPa and two exit flows of 100 kPa, one at 0°C and the other at 40°C. The tube has no external heat transfer and no work and all the flows are steady and have negligible kinetic energy. Find the fraction of the inlet flow that comes out at 0°C. Is this setup possible?

Solution:

C.V. The vortex tube. Steady, single inlet and two exit flows. No q or w.

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

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

States all given by temperature and pressure. Use constant heat capacity to evaluate changes in h and s. Solve for $x = \dot{m}_2/\dot{m}_1$ from the energy equation

$\dot{m}_3/\dot{m}_1 = 1 - x;$ $h_1 = x\, h_2 + (1\text{-}x)\, h_3$

$\Rightarrow$ $x = (h_1 - h_3)/(h_2 - h_3) = (T_1 - T_3)/(T_2 - T_3) = (20–40)/(0–40) = 0.5$

Evaluate the entropy generation

$$\dot{S}_{gen}/\dot{m}_1 = x\, s_2 + (1\text{-}x)s_3 - s_1 = 0.5(s_2 - s_1) + 0.5(s_3 - s_1)$$

$$= 0.5\,[C_p \ln(T_2 / T_1) - R \ln(P_2 / P_1)] + 0.5[C_p \ln(T_3 / T_1) - R \ln(P_3/ P_1)]$$

$$= 0.5\left[1.004 \ln\left(\frac{273.15}{293.15}\right) - 0.287 \ln\left(\frac{100}{200}\right)\right]$$

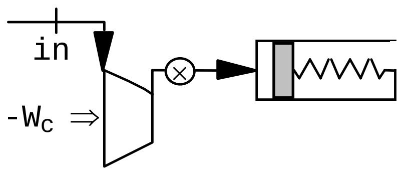
$$+ 0.5\left[1.004 \ln\left(\frac{313.15}{293.15}\right) - 0.287 \ln\left(\frac{100}{200}\right)\right]$$

= **0.1966 kJ/kg K > 0** **So this is possible**.

9.119

An initially empty spring-loaded piston/cylinder requires 100 kPa to float the piston. A compressor with a line and valve now charges the cylinder with water to a final pressure of 1.4 MPa at which point the volume is 0.6 m^3, state 2. The inlet condition to the reversible adiabatic compressor is saturated vapor at 100 kPa. After charging the valve is closed and the water eventually cools to room temperature, 20°C, state 3. Find the final mass of water, the piston work from 1 to 2, the required compressor work, and the final pressure, P_3.

Solution:



Process 1→2: transient, adiabatic.
for C.V. compressor + cylinder
Assume process is reversible

Continuity: $m_2 - 0 = m_{in}$, Energy: $m_2u_2 - \emptyset = (m_{in}h_{in}) - W_c - {}_1W_2$

Entropy Eq.: $m_2s_2 - \emptyset = m_{in}s_{in} + 0 \quad \Rightarrow \quad s_2 = s_{in}$

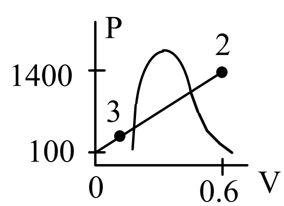
Inlet state: Table B.1.2, $h_{in} = 2675.5$ kJ/kg, $s_{in} = 7.3594$ kJ/kg K

$${}_1W_2 = \int PdV = \frac{1}{2}(P_{float} + P_2)(V_2 - \emptyset) = \frac{1}{2}(100+1400)0.6 = \mathbf{450\ kJ}$$

State 2: P_2 , $s_2 = s_{in}$ Table B.1.3 $\Rightarrow$ $v_2 = 0.2243$, $u_2 = 2984.4$ kJ/kg

$m_2 = V_2/v_2 = 0.6/0.2243 = \mathbf{2.675\ kg}$

$W_c = m_{in}h_{in} - m_2u_2 - {}_1W_2 = 2.675 \times (2675.5 - 2984.4) - 450 = \mathbf{-1276.3\ kJ}$



State 3 must be on line & 20°C

Assume 2-phase ⇒ $P_3 = P_{sat}(20°C) = 2.339$ kPa

less than P_{float} so compressed liquid

Table B.1.1: $v_3 \cong v_f(20°C) = 0.001002 \quad \Rightarrow \quad V_3 = m_3v_3 = 0.00268\ m^3$

On line: $P_3 = 100 + (1400 - 100) \times 0.00268/0.6 = \mathbf{105.8\ kPa}$

9.120

In a heat-powered refrigerator, a turbine is used to drive the compressor using the same working fluid. Consider the combination shown in Fig. P9.120 where the turbine produces just enough power to drive the compressor and the two exit flows are mixed together. List any assumptions made and find the ratio of mass flow rates $\dot{m}_3/\dot{m}_1$ and T_5 (x_5 if in two-phase region) if the turbine and the compressor are reversible and adiabatic

Solution:

CV: compressor

$s_{2S} = s_1 = 0.7082$ kJ/kg K $\rightarrow T_{2S} = 52.6°C$

$w_{SC} = h_1 - h_{2S} = 178.61 - 212.164 = -33.554$ kJ/kg

CV: turbine

$s_{4S} = s_3 = 0.6444 = 0.2767 + x_{4S} \times 0.4049 \quad => \quad x_{4S} = 0.9081$

$h_{4S} = 76.155 + 0.9081 \times 127.427 = 191.875$ kJ/kg

$w_{ST} = h_3 - h_{4S} = 209.843 - 191.875 = 17.968$ kJ/kg

As $\dot{w}_{TURB} = -\dot{w}_{COMP}$, $\dot{m}_3/\dot{m}_1 = -\dfrac{w_{SC}}{w_{ST}} = \dfrac{33.554}{17.968} = \mathbf{1.867}$

CV: mixing portion

$\dot{m}_1 h_{2S} + \dot{m}_3 h_{4S} = (\dot{m}_1 + \dot{m}_3) h_5$

$1 \times 212.164 + 1.867 \times 191.875 = 2.867\ h_5$

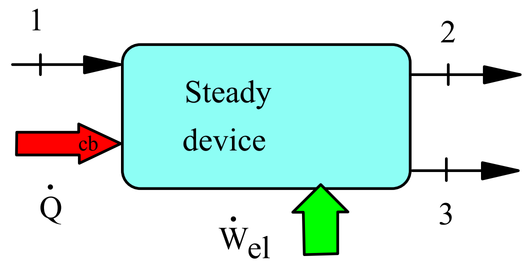
$\Rightarrow h_5 = 198.980 = 76.155 + x_5 \times 127.427 \quad => \quad x_5 = \mathbf{0.9639}$

9.121

A stream of ammonia enters a steady flow device at 100 kPa, 50°C, at the rate of 1 kg/s. Two streams exit the device at equal mass flow rates; one is at 200 kPa, 50°C, and the other as saturated liquid at 10°C. It is claimed that the device operates in a room at 25°C on an electrical power input of 250 kW. Is this possible?

Solution:

Control volume: Steady device out to ambient 25°C.



Energy Eq.6.10: $\dot{m}_1h_1 + \dot{Q} + \dot{W}_{el} = \dot{m}_2h_2 + \dot{m}_3h_3$

Entropy Eq.9.7: $\dot{m}_1s_1 + \dot{Q}/T_{room} + \dot{S}_{gen} = \dot{m}_2s_2 + \dot{m}_3s_3$

State 1: Table B.2.2, $h_1 = 1581.2$ kJ/kg, $s_1 = 6.4943$ kJ/kg K

State 2: Table B.2.2 $h_2 = 1576.6$ kJ/kg, $s_2 = 6.1453$ kJ/kg K

State 3: Table B.2.1 $h_3 = 226.97$ kJ/kg, $s_3 = 0.8779$ kJ/kg K

From the energy equation

$$\dot{Q} = 0.5 \times 1576.6 + 0.5 \times 226.97 - 1 \times 1581.2 - 250 = -929.4 \text{ kW}$$

From the entropy equation

$$\dot{S}_{gen} = 0.5\times6.1453 + 0.5 \times 0.8779 - 1 \times 6.4943 - (-929.4)/298.15$$
$$= 0.1345 \text{ kW/K} > \emptyset$$

since $\dot{S}_{gen} > \emptyset$ this is possible

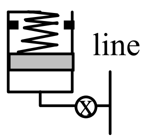
9.122

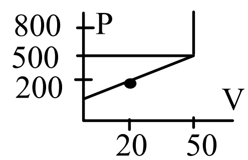
A frictionless piston/cylinder is loaded with a linear spring, spring constant 100 kN/m and the piston cross-sectional area is 0.1 m^2. The cylinder initial volume of 20 L contains air at 200 kPa and ambient temperature, 10°C. The cylinder has a set of stops that prevent its volume from exceeding 50 L. A valve connects to a line flowing air at 800 kPa, 50°C. The valve is now opened, allowing air to flow in until the cylinder pressure reaches 800 kPa, at which point the temperature inside the cylinder is 80°C. The valve is then closed and the process ends.

a) Is the piston at the stops at the final state?

b) Taking the inside of the cylinder as a control volume, calculate the heat transfer during the process.

c) Calculate the net entropy change for this process.





$T_o = 10^oC = 283.15$ K

$A_p = 0.1\ m^2$, $V_{stop} = 50$ L

Air from Table A.5: $R = 0.287$, $C_p = 1.004$, $C_v = 0.717$ kJ/kg-K

State 1: $T_1 = 10^oC$, $P_1 = 200$ kPa, $V_1 = 20\ L = 0.02\ m^3$,

$m_1 = P_1V_1/RT_1 = 200\times0.02/(0.287\times283.15) = 0.0492$ kg

State 2: $T_2 = 80^oC$, $P_2 = 800$ kPa, Inlet: $T_i = 50^oC$, $P_i = 800$ kPa

a) $P_{stop} = P_1 + \frac{k_s}{A_p^2}(V_{stop} - V_1) = 500$ kPa, $\mathbf{P_2 > P_{stop}}$ **→ Piston hits stops**

$V_2 = V_{stop} = 50$ L, $m_2 = PV/RT = 0.3946$ kg

b) 1^{st} Law: ${}_1Q_2 + m_ih_i = m_2u_2 - m_1u_1 + m_eh_e + {}_1W_2$; $m_e = 0$, $m_i = m_2 - m_1$

${}_1W_2 = \int P\,dV = (P_1 + P_{stop})(V_{stop} - V_1)/2 = 10.5$ kJ

Assume constant specific heat

${}_1Q_2 = m_2C_vT_2 - m_1C_vT_1 - (m_2 - m_1)\,C_pT_i + {}_1W_2$ **= -11.6 kJ**

c) 2^{nd} Law: $\Delta S_{net} = m_2s_2 - m_1s_1 - m_is_i - \frac{Q_{cv}}{T_o}$

$\Delta S_{net} = m_2(s_2 - s_i) - m_1(s_1 - s_i) - \frac{Q_{cv}}{T_o}$

$s_2 - s_i = C_p \ln(T_2 / T_i) - R \ln(P_2 / P_i) = 0.08907$ kJ/kg-K $(P_2 = P_i)$

$s_1 - s_i = C_p \ln(T_1 / T_i) - R \ln(P_1 / P_i) = 0.26529$ kJ/kg-K

$\mathbf{\Delta S_{net} = 0.063\ kJ/K}$

9.123

An insulated piston/cylinder contains R-22 at 20°C, 85% quality, at a cylinder volume of 50 L. A valve at the closed end of the cylinder is connected to a line flowing R-22 at 2 MPa, 60°C. The valve is now opened, allowing R-22 to flow in, and at the same time the external force on the piston is decreased, and the piston moves. When the valve is closed, the cylinder contents are at 800 kPa, 20°C, and a positive work of 50 kJ has been done against the external force. What is the final volume of the cylinder? Does this process violate the second law of thermodynamics?

Solution:

C.V. Cylinder volume. A transient problem.

Continuity Eq.: $m_2 - m_1 = m_i$

Energy Eq.: $m_2u_2 - m_1u_1 = {}_1Q_2 + m_ih_i - {}_1W_2$

Entropy Eq.: $m_2s_2 - m_1s_1 = {}_1Q_2/T + m_is_i + {}_1S_{2\ gen}$

Process: ${}_1Q_2 = 0,\ {}_1W_2 = 50$ kJ

State 1: $T_1 = 20^oC$, $x_1 = 0.85$, $V_1 = 50\ L = 0.05\ m^3$

$P_1 = P_g = 909.9$ kPa, $u_1 = u_f + x_1u_{fg} = 208.1$ kJ/kg

$v_1 = v_f + x_1v_{fg} = 0.000824 + 0.85\times0.02518 = 0.022226\ m^3/kg$,

$s_1 = s_f + x_1s_{fg} = 0.259 + 0.85\times0.6407 = 0.8036$ kJ/kg K

$m_1 = V_1/v_1 = 2.25$ kg

State 2: $T_2 = 20^oC$, $P_2 = 800$ kPa, superheated, $v_2 = 0.03037\ m^3/kg$,

$u_2 = 234.44$ kJ/kg, $s_2 = 0.9179$ kJ/kg K

Inlet: $T_i = 60^oC$, $P_i = 2$ MPa, $h_i = 271.56$ kJ/kg, $s_i = 0.8873$ kJ/kg K

Solve for the mass m_2 from the energy equation (the only unknown)

$$m_2 = [m_1u_1 - {}_1W_2 - m_1h_i] / [u_2 - h_i]$$

$$= \frac{2.25 \times 208.1 - 50 - 2.25 \times 271.56}{234.44 - 271.56} = 5.194 \text{ kg}$$

$$\mathbf{V_2 = m_2v_2 = 0.158\ m^3}$$

Now check the second law

$${}_1S_{2\ gen} = m_2s_2 - m_1s_1 - {}_1Q_2/T - m_is_i$$

$$= 5.194 \times 0.9179 - 2.25 \times 0.8036 - 0 - (5.194 - 2.25)\ 0.8873$$

$$= \mathbf{0.347\ kJ/K \geq 0}, \quad \textbf{Satisfies 2}^{\textbf{nd}} \textbf{ Law}$$

9.124

Air enters an insulated turbine at 50°C, and exits the turbine at - 30°C, 100 kPa. The isentropic turbine efficiency is 70% and the inlet volumetric flow rate is 20 L/s. What is the turbine inlet pressure and the turbine power output?

C.V.: Turbine, $\eta_s = 0.7$, Insulated

Air: $C_p = 1.004$ kJ/kg-K, $R = 0.287$ kJ/kg-K, $k = 1.4$

Inlet: $T_i = 50^oC$, $\dot{V}_i = 20\ L/s = 0.02\ m^3/s$

Exit: $T_e = -30^oC$, $P_e = 100$ kPa

a) 1^{st} Law steady flow: $q + h_i = h_e + w_T$; $q = 0$

Assume Constant Specific Heat

$w_T = h_i - h_e = C_p(T_i - T_e) = 80.3$ kJ/kg

$w_{Ts} = w/\eta = 114.7$ kJ/kg, $w_{Ts} = C_p(T_i - T_{es})$

Solve for $T_{es} = 208.9$ K

Isentropic Process: $P_e = P_i\,(T_e / T_i)^{\frac{k}{k-1}}$ => $\mathbf{P_i = 461\ kPa}$

b) $\dot{W}_T = \dot{m}w_T$; $\dot{m} = P\dot{V}/RT = 0.099$ kg/s => $\dot{W}_T = \mathbf{7.98\ kW}$

9.125

A certain industrial process requires a steady 0.5 kg/s supply of compressed air at 500 kPa, at a maximum temperature of 30°C. This air is to be supplied by installing a compressor and aftercooler, see Fig. P9.46. Local ambient conditions are 100 kPa, 20°C. Using an isentropic compressor efficiency of 80%, determine the power required to drive the compressor and the rate of heat rejection in the aftercooler.

Air: R = 0.287 kJ/kg-K, C_p = 1.004 kJ/kg-K, k = 1.4

State 1: $T_1 = T_o = 20^oC$, $P_1 = P_o = 100$ kPa, $\dot{m} = 0.5$ kg/s

State 2: $P_2 = P_3 = 500$ kPa

State 3: $T_3 = 30^oC$, $P_3 = 500$ kPa

Assume η_s = 80 % (Any value between 70%-90% is OK)

Compressor: Assume Isentropic

$$T_{2s} = T_1 \left(P_2/P_1\right)^{\frac{k-1}{k}}, \quad T_{2s} = 464.6 \text{ K}$$

1^{st} Law: $q_c + h_1 = h_2 + w_c$; $q_c = 0$, assume constant specific heat

$$w_{cs} = C_p(T_1 - T_{2s}) = -172.0 \text{ kJ/kg}$$

$\eta s = w_{cs}/w_c$, $w_c = w_{cs}/\eta s = -215$, $\dot{W}_C = \dot{m}w_C =$ **-107.5 kW**

$w_c = C_p(T_1 - T_2)$, solve for $T_2 = 507.5$ K

Aftercooler:

1^{st} Law: $q + h_2 = h_3 + w$; $w = 0$, assume constant specific heat

$q = C_p(T_3 - T_2) = 205$ kJ/kg, $\dot{Q} = \dot{m}q =$ **-102.5 kW**

9.126

Consider the scheme shown in Fig. P9.126 for producing fresh water from salt water. The conditions are as shown in the figure. Assume that the properties of salt water are the same as for pure water, and that the pump is reversible and adiabatic.

a. Determine the ratio $(\dot{m}_7/\dot{m}_1)$, the fraction of salt water purified.

b. Determine the input quantities, w_P and q_H.

c. Make a second law analysis of the overall system.

C.V. Flash evaporator: Steady flow, no external q, no work.

Energy Eq.: $\dot{m}_1 h_4 = (\dot{m}_1 - \dot{m}_7)h_5 + \dot{m}_7 h_6$

Table B.1.1 or $632.4 = \big(1 - (\dot{m}_7/\dot{m}_1)\big)\ 417.46 + (\dot{m}_7/\dot{m}_1)\ 2675.5$

$\Rightarrow \dot{m}_7/\dot{m}_1 = \mathbf{0.0952}$

C.V. Pump steady flow, incompressible liq.:

$w_P = -\int v dP \approx -v_1(P_2 - P_1) = -\ 0.001001(700 - 100) = \mathbf{-0.6\ kJ/kg}$

$h_2 = h_1 - w_P = 62.99 + 0.6 = 63.6$ kJ/kg

C.V. Heat exchanger: $h_2 + (\dot{m}_7/\dot{m}_1)h_6 = h_3 + (\dot{m}_7/\dot{m}_1)h_7$

$63.6 + 0.0952 \times 2675.5 = h_3 + 0.0952 \times 146.68 \Rightarrow h_3 = 304.3$ kJ/kg

C.V. Heater: $q_H = h_4 - h_3 = 632.4 - 304.3 = \mathbf{328.1\ kJ/kg}$

CV: entire unit, entropy equation per unit mass flow rate at state 1

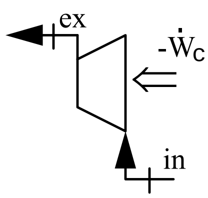
$S_{C.V.,gen} = -\ q_H/T_H + \big(1 - (\dot{m}_7/\dot{m}_1)\big)s_5 + (\dot{m}_7/\dot{m}_1)s_7 - s_1$

$= (-328.1/473.15) + 0.9048 \times 1.3026 + 0.0952 \times 0.5053 - 0.2245$

$= 0.3088$ kJ/K kg m_1

9.127

Supercharging of an engine is used to increase the inlet air density so that more fuel can be added, the result of which is an increased power output. Assume that ambient air, 100 kPa and 27°C, enters the supercharger at a rate of 250 L/s. The supercharger (compressor) has an isentropic efficiency of 75%, and uses 20 kW of power input. Assume that the ideal and actual compressor have the same exit pressure. Find the ideal specific work and verify that the exit pressure is 175 kPa. Find the percent increase in air density entering the engine due to the supercharger and the entropy generation.



C.V.: Air in compressor (steady flow)

Cont: $\dot{m}_{in} = \dot{m}_{ex} = \dot{m} = \dot{V}/v_{in} = 0.29$ kg/s

Energy: $\dot{m}h_{in} - \dot{W} = \dot{m}h_{ex}$ Assume: $\dot{Q} = 0$

Entropy: $\dot{m}s_{in} + \dot{S}_{gen} = \dot{m}s_{ex}$

$$v_{in} = \frac{RT_{in}}{P_{in}} = 0.8614 \text{ m}^3\text{/kg},\ \ s^o_{Ti} = 6.86975 \text{ kJ/kg K},\ \ h_{in} = 300.62 \text{ kJ/kg}$$

$$\eta_c = w_{C\,s}/w_{C\,ac} \Rightarrow\ \ -\dot{W}_S = -\dot{W}_{AC} \times \eta_c = 15 \text{ kW}$$

$$-w_{C\,s} = -\dot{W}_S/\dot{m} = 51.724 \text{ kJ/kg},\quad -w_{C\,ac} = 68.966 \text{ kJ/kg}$$

Table A.7: $h_{ex\,s} = h_{in} - w_{C\,s} = 300.62 + 51.724 = 352.3$ kJ/kg

$$\Rightarrow T_{ex\,s} = 351.5 \text{ K},\ \ s^o_{Te} = 7.02830 \text{ kJ/kg K}$$

$$P_{ex} = P_{in} \times e^{(s^o_{T\,ex} - s^o_{T\,in})/R} = 100 \times \exp\left[\frac{7.0283 - 6.86975}{0.287}\right]$$

$= \mathbf{173.75\ kPa}$

The actual exit state is

$$h_{ex\,ac} = h_{in} - w_{C\,ac} = 369.6 \text{ kJ/kg} \Rightarrow T_{ex\,ac} = 368.6 \text{ K}$$

$$v_{ex} = RT_{ex}/P_{ex} = 0.6088 \text{ m}^3\text{/kg},\ \ s^o_{Tex\,ac} = 7.0764$$

$\rho_{ex}/\rho_{in} = v_{in}/v_{ex} = 0.8614/0.6088 =$ **1.415 or 41.5% increase**

$$s_{gen} = s_{ex} - s_{in} = 7.0764 - 6.86975 - 0.287 \ln\left(\frac{173.75}{100}\right) = \mathbf{0.0481\ kJ/kg\ K}$$

9.128

A jet-ejector pump, shown schematically in Fig. P9.128, is a device in which a low-pressure (secondary) fluid is compressed by entrainment in a high-velocity (primary) fluid stream. The compression results from the deceleration in a diffuser. For purposes of analysis this can be considered as equivalent to the turbine-compressor unit shown in Fig. P9.120 with the states 1, 3, and 5 corresponding to those in Fig. P9.128. Consider a steam jet-pump with state 1 as saturated vapor at 35 kPa; state 3 is 300 kPa, 150°C; and the discharge pressure, P_5, is 100 kPa.

a. Calculate the ideal mass flow ratio, $\dot{m}_1/\dot{m}_3$.

b. The efficiency of a jet pump is defined as $\eta = (\dot{m}_1/\dot{m}_3)_{actual} / (\dot{m}_1/\dot{m}_3)_{ideal}$ for the same inlet conditions and discharge pressure. Determine the discharge temperature of the jet pump if its efficiency is 10%.

a) ideal processes (isen. comp. & exp.)

$$\left.\begin{array}{l}\text{expands 3-4s}\\ \text{comp} \quad \text{1-2s}\end{array}\right\} \text{then mix at const. P}$$

$s_{4s} = s_3 = 7.0778 = 1.3026 + x_{4s} \times 6.0568 \quad => \quad x_{4s} = 0.9535$

$h_{4s} = 417.46 + 0.9535 \times 2258.0 = 2570.5$ kJ/kg

$s_{2s} = s_1 = 7.7193 \rightarrow T_{2s} = 174°C \quad \& \quad h_{2s} = 2823.8$ kJ/kg

$\dot{m}_1(h_{2s} - h_1) = \dot{m}_3(h_3 - h_{4s})$

$$\Rightarrow (\dot{m}_1/\dot{m}_3)_{IDEAL} = \frac{2761.0 - 2570.5}{2823.8 - 2631.1} = \mathbf{0.9886}$$

b) real processes with jet pump eff. = 0.10

$\Rightarrow (\dot{m}_1/\dot{m}_3)_{ACTUAL} = 0.10 \times 0.9886 = 0.09886$

1st law $\quad \dot{m}_1 h_1 + \dot{m}_3 h_3 = (\dot{m}_1 + \dot{m}_3) h_5$

$0.09886 \times 2631.1 + 1 \times 2761.0 = 1.09896\, h_5$

State 5: $h_5 = 2749.3$ kJ/kg, $P_5 = 100$ kPa $\quad => \quad T_5 = \mathbf{136.5\ ^oC}$

9.129

A rigid steel bottle, $V = 0.25\ m^3$, contains air at 100 kPa, 300 K. The bottle is now charged with air from a line at 260 K, 6 MPa to a bottle pressure of 5 MPa, state 2, and the valve is closed. Assume that the process is adiabatic, and the charge always is uniform. In storage, the bottle slowly returns to room temperature at 300 K, state 3. Find the final mass, the temperature T_2, the final pressure P_3, the heat transfer ${}_1Q_3$ and the total entropy generation.

C.V. Bottle. Flow in, no work, no heat transfer.

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

Energy Eq.6.16: $m_2u_2 - m_1u_1 = m_{in}h_{in}$

State 1 and inlet: Table A.7, $u_1 = 214.36$ kJ/kg, $h_{in} = 260.32$ kJ/kg

$$m_1 = P_1V/RT_1 = (100 \times 0.25)/(0.287 \times 300) = 0.290 \text{ kg}$$

$$m_2 = P_2V/RT_2 = 5000 \times 0.25/(0.287 \times T_2) = 4355.4/T_2$$

Substitute into energy equation

$$u_2 + 0.00306\ T_2 = 260.32$$

Now trial and error on T_2

$T_2 = 360$ => LHS = 258.63 (low); $T_2 = 370$ => LHS = 265.88 (high)

Interpolation $T_2 = 362.3$ K (LHS = 260.3 OK)

$m_2 = 4355.4/362.3 = 12.022$ kg ; $P_3 = m_2RT_3/V =$ **4140 kPa**

Now use the energy equation from the beginning to the final state

$${}_1Q_3 = m_2u_3 - m_1u_1 - m_{in}h_{in} = (12.022 - 0.29)\ 214.36 - 11.732 \times 260.32$$

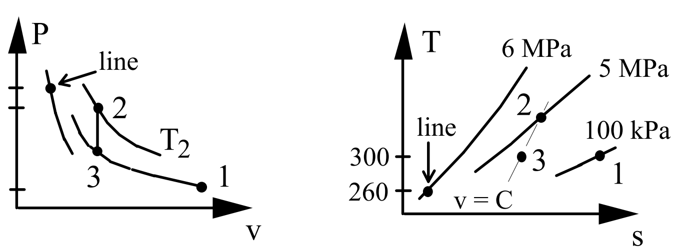
$$= \mathbf{-539.2\ kJ}$$

Entropy equation from state 1 to state 3 with change in s from Eq.8.28

$$S_{gen} = m_2s_3 - m_1s_1 - m_{in}s_{in} - {}_1Q_3/T = m_2(s_3 - s_{in}) - m_1(s_1 - s_{in}) - {}_1Q_3/T$$

$$= 12.022[6.8693 - 6.7256 - R \ln(4140/6000)]$$

$$- 0.29[6.8693 - 6.7256 - R \ln(100/6000)] + 539.2/300 = \mathbf{4.423\ kJ/K}$$



Problem could have been solved with constant specific heats from A.5 in which case we would get the energy explicit in T_2 (no iterations).

9.130

A horizontal, insulated cylinder has a frictionless piston held against stops by an external force of 500 kN. The piston cross-sectional area is 0.5 m^2, and the initial volume is 0.25 m^3. Argon gas in the cylinder is at 200 kPa, 100°C. A valve is now opened to a line flowing argon at 1.2 MPa, 200°C, and gas flows in until the cylinder pressure just balances the external force, at which point the valve is closed. Use constant heat capacity to verify that the final temperature is 645 K and find the total entropy generation.

Solution:

The process has inlet flow, no work (volume constant) and no heat transfer.

Continuity Eq.6.15: $m_2 - m_1 = m_i$

Energy Eq.6.16: $m_2 u_2 - m_1 u_1 = m_i h_i$

$m_1 = P_1V_1/RT_1 = 200 \times 0.25/(0.2081 \times 373.15) = 0.644$ kg

Force balance: $P_2A = F \quad \Rightarrow \quad P_2 = \frac{500}{0.5} = 1000$ kPa

For argon use constant heat capacities so the energy equation is:

$$m_2\ C_{Vo}\, T_2 - m_1\, C_{Vo}\, T_1 = (m_2 - m_1)\, C_{Po}\, T_{in}$$

We know P_2 so only 1 unknown for state 2.

Use ideal gas law to write $m_2T_2 = P_2V_1/R$ and $m_1 T_1 = P_1V_1/R$

and divide the energy equation with C_{Vo} to solve for the change in mass

$$(P_2 V_1 - P_1V_1)/R = (m_2 - m_1)(C_{Po}/C_{Vo})\, T_{in}$$

$$(m_2 - m_1) = (P_2 - P_1)V_1/(R\, k\, T_{in})$$

$$= (1000 - 200)\times 0.25/(0.2081\times 1.667\times 473.15) = 1.219 \text{ kg}$$

$$m_2 = 1.219 + 0.644 = 1.863 \text{ kg.}$$

$T_2 = P_2V_1/(m_2R) = 1000\times 0.25/(1.863\times 0.2081) = 645$ K **OK**

Entropy Eq.9.12: $m_2s_2 - m_1s_1 = m_is_i + 0 + {}_1S_{2\,gen}$

$${}_1S_{2\,gen} = m_1(s_2 - s_1) + (m_2 - m_1)(s_2 - s_i)$$

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

$$= 0.644\left[0.52 \ln\frac{645}{373.15} - 0.2081 \ln\frac{1000}{200}\right]$$

$$+ 1.219\left[0.52 \ln\frac{645}{473.15} - 0.2081 \ln\frac{1000}{1200}\right]$$

$= -\,0.03242 + 0.24265 =$ **0.21 kJ/K**

9.131

A rigid 1.0 m^3 tank contains water initially at 120°C, with 50 % liquid and 50% vapor, by volume. A pressure-relief valve on the top of the tank is set to 1.0 MPa (the tank pressure cannot exceed 1.0 MPa - water will be discharged instead). Heat is now transferred to the tank from a 200°C heat source until the tank contains saturated vapor at 1.0 MPa. Calculate the heat transfer to the tank and show that this process does not violate the second law.

Solution:

C.V. Tank and walls out to the source. Neglect storage in walls. There is flow out and no boundary or shaft work.

Continuity Eq.6.15: $m_2 - m_1 = - m_e$

Energy Eq.6.16: $m_2 u_2 - m_1 u_1 = - m_e h_e + {}_1Q_2$

Entropy Eq.9.12: $m_2 s_2 - m_1 s_1 = - m_e s_e + \int dQ/T + {}_1S_{2\,gen}$

State 1: $T_1 = 120^oC$, Table B.1.1

$v_f = 0.00106\ m^3/kg$, $m_{liq} = 0.5V_1/v_f = 471.7\ kg$

$v_g = 0.8919\ m^3/kg$, $m_g = 0.5V_1/v_g = 0.56\ kg$,

$m_1 = 472.26\ kg$, $x_1 = m_g/m_1 = 0.001186$

$u_1 = u_f + x_1 u_{fg} = 503.5 + 0.001186 \times 2025.8 = 505.88\ kJ/kg$,

$s_1 = s_f + x_1 s_{fg} = 1.5275 + 0.001186 \times 5.602 = 1.5341\ kJ/kg\text{-}K$

State 2: $P_2 = 1.0\ MPa$, sat. vap. $x_2 = 1.0$, $V_2 = 1 m^3$

$v_2 = v_g = 0.19444\ m^3/kg$, $m_2 = V_2/v_2 = 5.14\ kg$

$u_2 = u_g = 2583.6\ kJ/kg$, $s_2 = s_g = 6.5864\ kJ/kg\text{-}K$

Exit: $P_e = 1.0\ MPa$, sat. vap. $x_e = 1.0$, $h_e = h_g = 2778.1\ kJ/kg$,

$s_e = s_g = 6.5864\ kJ/kg$, $m_e = m_1 - m_2 = 467.12\ kg$

From the energy equation we get

$${}_1Q_2 = m_2 u_2 - m_1 u_1 + m_e h_e = \mathbf{1\ 072\ 080\ kJ}$$

From the entropy Eq.9.24 (with 9.25 and 9.26) we get

$${}_1S_{2\,gen} = m_2 s_2 - m_1 s_1 + m_e s_e - \frac{{}_1Q_2}{T_H}; \qquad T_H = 200^oC = 473\ K$$

$${}_1S_{2\,gen} = \Delta S_{net} = \mathbf{120.4\ kJ/K \geq 0} \quad \textbf{Process Satisfies 2}^{\textbf{nd}}\textbf{ Law}$$

9.132

A certain industrial process requires a steady 0.5 kg/s of air at 200 m/s, at the condition of 150 kPa, 300 K. This air is to be the exhaust from a specially designed turbine whose inlet pressure is 400 kPa. The turbine process may be assumed to be reversible and polytropic, with polytropic exponent n = 1.20.

a) What is the turbine inlet temperature?

b) What are the power output and heat transfer rate for the turbine?

c) Calculate the rate of net entropy increase, if the heat transfer comes from a source at a temperature 100°C higher than the turbine inlet temperature.

Solution:

C.V. Turbine, this has heat transfer, PV^n = Constant, n = 1.2

Exit: $T_e = 300K$, $P_e = 150$ kPa, $\mathbf{V}_e = 200$ m/s

a) Process polytropic Eq.8.37: $T_e / T_i = (P_e/P_i)^{\frac{n-1}{n}}$ => $T_i = 353.3$ K

b) 1st Law Eq.6.12: $\dot{m}_i(h + \mathbf{V}^2/2)_{in} + \dot{Q} = \dot{m}_{ex}(h + \mathbf{V}^2/2)_{ex} + \dot{W}_T$

Reversible shaft work in a polytropic process, Eq.9.14 and Eq.9.19:

$$w_T = -\int v\, dP + (\mathbf{V}_i^2 - \mathbf{V}_e^2)/2 = -\frac{n}{n-1}(P_e v_e - P_i v_i) + (\mathbf{V}_i^2 - \mathbf{V}_e^2)/2$$

$$= -\frac{n}{n-1}R(T_e - T_i) - \mathbf{V}_e^2/2 = 71.8 \text{ kJ/kg}$$

$\dot{W}_T = \dot{m}w_T$ = **35.9 kW**

Assume constant specific heat in the energy equation

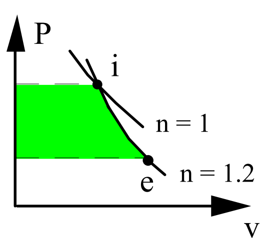
$\dot{Q} = \dot{m}[C_P (T_e - T_i) + \mathbf{V}_e^2/2] + \dot{W}_T$ = **19.2 kW**

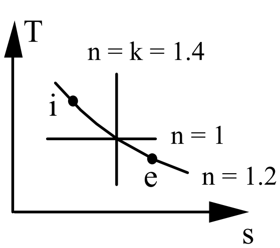
c) 2nd Law Eq.9.7 or 9.23 with change in entropy from Eq.8.25:

$dS_{net}/dt = \dot{S}_{gen} = \dot{m}(s_e - s_i) - \dot{Q}_H/T_H$, $T_H = T_i + 100 = 453.3$ K

$s_e - s_i = C_p \ln(T_e / T_i) - R \ln(P_e / P_i) = 0.1174$ kJ/kg K

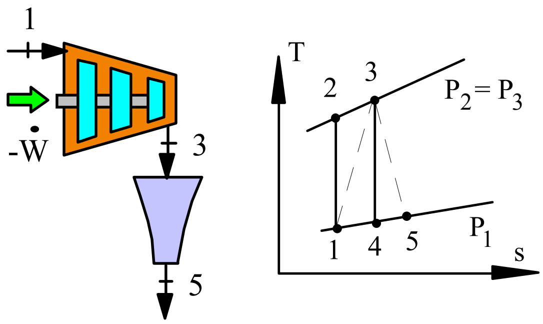
$dS_{net}/dt = 0.5 \times 0.1174 - 19.2/453.3 = 0.0163$ kW/K





9.133

Assume both the compressor and the nozzle in Problem 9.37 have an isentropic efficiency of 90% the rest being unchanged. Find the actual compressor work and its exit temperature and find the actual nozzle exit velocity.



C.V. Ideal compressor, inlet: 1 exit: 2

Adiabatic : $q = 0$.
Reversible: $s_{gen} = 0$

Energy Eq.6.13: $h_1 + 0 = w_C + h_2$;

Entropy Eq.9.8: $s_1 + 0/T + 0 = s_2$

$$- w_{Cs} = h_2 - h_1 , \quad s_2 = s_1$$

Properties use air Table A.5: $C_{Po} = 1.004 \frac{kJ}{kg\ K}$, $R = 0.287 \frac{kJ}{kg\ K}$, $k = 1.4$,

Process gives constant s (isentropic) which with constant C_{Po} gives Eq.8.32

$$=> \quad T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 290\ (400/100)^{\ 0.2857} = \mathbf{430.9\ K}$$

$$\Rightarrow \quad -w_{Cs} = C_{Po}(T_2 - T_1) = 1.004\ (430.9 - 290) = \mathbf{141.46\ kJ/kg}$$

The ideal nozzle then expands back down to state 1 (constant s). The actual compressor discharges at state 3 however, so we have:

$$w_C = w_{Cs}/\eta_C = \mathbf{-157.18} \quad \Rightarrow \quad T_3 = T_1 - w_C/C_p = \mathbf{446.6\ K}$$

Nozzle receives air at 3 and exhausts at 5. We must do the ideal (exit at 4) first.

$$s_4 = s_3 \Rightarrow \text{Eq.8.32:} \qquad T_4 = T_3\ (P_4/P_3)^{\frac{k-1}{k}} = 300.5\ K$$

$$\frac{1}{2}\mathbf{V}_s^2 = C_p(T_3 - T_4) = 146.68 \Rightarrow \frac{1}{2}\mathbf{V}_{ac}^2 = 132\ kJ/kg \Rightarrow V_{ac} = \mathbf{513.8\ m/s}$$

If we need it, the actual nozzle exit (5) can be found:

$$T_5 = T_3 - \mathbf{V}_{ac}^2/2C_p = 315\ K$$

Problems solved with P_r and v_r functions

9.28

A compressor receives air at 290 K, 100 kPa and a shaft work of 5.5 kW from a gasoline engine. It should deliver a mass flow rate of 0.01 kg/s air to a pipeline. Find the maximum possible exit pressure of the compressor.

Solution:

C.V. Compressor, Steady single inlet and exit flows. Adiabatic: $\dot{Q} = 0$.

Continuity Eq.6.11: $\dot{m}_i = \dot{m}_e = \dot{m}$,

Energy Eq.6.12: $\dot{m}h_i = \dot{m}h_e + \dot{W}_C$,

Entropy Eq.9.8: $\dot{m}s_i + \dot{S}_{gen} = \dot{m}s_e$ (Reversible $\dot{S}_{gen} = 0$)

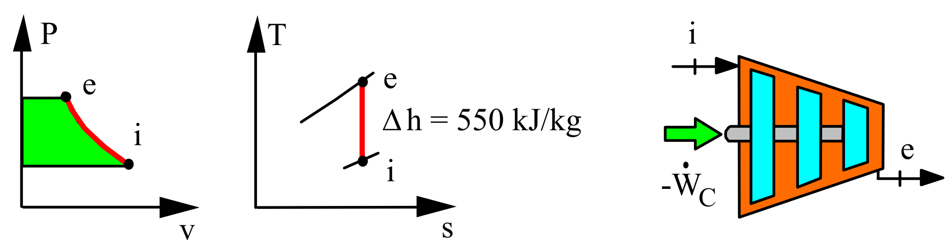
$$\dot{W}_c = \dot{m}w_c \;\; => \;\; -w_c = -\dot{W}/\dot{m} = 5.5/0.01 = 550 \text{ kJ/kg}$$

Use Table A.7, $h_i = 290.43$ kJ/kg, $P_{r\,i} = 0.9899$

$$h_e = h_i + (-w_c) = 290.43 + 550 = 840.43 \text{ kJ/kg}$$

A.7 => $T_e = 816.5$ K, $P_{r\,e} = 41.717$

$P_e = P_i\,(P_{r\,e}/P_{r\,i}) = 100 \times (41.717/0.9899) =$ **4214 kPa**



9.32

Do the previous problem using the air tables in A.7
The exit nozzle in a jet engine receives air at 1200 K, 150 kPa with neglible kinetic energy. The exit pressure is 80 kPa and the process is reversible and adiabatic. Use constant heat capacity at 300 K to find the exit velocity.

Solution:
C.V. Nozzle, Steady single inlet and exit flow, no work or heat transfer.

Energy Eq.6.13: $h_i = h_e + \mathbf{V}_e^2/2 \quad (Z_i = Z_e)$

Entropy Eq.9.8: $s_e = s_i + \int dq/T + s_{gen} = s_i + 0 + 0$

Process: $q = 0$, $s_{gen} = 0$ as used above leads to $s_e = s_i$

Inlet state: $h_i = 1277.8$ kJ/kg, $P_{r\,i} = 191.17$

The constant s is done using the P_r function from A.7.2

$$P_{r\,e} = P_{r\,i}\,(P_e / P_i) = 191.17\,(80/150) = 101.957$$

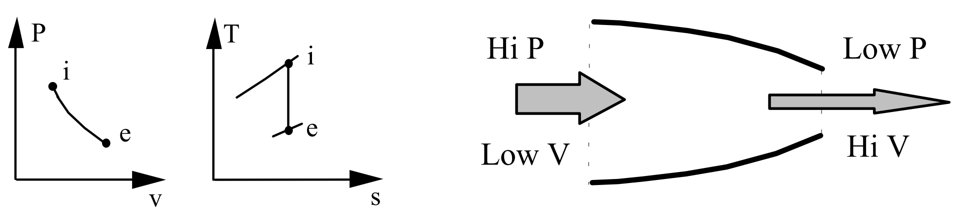
Interpolate in A.7 =>

$$T_e = 1000 + 50\,\frac{101.957 - 91.651}{111.35 - 91.651} = 1026.16 \text{ K}$$

$$h_e = 1046.2 + 0.5232 \times (1103.5 - 1046.2) = 1076.2 \text{ kJ/kg}$$

From the energy equation we have $\mathbf{V}_e^2/2 = h_i - h_e$, so then

$$\mathbf{V}_e = \sqrt{2\,(h_i - h_e)} = \sqrt{2(1277.8 - 1076.2) \times 1000} = \mathbf{635\ m/s}$$



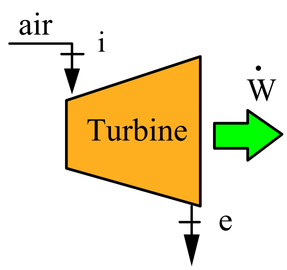
9.34

Air enters a turbine at 800 kPa, 1200 K, and expands in a reversible adiabatic process to 100 kPa. Calculate the exit temperature and the work output per kilogram of air, using

a. The ideal gas tables, Table A.7

b. Constant specific heat, value at 300 K from table A.5

Solution:



C.V. Air turbine.

Adiabatic: $q = 0$, reversible: $s_{gen} = 0$

Energy Eq.6.13: $w_T = h_i - h_e$,

Entropy Eq.9.8: $s_e = s_i$

a) Table A.7: $h_i = 1277.8$ kJ/kg, $P_{r\,i} = 191.17$

The constant s process is done using the P_r function from A.7.2

$$\Rightarrow P_{r\,e} = P_{r\,i}\,(P_e / P_i) = 191.17 \left(\frac{100}{800}\right) = 23.896$$

Interpolate in A.7.1 $\Rightarrow$ $T_e = \mathbf{705.7\ K}$, $h_e = 719.7$ kJ/kg

$$w = h_i - h_e = 1277.8 - 719.7 = \mathbf{558.1\ kJ/kg}$$

b) Table A.5: $C_{Po} = 1.004$ kJ/kg K, $R = 0.287$ kJ/kg K, $k = 1.4$, then from Eq.8.32

$$T_e = T_i\,(P_e/P_i)^{\frac{k-1}{k}} = 1200 \left(\frac{100}{800}\right)^{0.286} = \mathbf{662.1\ K}$$

$$w = C_{Po}(T_i - T_e) = 1.004(1200 - 662.1) = \mathbf{539.8\ kJ/kg}$$

9.69

An old abandoned saltmine, 100 000 m^3 in volume, contains air at 290 K, 100 kPa. The mine is used for energy storage so the local power plant pumps it up to 2.1 MPa using outside air at 290 K, 100 kPa. Assume the pump is ideal and the process is adiabatic. Find the final mass and temperature of the air and the required pump work.

Solution:

C.V. The mine volume and the pump

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

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

Entropy Eq.9.12: $m_2s_2 - m_1s_1 = \int dQ/T + {}_1S_{2\ gen} + m_{in}s_{in}$

Process: Adiabatic ${}_1Q_2 = 0$, Process ideal ${}_1S_{2\ gen} = 0$, $s_1 = s_{in}$

$\Rightarrow$ $m_2s_2 = m_1s_1 + m_{in}s_{in} = (m_1 + m_{in})s_1 = m_2s_1 \;\Rightarrow\; s_2 = s_1$

Constant s $\Rightarrow$ $P_{r2} = P_{r\,i}\,(P_2 / P_i) = 0.9899 \left(\frac{2100}{100}\right) = 20.7879$

A.7.2 $\Rightarrow$ $T_2 =$ **680 K** , $u_2 = 496.94$ kJ/kg

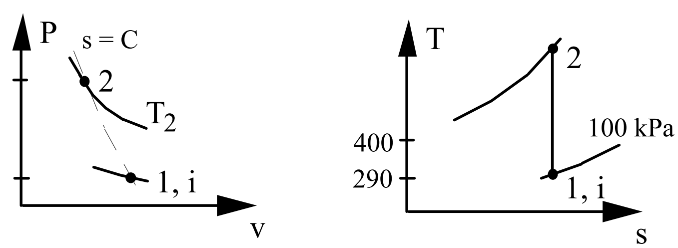
$m_1 = P_1V_1/RT_1 = 100{\times}10^5/(0.287 \times 290) = 1.20149 \times 10^5$ kg

$m_2 = P_2V_2/RT_2 = 100 \times 21{\times}10^5/(0.287 \times 680) = \mathbf{10.760 \times 10^5\ kg}$

$\Rightarrow$ $m_{in} = 9.5585{\times}10^5$ kg

${}_1W_2 = m_{in}h_{in} + m_1u_1 - m_2u_2$

$= m_{in}(290.43) + m_1(207.19) - m_2(496.94) = \mathbf{-2.322 \times 10^8\ kJ}$



9.89

Calculate the air temperature and pressure at the stagnation point right in front of a meteorite entering the atmosphere (-50 °C, 50 kPa) with a velocity of 2000 m/s. Do this assuming air is incompressible at the given state and repeat for air being a compressible substance going through an adiabatic compression.

Solution:

Kinetic energy: $\frac{1}{2}\mathbf{V}^2 = \frac{1}{2}(2000)^2/1000 = 2000$ kJ/kg

Ideal gas: $v_{atm} = RT/P = 0.287 \times 223/50 = 1.28$ m^3/kg

a) incompressible

Energy Eq.6.13: $\Delta h = \frac{1}{2}\mathbf{V}^2 = 2000$ kJ/kg

If A.5 $\Delta T = \Delta h/C_p = 1992$ K unreasonable, too high for that C_p

Use A.7: $h_{st} = h_o + \frac{1}{2}\mathbf{V}^2 = 223.22 + 2000 = 2223.3$ kJ/kg

$T_{st} = 1977$ K

Bernoulli (incompressible) Eq.9.17:

$$\Delta P = P_{st} - P_o = \frac{1}{2}\mathbf{V}^2/v = 2000/1.28 = 1562.5 \text{ kPa}$$

$$P_{st} = 1562.5 + 50 = 1612.5 \text{ kPa}$$

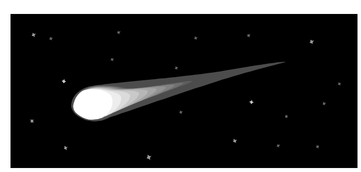
b) compressible

$T_{st} = 1977$ K the same energy equation.

From A.7.2: Stagnation point $P_{r\,st} = 1580.3$; Free $P_{r\,o} = 0.39809$

$$P_{st} = P_o \times \frac{P_{r\,st}}{P_{r\,o}} = 50 \times \frac{1580.3}{0.39809}$$

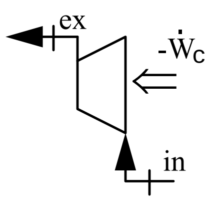
$= \mathbf{198\ 485\ kPa}$



Notice that this is highly compressible, v is not constant.

9.127

Supercharging of an engine is used to increase the inlet air density so that more fuel can be added, the result of which is an increased power output. Assume that ambient air, 100 kPa and 27°C, enters the supercharger at a rate of 250 L/s. The supercharger (compressor) has an isentropic efficiency of 75%, and uses 20 kW of power input. Assume that the ideal and actual compressor have the same exit pressure. Find the ideal specific work and verify that the exit pressure is 175 kPa. Find the percent increase in air density entering the engine due to the supercharger and the entropy generation.



C.V.: Air in compressor (steady flow)

Cont: $\dot{m}_{in} = \dot{m}_{ex} = \dot{m} = \dot{V}/v_{in} = 0.29$ kg/s

Energy: $\dot{m}h_{in} - \dot{W} = \dot{m}h_{ex}$ Assume: $\dot{Q} = 0$

Entropy: $\dot{m}s_{in} + \dot{S}_{gen} = \dot{m}s_{ex}$

Inlet state: $v_{in} = RT_{in}/P_{in} = 0.8614\ m^3/kg$, $P_{r\,in} = 1.1167$

$$\eta_c = w_{C\,s}/w_{C\,ac} \Rightarrow -\dot{W}_S = -\dot{W}_{AC} \times \eta_c = 15\ kW$$

$$-w_{C\,s} = -\dot{W}_S/\dot{m} = 51.724\ kJ/kg, \quad -w_{C\,ac} = 68.966\ kJ/kg$$

Table A.7: $h_{ex\,s} = h_{in} - w_{C\,s} = 300.62 + 51.724 = 352.3\ kJ/kg$

$$\Rightarrow T_{ex\,s} = 351.5\ K, \quad P_{r\,ex} = 1.949$$

$$P_{ex} = P_{in} \times P_{r\,ex}/P_{r\,in} = 100 \times 1.949 / 1.1167 = \mathbf{174.5\ kPa}$$

The actual exit state is

$$h_{ex\,ac} = h_{in} - w_{C\,ac} = 369.6\ kJ/kg \quad \Rightarrow T_{ex\,ac} = 368.6\ K$$

$$v_{ex} = RT_{ex}/P_{ex} = 0.606\ m^3/kg$$

$$\rho_{ex}/\rho_{in} = v_{in}/v_{ex} = 0.8614/0.606 = \mathbf{1.42 \text{ or } 42\ \%\ increase}$$

$$s_{gen} = s_{ex} - s_{in} = 7.0767 - 6.8693 - 0.287\ \ln(174/100)] = \mathbf{0.0484\ kJ/kg\ K}$$