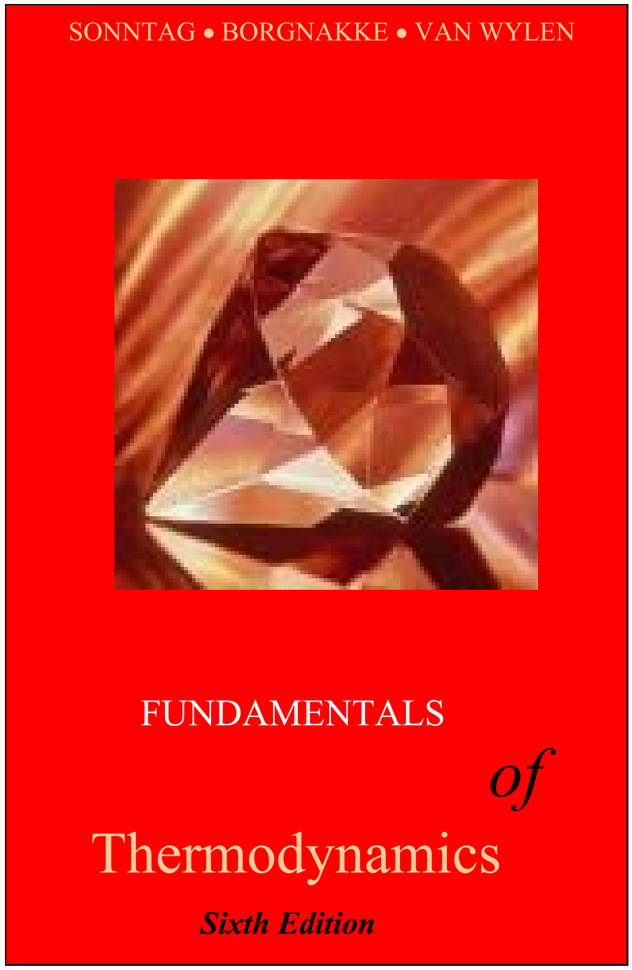
SOLUTION MANUAL
SI UNIT PROBLEMS
CHAPTER 6



CONTENT

Correspondence List

This chapter 6 homework problem set corresponds to the 5th edition chapter 6 as follows.

Problems 1-21 are all new.

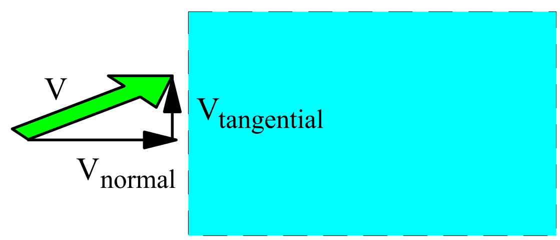
New	5th	New	5th	New	5th	New	5th
		50	new	80	37 mod	110	new
		51	33	81	34	111	49
22	1	52	new	82	41	112	new
23	2	53	32	83	new	113	48
24	new	54	new	84	14	114	51
25	4	55	new	85	new	115	new
26	5	56	36	86	13	116	new
27	new	57	new	87	new	117	new
28	6	58	new	88	new	118	50
29	new	59	38 mod	89	new	119	52
30	18	60	new	90	new	120	new
31	new	61	new	91	new	121	57
32	19	62	new	92	8	122	59
33	new	63	9	93	new	123	new
34	new	64	new	94	16	124	15
35	new	65	new	95	new	125	new
36	new	66	10	96	27	126	new
37	20	67	12	97	new	127	new
38	new	68	new	98	new	128	44
39	22	69	new	99	39a	129	45
40	23	70	new	100	39b	130	55
41	new	71	new	101	40a	131	56
42	new	72	35	102	42	132	62
43	24	73	new	103	43	133	63
44	new	74	11 mod	104	new	134	65
45	26 mod	75	new	105	46	135	new
46	new	76	new	106	47	136	new
47	25	77	new	107	new	137	new
48	new	78	29	108	58 mod	138	new
49	30	79	31	109	53		

CONCEPT-STUDY GUIDE PROBLEMS

6.1

A mass flow rate into a control volume requires a normal velocity component. Why?

The tangential velocity component does not bring any substance across the control volume surface as it flows parallel to it, the normal component of velocity brings substance in or out of the control volume according to its sign. The normal component must be into the control volume to bring mass in, just like when you enter a bus (it does not help that you run parallel with the bus side).



6.2

A temperature difference drives a heat transfer. Does a similar concept apply to $\dot{m}$?

Yes. A pressure difference drives the flow. The fluid is accelerated in the direction of a lower pressure as it is being pushed harder behind it than in front of it. This also means a higher pressure in front can decelerate the flow to a lower velocity which happens at a stagnation on a wall.

6.3

Can a steady state device have boundary work?

No. Any change in size of the control volume would require either a change in mass inside or a change in state inside, neither of which is possible in a steady-state process.

6.4

Can you say something about changes in $\dot{m}$ and $\dot{V}$ through a steady flow device?

The continuity equation expresses the conservation of mass, so the total amount of $\dot{m}$ entering must be equal to the total amount leaving. For a single flow device the mass flow rate is constant through it, so you have the same mass flow rate across any total cross-section of the device from the inlet to the exit.

The volume flow rate is related to the mass flow rate as

$$\dot{V} = v\,\dot{m}$$

so it can vary if the state changes (then v changes) for a constant mass flow rate.

This also means that the velocity can change (influenced by the area as $\dot{V} = \mathbf{V}A$) and the flow can experience an acceleration (like in a nozzle) or a deceleration (as in a diffuser).

6.5

How does a nozzle or sprayhead generate kinetic energy?

By accelerating the fluid from a high pressure towards the lower pressure, which is outside the nozzle. The higher pressure pushes harder than the lower pressure so there is a net force on any mass element to accelerate it.

6.6

Liquid water at 15°C flows out of a nozzle straight up 15 m. What is nozzle $\mathbf{V}_{exit}$?

Energy Eq.6.13: $h_{exit} + \frac{1}{2}\mathbf{V}_{exit}^2 + gH_{exit} = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gH_2$

If the water can flow 15 m up it has specific potential energy of gH_2 which must equal the specific kinetic energy out of the nozzle $\mathbf{V}_{exit}^2/2$. The water does not change P or T so h is the same.

$$\mathbf{V}_{exit}^2/2 = g(H_2 - H_{exit}) = gH \quad =>$$
$$\mathbf{V}_{exit} = \sqrt{2gH} = \sqrt{2 \times 9.807 \times 15 \text{ m}^2/\text{s}^2} = \mathbf{17.15 \text{ m/s}}$$

6.7

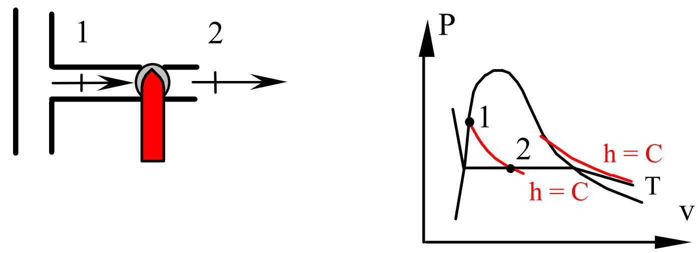
What is the difference between a nozzle flow and a throttle process?

In both processes a flow moves from a higher to a lower pressure. In the nozzle the pressure drop generates kinetic energy, whereas that does not take place in the throttle process. The pressure drop in the throttle is due to a flow restriction and represents a loss.

6.8

If you throttle a saturated liquid what happens to the fluid state? If it is an ideal gas?

The throttle process is approximated as a constant enthalpy process. Changing the state from saturated liquid to a lower pressure with the same h gives a two-phase state so some of the liquid will vaporize and it becomes colder.



If the same process happens in an ideal gas then same h gives the same temperature (h a function of T only) at the lower pressure.

6.9

R-134a at 30^{o}C, 800 kPa is throttled so it becomes cold at –10^{o}C. What is exit P?

State 1 is slightly compressed liquid so

Table B.5.1: $h = h_f = 241.79$ kJ/kg

At the lower temperature it becomes two-phase since the throttle flow has constant h and at –10^{o}C: $h_g = 392.28$ kJ/kg

$$P = P_{sat} = \mathbf{210.7\ kPa}$$

6.10

Air at 500 K, 500 kPa is expanded to 100 kPa in two steady flow cases. Case one is a throttle and case two is a turbine. Which has the highest exit T? Why?

1. Throttle.

In the throttle flow no work is taken out, no kinetic energy is generated and we assume no heat transfer takes place and no potential energy change. The energy equation becomes constant h, which gives constant T since it is an ideal gas.

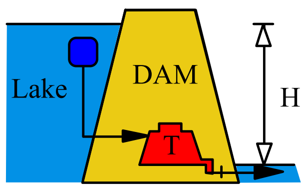
2. Turbine.

In the turbine work is taken out on a shaft so the fluid expands and P and T drops.

6.11

A turbine at the bottom of a dam has a flow of liquid water through it. How does that produce power? Which terms in the energy equation are important?

The water at the bottom of the dam in the turbine inlet is at a high pressure. It runs through a nozzle generating kinetic energy as the pressure drops. This high kinetic energy flow impacts a set of rotating blades or buckets which converts the kinetic energy to power on the shaft so the flow leaves at low pressure and low velocity.



6.12

A windmill takes a fraction of the wind kinetic energy out as power on a shaft. In what manner does the temperature and wind velocity influence the power? Hint: write the power as mass flow rate times specific work.

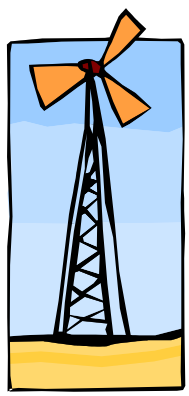
The work as a fraction f of the flow of kinetic energy becomes

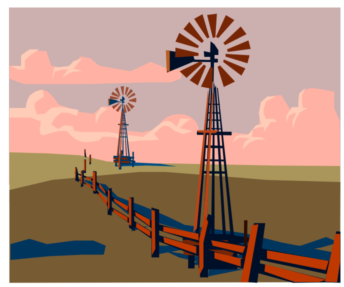
$$\dot{W} = \dot{m}w = \dot{m}\, f \frac{1}{2} \mathbf{V}_{in}^2 = \rho A \mathbf{V}_{in}\, f \frac{1}{2} \mathbf{V}_{in}^2$$

so the power is proportional to the velocity cubed. The temperature enters through the density, so assuming air as ideal gas

$$\rho = 1/v = P/RT$$

and the power is inversely proportional to temperature.





6.13

If you compress air the temperature goes up, why? When the hot air, high P flows in long pipes it eventually cools to ambient T. How does that change the flow?

As the air is compressed, volume decreases so work is done on a mass element, its energy and hence temperature goes up. If it flows at nearly constant P and cools its density increases (v decreases) so it slows down for same mass flow rate ($\dot{m} = \rho A \mathbf{V}$) and flow area.

6.14

In a boiler you vaporize some liquid water at 100 kPa flowing at 1 m/s. What is the velocity of the saturated vapor at 100 kPa if the pipe size is the same? Can the flow then be constant P?

The continuity equation with average values is written

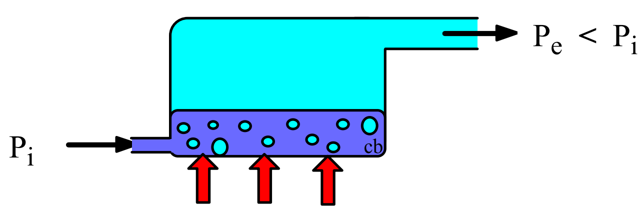
$$\dot{m}_i = \dot{m}_e = \dot{m} = \rho A \mathbf{V} = A\mathbf{V}/v = A\mathbf{V}_i/v_i = A\mathbf{V}_e/v_e$$

From Table B.1.2 at 100 kPa we get

$$v_f = 0.001043 \ \ m^3/kg; \quad v_g = 1.694 \ \ m^3/kg$$

$$\mathbf{V}_e = \mathbf{V}_i \, v_e/v_i = 1 \, \frac{1.694}{0.001043} = \mathbf{1624 \ m/s}$$

To accelerate the flow up to that speed you need a large force (ΔPA) so a large pressure drop is needed.

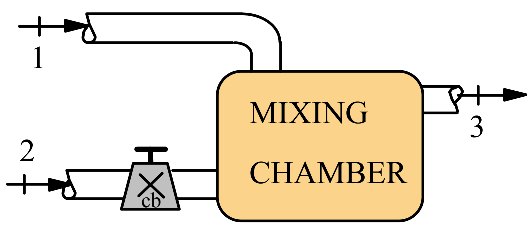


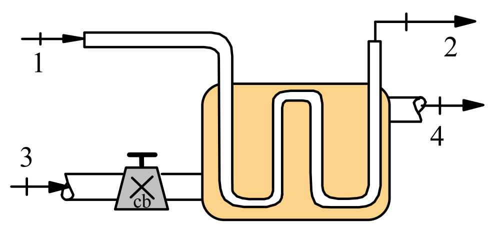
6.15

A mixing chamber has all flows at the same P, neglecting losses. A heat exchanger has separate flows exchanging energy, but they do not mix. Why have both kinds?

You might allow mixing when you can use the resulting output mixture, say it is the same substance. You may also allow it if you definitely want the outgoing mixture, like water out of a faucet where you mix hot and cold water. Even if it is different substances it may be desirable, say you add water to dry air to make it more moist, typical for a winter time air-conditioning set-up.

In other cases it is different substances that flow at different pressures with one flow heating or cooling the other flow. This could be hot combustion gases heating a flow of water or a primary fluid flow around a nuclear reactor heating a transfer fluid flow. Here the fluid being heated should stay pure so it does not absorb gases or radioactive particles and becomes contaminated. Even when the two flows have the same substance there may be a reason to keep them at separate pressures.





6.16

In a co-flowing (same direction) heat exchanger 1 kg/s air at 500 K flows into one channel and 2 kg/s air flows into the neighboring channel at 300 K. If it is infinitely long what is the exit temperature? Sketch the variation of T in the two flows.

C.V. mixing section (no $\dot{W}$, $\dot{Q}$)

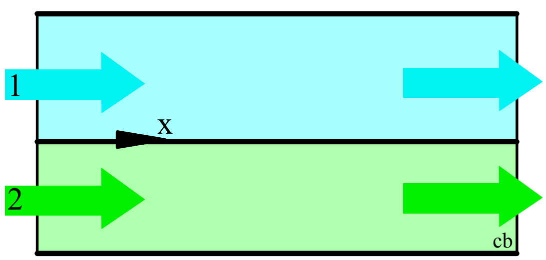
Continuity Eq.: $\dot{m}_1 = \dot{m}_3$ and $\dot{m}_2 = \dot{m}_4$

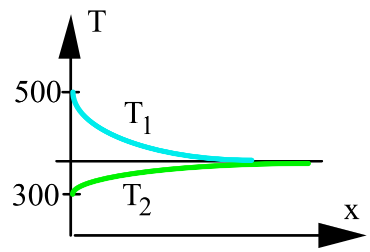
Energy Eq.6.10: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_1 h_3 + \dot{m}_2 h_4$

Same exit T: $h_3 = h_4 = [\dot{m}_1 h_1 + \dot{m}_2 h_2] / [\dot{m}_1 + \dot{m}_2]$

Using conctant specific heat

$$T_3 = T_4 = \frac{\dot{m}_1}{\dot{m}_1 + \dot{m}_2} T_1 + \frac{\dot{m}_2}{\dot{m}_1 + \dot{m}_2} T_2 = \frac{1}{3} \times 500 + \frac{2}{3} \times 300 = \mathbf{367\ K}$$





6.17

Air at 600 K flows with 3 kg/s into a heat exchanger and out at 100^{o}C. How much (kg/s) water coming in at 100 kPa, 20^{o}C can the air heat to the boiling point?

C.V. Total heat exchanger. The flows are not mixed so the two flowrates are constant through the device. No external heat transfer and no work.

Energy Eq.6.10: $\dot{m}_{air}h_{air\ in} + \dot{m}_{water}h_{water\ in} = \dot{m}_{air}h_{air\ out} + \dot{m}_{water}h_{water\ out}$

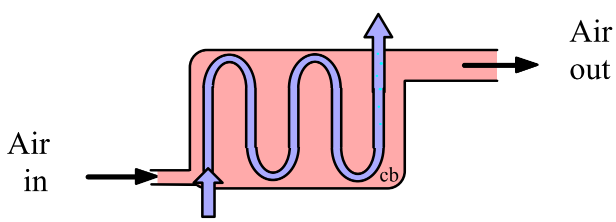
$$\dot{m}_{air}[h_{air\ in} - h_{air\ out}] = \dot{m}_{water}[h_{water\ out} - h_{water\ in}]$$

Table B.1.2: $h_{water\ out} - h_{water\ in} = 2675.46 - 83.94 = 2591.5$ kJ/kg

Table A.7.1: $h_{air\ in} - h_{air\ out} = 607.32 - 374.14 = 233.18$ kJ/kg

Solve for the flow rate of water from the energy equation

$$\dot{m}_{water} = \dot{m}_{air} \frac{h_{air\ in} - h_{air\ out}}{h_{water\ out} - h_{water\ in}} = 3 \times \frac{233.18}{2591.5} = \mathbf{0.27\ kg/s}$$



6.18

Steam at 500 kPa, 300^{o}C is used to heat cold water at 15^{o}C to 75^{o}C for domestic hot water supply. How much steam per kg liquid water is needed if the steam should not condense?

Solution:
C.V. Each line separately. No work but there is heat transfer out of the steam flow and into the liquid water flow.

Water line energy Eq.: $\dot{m}_{liq}h_i + \dot{Q} = \dot{m}_{liq}h_e \quad \Rightarrow \quad \dot{Q} = \dot{m}_{liq}(h_e - h_i)$

For the liquid water look in Table B.1.1

$$\Delta h_{liq} = h_e - h_i = 313.91 - 62.98 = 250.93 \text{ kJ/kg}$$

$$(\cong C_p\ \Delta T = 4.18\ (75 - 15) = 250.8 \text{ kJ/kg})$$

Steam line energy has the same heat transfer but it goes out

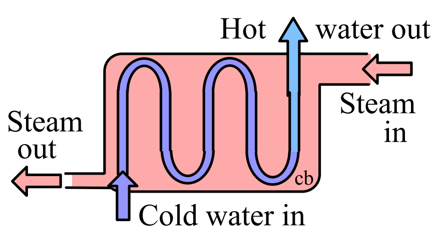
Steam Energy Eq.: $\dot{m}_{steam}h_i = \dot{Q} + \dot{m}_{steam}h_e \quad \Rightarrow \quad \dot{Q} = \dot{m}_{steam}(h_i - h_e)$

For the steam look in Table B.1.3 at 500 kPa

$$\Delta h_{steam} = h_i - h_e = 3064.2 - 2748.67 = 315.53 \text{ kJ/kg}$$

Now the heat transfer for the steam is substituted into the energy equation for the water to give

$$\dot{m}_{steam} / \dot{m}_{liq} = \Delta h_{liq} / \Delta h_{steam} = \frac{250.93}{315.53} = \mathbf{0.795}$$

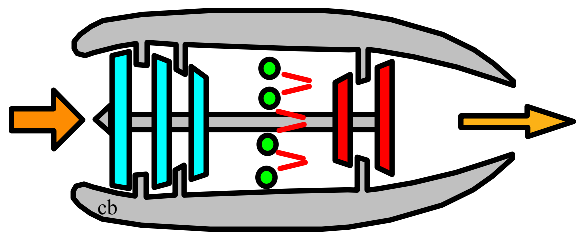


6.19

Air at 20 m/s, 260 K, 75 kPa with 5 kg/s flows into a jet engine and it flows out at 500 m/s, 800 K, 75 kPa. What is the change (power) in flow of kinetic energy?

$$\dot{m}\,\Delta KE = \dot{m}\,\frac{1}{2}(\mathbf{V}_e^2 - \mathbf{V}_i^2)$$

$$= 5\text{ kg/s} \times \frac{1}{2}(500^2 - 20^2)\text{ (m/s)}^2\,\frac{1}{1000}\text{ (kW/W)} = \mathbf{624\ kW}$$



6.20

An initially empty cylinder is filled with air from 20°C, 100 kPa until it is full. Assuming no heat transfer is the final temperature larger, equal to or smaller than 20°C? Does the final T depend on the size of the cylinder?

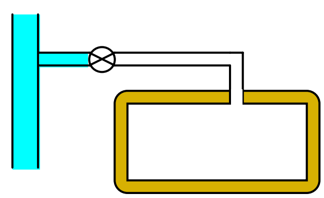
This is a transient problem with no heat transfer and no work. The balance equations for the tank as C.V. become

Continuity Eq.: $m_2 - 0 = m_i$

Energy Eq.: $m_2u_2 - 0 = m_ih_i + Q - W = m_ih_i + 0 - 0$

Final state: $u_2 = h_i$ & $P_2 = P_i$

$T_2 > T_i$ and it does not depend on V



6.21

A cylinder has 0.1 kg air at 25^{o}C, 200 kPa with a 5 kg piston on top. A valve at the bottom is opened to let the air out and the piston drops 0.25 m towards the bottom. What is the work involved in this process? What happens to the energy?

If we neglect acceleration of piston then P = C = $P_{equilibrium}$

$$W = P\ \Delta V$$

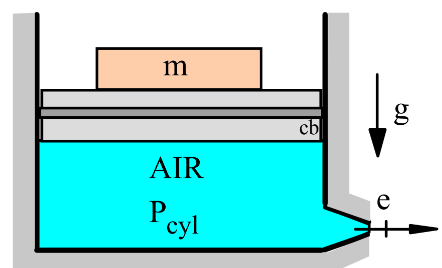
To get the volume change from the height we need the cylinder area. The force balance on the piston gives

$$P = P_o + \frac{m_p g}{A} \quad \Rightarrow \qquad A = \frac{m_p g}{P - P_o} = \frac{5 \times 9.807}{100 \times 1000} = 0.000\ 49\ m^2$$

$$\Delta V = -\ AH = -0.000\ 49 \times 0.25 = -0.000\ 1225\ m^3$$

$$W = P\ \Delta V = 200\ kPa \times (-0.000\ 1225)\ m^3 = \mathbf{-0.0245\ kJ}$$

The air that remains inside has not changed state and therefore not energy. The work leaves as flow work Pv Δm.



Continuity equation and flow rates

6.22

Air at 35°C, 105 kPa, flows in a 100 mm × 150 mm rectangular duct in a heating system. The volumetric flow rate is 0.015 m^3/s. What is the velocity of the air flowing in the duct and what is the mass flow rate?

Solution:

Assume a constant velocity across the duct area with

$$A = 100 \times 150 \times 10^{-6}\ m^2 = 0.015\ m^2$$

and the volumetric flow rate from Eq.6.3,

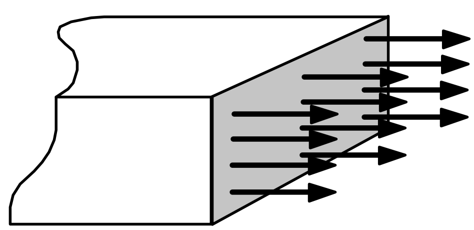
$$\dot{V} = \dot{m}v = A\mathbf{V}$$

$$\mathbf{V} = \frac{\dot{V}}{A} = \frac{0.015\ m^3/s}{0.015\ m^2} = \mathbf{1.0\ m/s}$$

Ideal gas so note:

$$v = \frac{RT}{P} = \frac{0.287 \times 308.2}{105} = 0.8424\ m^3/kg$$

$$\dot{m} = \frac{\dot{V}}{v} = \frac{0.015}{0.8424} = \mathbf{0.0178\ kg/s}$$



6.23

A boiler receives a constant flow of 5000 kg/h liquid water at 5 MPa, 20°C and it heats the flow such that the exit state is 450°C with a pressure of 4.5 MPa. Determine the necessary minimum pipe flow area in both the inlet and exit pipe(s) if there should be no velocities larger than 20 m/s.

Solution:

Mass flow rate from Eq.6.3, both $\mathbf{V} \le 20$ m/s

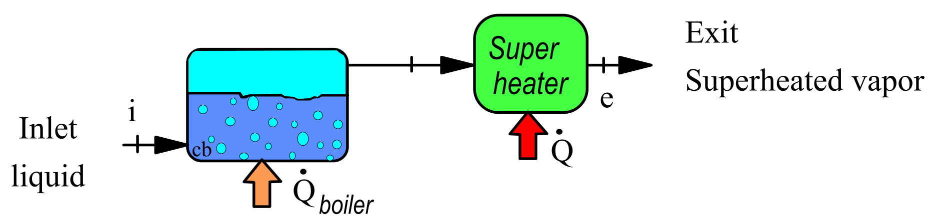
$$\dot{m}_i = \dot{m}_e = (A\mathbf{V}/v)_i = (A\mathbf{V}/v)_e = 5000 \frac{1}{3600} \text{ kg/s}$$

Table B.1.4 $\quad v_i = 0.001 \text{ m}^3/\text{kg}$,

Table B.1.3 $\quad v_e = (0.08003 + 0.00633)/2 = 0.07166 \text{ m}^3/\text{kg}$,

$$A_i \ge v_i \dot{m}/\mathbf{V}_i = 0.001 \times \frac{5000}{3600} / 20 = 6.94 \times 10^{-5} \text{ m}^2 = \mathbf{0.69\ cm^2}$$

$$A_e \ge v_e \dot{m}/\mathbf{V}_e = 0.07166 \times \frac{5000}{3600} / 20 = 4.98 \times 10^{-3} \text{ m}^2 = \mathbf{50\ cm^2}$$



6.24

An empty bathtub has its drain closed and is being filled with water from the faucet at a rate of 10 kg/min. After 10 minutes the drain is opened and 4 kg/min flows out and at the same time the inlet flow is reduced to 2 kg/min. Plot the mass of the water in the bathtub versus time and determine the time from the very beginning when the tub will be empty.

Solution:

During the first 10 minutes we have

$$\frac{dm_{cv}}{dt} = \dot{m}_i = 10 \text{ kg/min} , \qquad \Delta m = \dot{m}\, \Delta t_1 = 10 \times 10 = 100 \text{ kg}$$

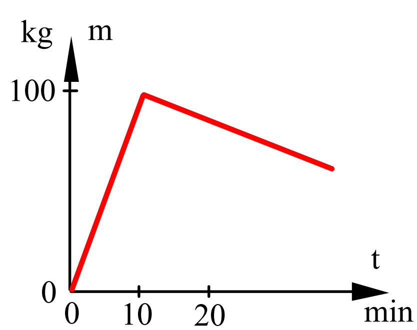
So we end up with 100 kg after 10 min. For the remaining period we have

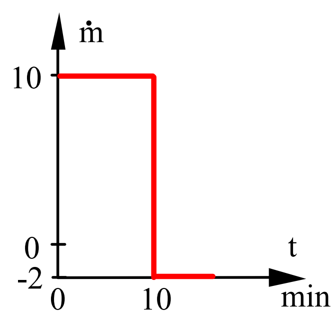
$$\frac{dm_{cv}}{dt} = \dot{m}_i - \dot{m}_e = 2 - 4 = -2 \text{ kg/min}$$

$$\Delta m_2 = \dot{m}_{net}\, \Delta t_2 \rightarrow \quad \Delta t_2 = \frac{\Delta m}{\dot{m}_{net}} = -100/-2 = 50 \text{ min.}$$

So it will take an additional 50 min. to empty

$$\Delta t_{tot} = \Delta t_1 + \Delta t_2 = 10 + 50 = \mathbf{60\ min.}$$





6.25

Nitrogen gas flowing in a 50-mm diameter pipe at 15°C, 200 kPa, at the rate of 0.05 kg/s, encounters a partially closed valve. If there is a pressure drop of 30 kPa across the valve and essentially no temperature change, what are the velocities upstream and downstream of the valve?

Solution:

Same inlet and exit area: $A = \frac{\pi}{4}(0.050)^2 = 0.001963 \text{ m}^2$

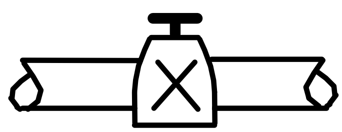
Ideal gas: $v_i = \frac{RT_i}{P_i} = \frac{0.2968 \times 288.2}{200} = 0.4277 \text{ m}^3\text{/kg}$

From Eq.6.3,

$$\mathbf{V}_i = \frac{\dot{m}v_i}{A} = \frac{0.05 \times 0.4277}{0.001963} = \mathbf{10.9\ m/s}$$

Ideal gas: $v_e = \frac{RT_e}{P_e} = \frac{0.2968 \times 288.2}{170} = 0.5032 \text{ m}^3\text{/kg}$

$$\mathbf{V}_e = \frac{\dot{m}v_e}{A} = \frac{0.05 \times 0.5032}{0.001963} = \mathbf{12.8\ m/s}$$



6.26

Saturated vapor R-134a leaves the evaporator in a heat pump system at 10°C, with a steady mass flow rate of 0.1 kg/s. What is the smallest diameter tubing that can be used at this location if the velocity of the refrigerant is not to exceed 7 m/s?

Solution:

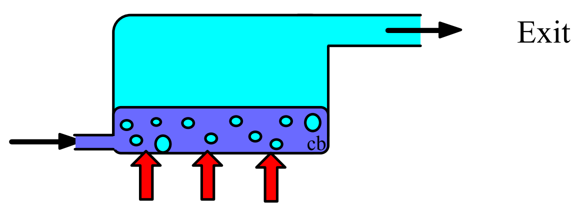
Mass flow rate Eq.6.3: $\dot{m} = \dot{V}/v = A\mathbf{V}/v$

Exit state Table B.5.1: (T = 10°C, x =1) => $v = v_g = 0.04945\ \mathrm{m^3/kg}$

The minimum area is associated with the maximum velocity for given $\dot{m}$

$$A_{MIN} = \frac{\dot{m} v_g}{\mathbf{V}_{MAX}} = \frac{0.1\ \mathrm{kg/s} \times 0.04945\ \mathrm{m^3/kg}}{7\ \mathrm{m/s}} = 0.000706\ \mathrm{m^2} = \frac{\pi}{4} D_{MIN}^2$$

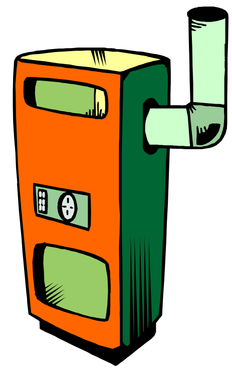
D_{MIN} = **0.03 m = 30 mm**



6.27

A hot air home heating system takes 0.25 m^3/s air at 100 kPa, 17^{o}C into a furnace and heats it to 52^{o}C and delivers the flow to a square duct 0.2 m by 0.2 m at 110 kPa. What is the velocity in the duct?

Solution:



The inflate flow is given by a $\dot{m}_i$

Continuity Eq.: $\dot{m}_i = \dot{V}_i / v_i = \dot{m}_e = A_e \mathbf{V}_e / v_e$

$$\text{Ideal gas: } v_i = \frac{RT_i}{P_i} = \frac{0.287 \times 290}{100} = 0.8323 \ \frac{m^3}{kg}$$

$$v_e = \frac{RT_e}{P_e} = \frac{0.287 \times (52 + 273)}{110}$$

$$= 0.8479 \ m^3/\,kg$$

$$\dot{m}_i = \dot{V}_i/v_i = 0.25/0.8323 = 0.30 \text{ kg/s}$$

$$\mathbf{V}_e = \dot{m}\, v_e/\, A_e = \frac{0.3 \times 0.8479}{0.2 \times 0.2} \ \frac{m^3/s}{m^2} = \mathbf{6.36\ m/s}$$

6.28

Steam at 3 MPa, 400°C enters a turbine with a volume flow rate of 5 m^3/s. An extraction of 15% of the inlet mass flow rate exits at 600 kPa, 200°C. The rest exits the turbine at 20 kPa with a quality of 90%, and a velocity of 20 m/s. Determine the volume flow rate of the extraction flow and the diameter of the final exit pipe.

Solution:

Inlet flow : $\dot{m}_i = \dot{V}/v = 5/0.09936 = 50.32$ kg/ s (Table B.1.3)

Extraction flow : $\dot{m}_e = 0.15\ \dot{m}_i = 7.55$ kg/ s; $v = 0.35202\ m^3/kg$

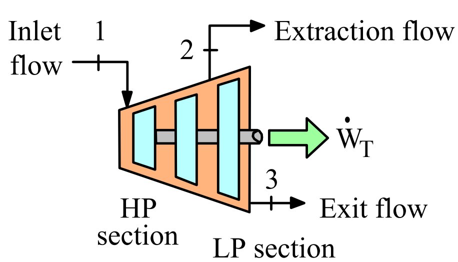
$$\dot{V}_{ex} = \dot{m}_e v = 7.55 \times 0.35202 = \mathbf{2.658\ m^3/\ s}$$

Exit flow : $\dot{m} = 0.85\ \dot{m}_i = 42.77$ kg /s

Table B.1.2 $v = 0.001017 + 0.9 \times 7.64835 = 6.8845\ m^3/kg$

$\dot{m} = A\mathbf{V}/v \Rightarrow \quad A = (\pi/4)\ D^2 = \dot{m}\ v/\mathbf{V} = 42.77 \times 6.8845/20 = 14.723\ m^2$

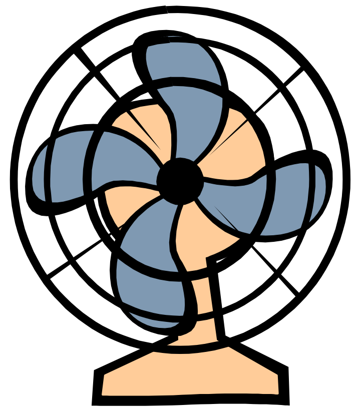
$\Rightarrow$ **D = 4.33 m**



6.29

A household fan of diameter 0.75 m takes air in at 98 kPa, 22°C and delivers it at 105 kPa, 23°C with a velocity of 1.5 m/s. What are the mass flow rate (kg/s), the inlet velocity and the outgoing volume flow rate in m^3/s?

Solution:



Continuity Eq. $\dot{m}_i = \dot{m}_e = A\mathbf{V}/v$

Ideal gas $v = RT/P$

Area : $A = \frac{\pi}{4} D^2 = \frac{\pi}{4} \times 0.75^2 = 0.442 \text{ m}^2$

$\dot{V}_e = A\mathbf{V}_e = 0.442 \times 1.5 = \mathbf{0.6627\ m^3/s}$

$v_e = \frac{RT_e}{P_e} = \frac{0.287 \times (23 + 273)}{105} = 0.8091 \text{ m}^3\text{/kg}$

$\dot{m}_i = \dot{V}_e/v_e = 0.6627/0.8091 = \mathbf{0.819\ kg/s}$

$AV_i / v_i = \dot{m}_i = A\mathbf{V}_e / v_e$

$\mathbf{V}_i = \mathbf{V}_e \times (v_i / v_e) = \mathbf{V}_e \times \frac{RT_i}{P_i v_e} = 1.5 \times \frac{0.287 \times (22 + 273)}{98 \times 0.8091} \mathbf{= 1.6\ m/s}$

Single flow single device processes

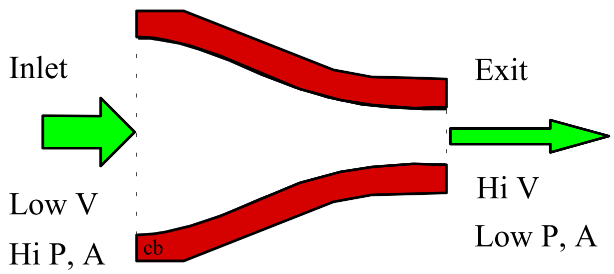
Nozzles, diffusers

6.30

Nitrogen gas flows into a convergent nozzle at 200 kPa, 400 K and very low velocity. It flows out of the nozzle at 100 kPa, 330 K. If the nozzle is insulated find the exit velocity.

Solution:

C.V. Nozzle steady state one inlet and exit flow, insulated so it is adiabatic.



Energy Eq.6.13: $h_1 + \emptyset = h_2 + \frac{1}{2}\mathbf{V}_2^2$

$$\mathbf{V}_2^2 = 2\,(h_1 - h_2) \cong 2\, C_{PN_2}\ (T_1 - T_2) = 2 \times 1.042\,(400 - 330)$$

$$= 145.88 \text{ kJ/kg} = 145\,880 \text{ J/kg}$$

$\Rightarrow$ $\mathbf{V}_2 = \mathbf{381.9\ m/s}$

6.31

A nozzle receives 0.1 kg/s steam at 1 MPa, 400$^{\mathrm{o}}$C with negligible kinetic energy. The exit is at 500 kPa, 350$^{\mathrm{o}}$C and the flow is adiabatic. Find the nozzle exit velocity and the exit area.

Solution:

Energy Eq.6.13: $h_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1 = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2$

Process: $Z_1 = Z_2$

State 1: $V_1 = 0$, Table B.1.3 $h_1 = 3263.88$ kJ/kg

State 2: Table B.1.3 $h_2 = 3167.65$ kJ/kg

Then from the energy equation

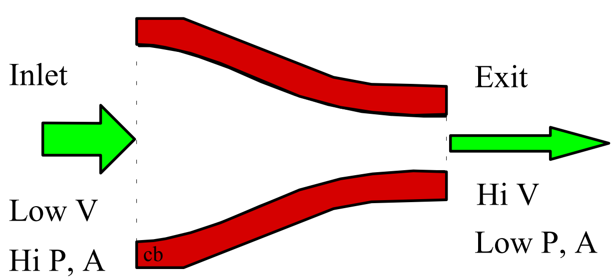
$$\frac{1}{2}\mathbf{V}_2^2 = h_1 - h_2 = 3263.88 - 3167.65 = 96.23 \text{ kJ/kg}$$

$$\mathbf{V}_2 = \sqrt{2(h_1 - h_2)} = \sqrt{2 \times 96.23 \times 1000} = \mathbf{438.7\ m/s}$$

The mass flow rate from Eq.6.3

$$\dot{m} = \rho A\mathbf{V} = A\mathbf{V}/v$$

$$A = \dot{m}v/\mathbf{V} = 0.1 \times 0.57012 / 438.7 = 0.00013 \text{ m}^2 = \mathbf{1.3\ cm^2}$$



6.32

Superheated vapor ammonia enters an insulated nozzle at 20°C, 800 kPa, shown in Fig. P6.32, with a low velocity and at the steady rate of 0.01 kg/s. The ammonia exits at 300 kPa with a velocity of 450 m/s. Determine the temperature (or quality, if saturated) and the exit area of the nozzle.

Solution:

C.V. Nozzle, steady state, 1 inlet and 1 exit flow, insulated so no heat transfer.

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

Process: $q = 0, \quad \mathbf{V}_i = 0$

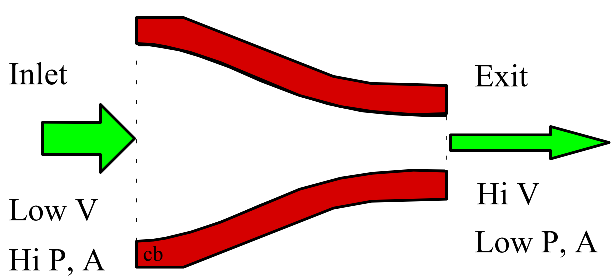
Table B.2.2: $h_i = 1464.9 = h_e + 450^2/(2\times1000) \quad \Rightarrow \quad h_e = 1363.6$ kJ/kg

Table B.2.1: $P_e = 300$ kPa Sat. state at −9.2°C :

$h_e = 1363.6 = 138.0 + x_e \times 1293.8$,

=> $x_e = \mathbf{0.947}$, $v_e = 0.001536 + x_e \times 0.4064 = 0.3864\ m^3/kg$

$$A_e = \dot{m}_e v_e/\mathbf{V}_e = 0.01 \times 0.3864 / 450 = \mathbf{8.56 \times 10^{-6}\ m^2}$$



6.33

In a jet engine a flow of air at 1000 K, 200 kPa and 30 m/s enters a nozzle, as shown in Fig. P6.33, where the air exits at 850 K, 90 kPa. What is the exit velocity assuming no heat loss?

Solution:

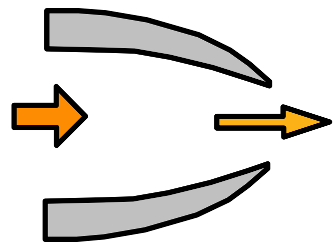
C.V. nozzle. No work, no heat transfer

Continuity $\dot{m}_i = \dot{m}_e = \dot{m}$

Energy : $\dot{m}\,(h_i + ½\mathbf{V}_i^2) = \dot{m}(h_e + ½\mathbf{V}_e^2)$

Due to high T take h from table A.7.1

$$½\mathbf{V}_e^2 = ½\,\mathbf{V}_i^2 + h_i - h_e$$
$$= \frac{1}{2000}(30)^2 + 1046.22 - 877.4$$
$$= 0.45 + 168.82 = 169.27 \text{ kJ/kg}$$



$$\mathbf{V}_e = (2000 \times 169.27)^{1/2} = \mathbf{581.8\ m/s}$$

6.34

In a jet engine a flow of air at 1000 K, 200 kPa and 40 m/s enters a nozzle where the air exits at 500 m/s, 90 kPa. What is the exit temperature assuming no heat loss?

Solution:

C.V. nozzle, no work, no heat transfer

Continuity $\dot{m}_i = \dot{m}_e = \dot{m}$

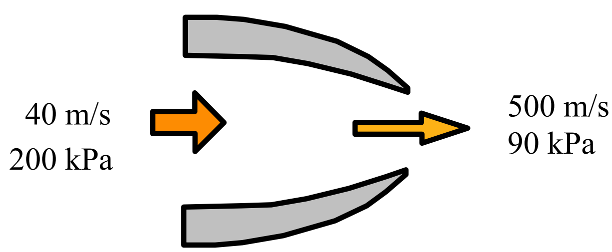
Energy : $\dot{m}\,(h_i + ½\mathbf{V}_i^2) = \dot{m}(h_e + ½\mathbf{V}_e^2)$

Due to the high T we take the h value from Table A.7.1

$$h_e = h_i + ½\,\mathbf{V}_i^2 - ½\mathbf{V}_e^2$$
$$= 1046.22 + 0.5 \times (40^2 – 500^2)\ (1/1000)$$
$$= 1046.22 – 124.2 = 922.02 \text{ kJ/kg}$$

Interpolation in Table A.7.1

$$T_e = 850 + 50\,\frac{922.02 - 877.4}{933.15 - 877.4} = \mathbf{890\ K}$$



6.35

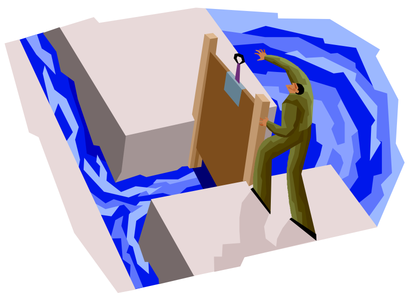
A sluice gate dams water up 5 m. There is a small hole at the bottom of the gate so liquid water at 20^{o}C comes out of a 1 cm diameter hole. Neglect any changes in internal energy and find the exit velocity and mass flow rate.

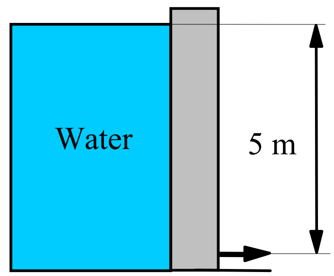
Solution:

Energy Eq.6.13: $h_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1 = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2$

Process: $h_1 = h_2$ both at P = 1 atm

$V_1 = 0$ $Z_1 = Z_2 + 5$ m





$$\frac{1}{2}\mathbf{V}_2^2 = g\,(Z_1 - Z_2)$$

$$\mathbf{V}_2 = \sqrt{2g(Z_1 - Z_2)} = \sqrt{2 \times 9.806 \times 5} = \mathbf{9.902\ m/s}$$

$$\dot{m} = \rho A\mathbf{V} = A\mathbf{V}/v = \frac{\pi}{4} D^2 \times (\mathbf{V}_2/v)$$

$$= \frac{\pi}{4} \times (0.01)^2 \times (9.902 / 0.001002) = \mathbf{0.776\ kg/s}$$

6.36

A diffuser, shown in Fig. P6.36, has air entering at 100 kPa, 300 K, with a velocity of 200 m/s. The inlet cross-sectional area of the diffuser is 100 mm^2. At the exit, the area is 860 mm^2, and the exit velocity is 20 m/s. Determine the exit pressure and temperature of the air.

Solution:

Continuity Eq.6.3: $\dot{m}_i = A_i\mathbf{V}_i/v_i = \dot{m}_e = A_e\mathbf{V}_e/v_e$,

Energy Eq.(per unit mass flow)6.13: $h_i + \frac{1}{2}\mathbf{V}_i^2 = h_e + \frac{1}{2}\mathbf{V}_e^2$

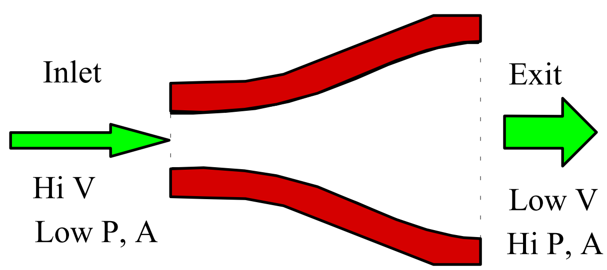
$$h_e - h_i = \frac{1}{2} \times 200^2/1000 - \frac{1}{2} \times 20^2/1000 = 19.8 \text{ kJ/kg}$$

$$T_e = T_i + (h_e - h_i)/C_p = 300 + 19.8/1.004 = \mathbf{319.72\ K}$$

Now use the continuity equation and the ideal gas law

$$v_e = v_i \left(\frac{A_e\mathbf{V}_e}{A_i\mathbf{V}_i}\right) = (RT_i/P_i)\left(\frac{A_e\mathbf{V}_e}{A_i\mathbf{V}_i}\right) = RT_e/P_e$$

$$P_e = P_i \left(\frac{T_e}{T_i}\right)\left(\frac{A_i\mathbf{V}_i}{A_e\mathbf{V}_e}\right) = 100\left(\frac{319.72}{300}\right)\left(\frac{100 \times 200}{860 \times 20}\right) = \mathbf{123.92\ kPa}$$



6.37

A diffuser receives an ideal gas flow at 100 kPa, 300 K with a velocity of 250 m/s and the exit velocity is 25 m/s. Determine the exit temperature if the gas is argon, helium or nitrogen.

Solution:

C.V. Diffuser: $\dot{m}_i = \dot{m}_e$ & assume no heat transfer $\Rightarrow$

Energy Eq.6.13: $h_i + \frac{1}{2}\mathbf{V}_i^2 = \frac{1}{2}\mathbf{V}_e^2 + h_e \Rightarrow h_e = h_i + \frac{1}{2}\mathbf{V}_i^2 - \frac{1}{2}\mathbf{V}_e^2$

$$h_e - h_i \approx C_p (T_e - T_i) = \frac{1}{2} (\mathbf{V}_i^2 - \mathbf{V}_e^2) = \frac{1}{2} (250^2 - 25^2)$$

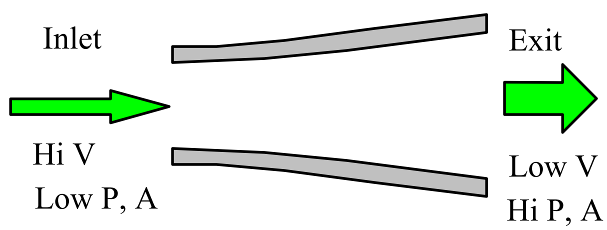
$$= 30937.5 \text{ J/kg} = 30.938 \text{ kJ/kg}$$

Specific heats for ideal gases are from table A.5

Argon $C_p = 0.52$ kJ/kg K; $\Delta T = \frac{30.938}{0.52} = 59.5$ $\mathbf{T_e = 359.5\ K}$

Helium $C_p = 5.913$ kJ/kg K; $\Delta T = \frac{30.938}{5.193} = 5.96$ $\mathbf{T_e = 306\ K}$

Nitrogen $C_p = 1.042$ kJ/kg K; $\Delta T = \frac{30.938}{1.042} = 29.7$ $\mathbf{T_e = 330\ K}$



6.38

Air flows into a diffuser at 300 m/s, 300 K and 100 kPa. At the exit the velocity is very small but the pressure is high. Find the exit temperature assuming zero heat transfer.

Solution:

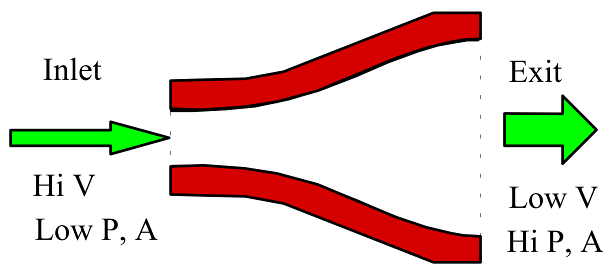
Energy Eq.: $h_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1 = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2$

Process: $Z_1 = Z_2$ and $V_2 = 0$

$h_2 = h_1 + \frac{1}{2}\mathbf{V}_1^2$

$T_2 = T_1 + \frac{1}{2} \times (\mathbf{V}_1^2 / C_p)$

$= 300 + \frac{1}{2} \times 300^2 / (1.004 \times 1000) = \mathbf{344.8K}$



6.39

The front of a jet engine acts as a diffuser receiving air at 900 km/h, -5°C, 50 kPa, bringing it to 80 m/s relative to the engine before entering the compressor. If the flow area is reduced to 80% of the inlet area find the temperature and pressure in the compressor inlet.

Solution:

C.V. Diffuser, Steady state, 1 inlet, 1 exit flow, no q, no w.

Continuity Eq.6.3: $\dot{m}_i = \dot{m}_e = (A\mathbf{V}/v)$

Energy Eq.6.12: $\dot{m}\,(h_i + \frac{1}{2}\mathbf{V}_i^2) = \dot{m}\,(\frac{1}{2}\mathbf{V}_e^2 + h_e)$

$$h_e - h_i = C_p\,(T_e - T_i) = \frac{1}{2}\mathbf{V}_i^2 - \frac{1}{2}\mathbf{V}_e^2 = \frac{1}{2}\left(\frac{900 \times 1000}{3600}\right)^2 - \frac{1}{2}(80)^2$$

$$= 28050 \text{ J/kg} = 28.05 \text{ kJ/kg}$$

$\Delta T = 28.05/1.004 = 27.9 \quad \Rightarrow \qquad T_e = -5 + 27.9 = 22.9°C$

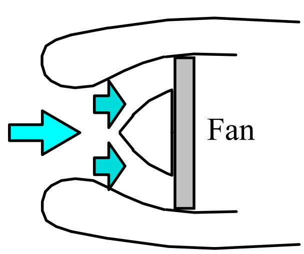
Now use the continuity eq.:

$$A_i\mathbf{V}_i / v_i = A_e\mathbf{V}_e / v_e \quad \Rightarrow \qquad v_e = v_i \left(\frac{A_e\mathbf{V}_e}{A_i\mathbf{V}_i}\right)$$

$$v_e = v_i \times \frac{0.8 \times 80}{1 \times 250} = v_i \times 0.256$$

Ideal gas: $Pv = RT \quad => \quad v_e = RT_e/P_e = RT_i \times 0.256/P_i$

$$P_e = P_i\,(T_e/T_i)/0.256 = 50 \times 296/268 \times 0.256 = \mathbf{215.7\ kPa}$$



Throttle flow

6.40

Helium is throttled from 1.2 MPa, 20°C, to a pressure of 100 kPa. The diameter of the exit pipe is so much larger than the inlet pipe that the inlet and exit velocities are equal. Find the exit temperature of the helium and the ratio of the pipe diameters.

Solution:

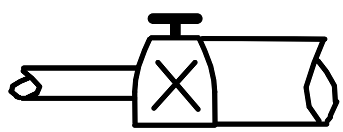
C.V. Throttle. Steady state,

Process with: $q = w = 0$; and $\mathbf{V}_i = \mathbf{V}_e$, $Z_i = Z_e$

Energy Eq.6.13: $h_i = h_e$, Ideal gas => $T_i = T_e = \mathbf{20°C}$

$$\dot{m} = \frac{A\mathbf{V}}{RT/P} \qquad \text{But } \dot{m}, \mathbf{V}, T \text{ are constant} \quad => \quad P_iA_i = P_eA_e$$

$$\Rightarrow \quad \frac{D_e}{D_i} = \left(\frac{P_i}{P_e}\right)^{1/2} = \left(\frac{1.2}{0.1}\right)^{1/2} = \mathbf{3.464}$$



6.41

Saturated vapor R-134a at 500 kPa is throttled to 200 kPa in a steady flow through a valve. The kinetic energy in the inlet and exit flow is the same. What is the exit temperature?

Solution:

Steady throttle flow

Continuity $\dot{m}_i = \dot{m}_e = \dot{m}$

Energy Eq.6.13: $h_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1 = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2$

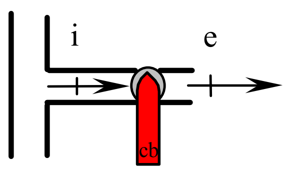
Process: $Z_1 = Z_2$ and $\mathbf{V}_2 = \mathbf{V}_1$

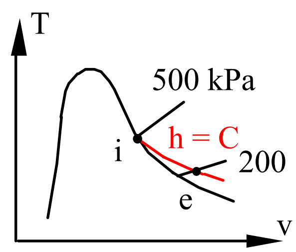
$\Rightarrow \quad h_2 = h_1 = 407.45$ kJ/kg from Table B.5.2

State 2: P_2 & $h_2 \quad \Rightarrow \quad$ superheated vapor

Interpolate between 0°C and 10°C in table B.5.2 in the 200 kPa subtable

$$T_2 = 0 + 10\,\frac{407.45 - 400.91}{409.5 - 400.91} = \mathbf{7.6^oC}$$





6.42

Saturated liquid R-12 at 25°C is throttled to 150.9 kPa in your refrigerator. What is the exit temperature? Find the percent increase in the volume flow rate.

Solution:

Steady throttle flow. Assume no heat transfer and no change in kinetic or potential energy.

$$h_e = h_i = h_{f\,25^oC} = 59.70 \text{ kJ/kg} = h_{f\,e} + x_e\, h_{fg\,e} \quad \text{at } 150.70 \text{ kPa}$$

From table B.3.1 we get $T_e = T_{sat}$ (150.9 kPa) = **-20°C**

$$x_e = \frac{h_e - h_{f\,e}}{h_{fg\,e}} = \frac{59.7 - 17.82}{160.92} = 0.26025$$

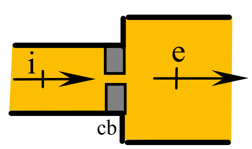
$$v_e = v_f + x_e\, v_{fg} = 0.000685 + x_e\, 0.10816 = 0.0288336 \text{ m}^3\text{/kg}$$

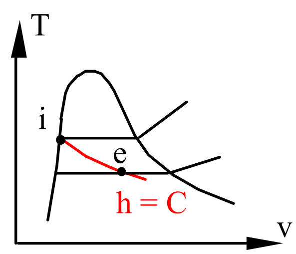
$$v_i = v_{f\,25^oC} = 0.000763 \text{ m}^3\text{/kg}$$

$\dot{V} = \dot{m}v$ so the ratio becomes

$$\frac{\dot{V}_e}{\dot{V}_i} = \frac{\dot{m}v_e}{\dot{m}v_i} = \frac{v_e}{v_i} = \frac{0.0288336}{0.000763} = \mathbf{37.79}$$

So the increase is 36.79 times or **3679 %**





6.43

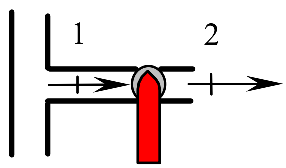
Water flowing in a line at 400 kPa, saturated vapor, is taken out through a valve to 100 kPa. What is the temperature as it leaves the valve assuming no changes in kinetic energy and no heat transfer?

Solution:

C.V. Valve. Steady state, single inlet and exit flow

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

Energy Eq.6.12: $\dot{m}_1 h_1 + \dot{Q} = \dot{m}_2 h_2 + \dot{W}$



Process: Throttling

Small surface area: $\dot{Q} = 0$;

No shaft: $\dot{W} = 0$

Table B.1.2: $h_2 = h_1 = 2738.6$ kJ/kg $\Rightarrow$ $\mathbf{T_2 = 131.1°C}$

6.44

Liquid water at 180^{o}C, 2000 kPa is throttled into a flash evaporator chamber having a pressure of 500 kPa. Neglect any change in the kinetic energy. What is the fraction of liquid and vapor in the chamber?

Solution:

Energy Eq.6.13: $h_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1 = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2$

Process: $Z_1 = Z_2$ and $\mathbf{V}_2 = \mathbf{V}_1$

$\Rightarrow \quad h_2 = h_1 = 763.71$ kJ/kg from Table B.1.4

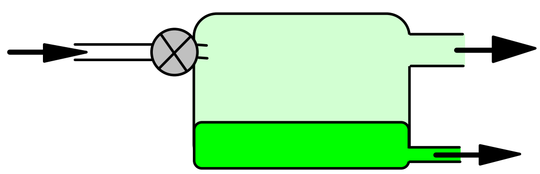
State 2: P_2 & h_2 $\Rightarrow$ 2 – phase

$h_2 = h_f + x_2\, h_{fg}$

$x_2 = (h_2 - h_f) / h_{fg} = \frac{763.71 - 640.21}{2108.47} = 0.0586$

Fraction of Vapor: $x_2 = 0.0586$ (5.86 %)

Liquid: $1 - x_2 = 0.941$ (94.1 %)



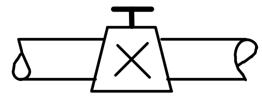
Two-phase out of the valve. The liquid drops to the bottom.

6.45

Water at 1.5 MPa, 150°C, is throttled adiabatically through a valve to 200 kPa. The inlet velocity is 5 m/s, and the inlet and exit pipe diameters are the same. Determine the state (neglecting kinetic energy in the energy equation) and the velocity of the water at the exit.

Solution:

CV: valve. $\dot{m}$ = const, A = const



$\Rightarrow \mathbf{V}_e = \mathbf{V}_i(v_e/v_i)$

Energy Eq.6.13:

$$h_i + \frac{1}{2}\mathbf{V}_i^2 = \frac{1}{2}\mathbf{V}_e^2 + h_e \quad \text{or} \quad (h_e - h_i) + \frac{1}{2}\mathbf{V}_i^2 \left[\left(\frac{v_e}{v_i}\right)^2 - 1\right] = 0$$

Now neglect the kinetic energy terms (relatively small) from table B.1.1 we have the compressed liquid approximated with saturated liquid same T

$$h_e = h_i = 632.18 \text{ kJ/kg} \ ; \quad v_i = 0.001090 \ \text{m}^3\text{/kg}$$

Table B.1.2: $h_e = 504.68 + x_e \times 2201.96$,

Substituting and solving, x_e = **0.0579**

$v_e = 0.001061 + x_e \times 0.88467 = \mathbf{0.052286\ m^3/kg}$

$\mathbf{V}_e = \mathbf{V}_i(v_e/v_i) = 5$ m/s (0.052286 / 0.00109) = **240 m/s**

6.46

R-134a is throttled in a line flowing at 25^{o}C, 750 kPa with negligible kinetic energy to a pressure of 165 kPa. Find the exit temperature and the ratio of exit pipe diameter to that of the inlet pipe (D_{ex}/D_{in}) so the velocity stays constant.

Solution:

Energy Eq.6.13: $h_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1 = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2$

Process: $Z_1 = Z_2$ and $\mathbf{V}_2 = \mathbf{V}_1$

State 1, Table B.5.1: $h_1 = 234.59$ kJ/kg, $v_1 = v_f = 0.000829$ m^3/kg

Use energy eq.: $\Rightarrow$ $h_2 = h_1 = 234.59$ kJ/kg

State 2: P_2 & h_2 $\Rightarrow$ 2 – phase and $T_2 = T_{sat}$ (165 kPa) = **-15°C**

$h_2 = h_f + x_2\, h_{fg} = 234.59$ kJ/kg

$x_2 = (h_2 - h_f) / h_{fg} = (234.59 - 180.19) / 209 = 0.2603$

$v_2 = v_f + x_2 \times v_{fg} = 0.000746 + 0.2603 \times 0.11932 = 0.0318$ m^3/kg

Now the continuity equation with $\mathbf{V}_2 = \mathbf{V}_1$ gives, from Eq.6.3,

$$\dot{m} = \rho A\mathbf{V} = A\mathbf{V}/v = A_1\mathbf{V}_1/v_1 = (A_2\, \mathbf{V}_1) / v_2$$

$$(A_2 / A_1) = v_2 / v_1 = (D_2 / D_1)^2$$

$$(D_2/D_1) = (v_2 / v_1)^{0.5} = (0.0318 / 0.000829)^{0.5} = \mathbf{6.19}$$

6.47

Methane at 3 MPa, 300 K is throttled through a valve to 100 kPa. Calculate the exit temperature assuming no changes in the kinetic energy and ideal gas behavior. Repeat the answer for real-gas behavior.

C.V. Throttle (valve, restriction), Steady flow, 1 inlet and exit, no q, w

Energy Eq.: $h_i = h_e$ => Ideal gas $T_i = T_e =$ **300 K**

Real gas : $\left.\begin{array}{l} h_i = h_e = 598.71 \\ P_e = 0.1 \text{ MPa} \end{array}\right\}$ Table B.7 $T_e =$ **13.85°C** (= **287 K**)

Turbines, Expanders

6.48

A steam turbine has an inlet of 2 kg/s water at 1000 kPa, 350^{o}C and velocity of 15 m/s. The exit is at 100 kPa, x = 1 and very low velocity. Find the specific work and the power produced.

Solution:

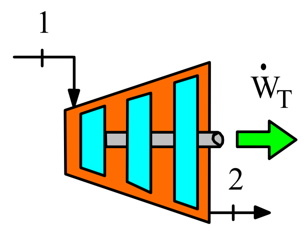
Energy Eq.6.13: $h_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1 = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2 + w_T$

Process: $Z_1 = Z_2$ and $\mathbf{V}_2 = 0$

Table B.1.3: $h_1 = 3157.65$ kJ/kg, $h_2 = 2675.46$ kJ/kg

$w_T = h_1 + \frac{1}{2}\mathbf{V}_1^2 - h_2 = 3157.65 + 15^2 / 2000 - 2675.46 =$ **482.3 kJ/kg**

$\dot{W}_T = \dot{m} \times w_T = 2 \times 482.3 =$ **964.6 kW**



6.49

A small, high-speed turbine operating on compressed air produces a power output of 100 W. The inlet state is 400 kPa, 50°C, and the exit state is 150 kPa, −30°C. Assuming the velocities to be low and the process to be adiabatic, find the required mass flow rate of air through the turbine.

Solution:

C.V. Turbine, no heat transfer, no ΔKE, no ΔPE

Energy Eq.6.13: $h_{in} = h_{ex} + w_T$

Ideal gas so use constant specific heat from Table A.5

$$w_T = h_{in} - h_{ex} \cong C_p(T_{in} - T_{ex})$$

$$= 1.004 \text{ (kJ/kg K) } [50 - (-30)] \text{ K} = 80.3 \text{ kJ/kg}$$

$$\dot{W} = \dot{m} w_T \quad \Rightarrow \quad \dot{m} = \dot{W}/w_T = 0.1/80.3 = \mathbf{0.00125\ kg/s}$$

The dentist's drill has a small air flow and is not really adiabatic.

6.50

A liquid water turbine receives 2 kg/s water at 2000 kPa, 20^{o}C and velocity of 15 m/s. The exit is at 100 kPa, 20^{o}C and very low velocity. Find the specific work and the power produced.

Solution:

Energy Eq.6.13: $h_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1 = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2 + w_T$

Process: $Z_1 = Z_2$ and $\mathbf{V}_2 = 0$

State 1: Table B.1.4 $h_1 = 85.82$ kJ/kg

State 2: Table B.1.1 $h_2 = 83.94$ (which is at 2.3 kPa so we should add $\Delta Pv = 97.7 \times 0.001$ to this)

$$w_T = h_1 + \frac{1}{2}\mathbf{V}_1^2 - h_2 = 85.82 + 15^2/2000 - 83.94 = \mathbf{1.99\ kJ/kg}$$

$$\dot{W}_T = \dot{m} \times w_T = 2 \times 1.9925 = \mathbf{3.985\ kW}$$

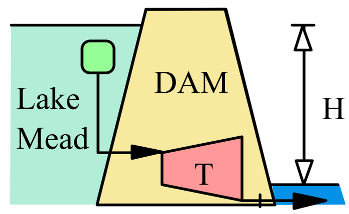
Notice how insignificant the specific kinetic energy is.

6.51

Hoover Dam across the Colorado River dams up Lake Mead 200 m higher than the river downstream. The electric generators driven by water-powered turbines deliver 1300 MW of power. If the water is 17.5°C, find the minimum amount of water running through the turbines.

Solution:

C.V.: H_2O pipe + turbines,



Continuity: $\dot{m}_{in} = \dot{m}_{ex}$;

Energy Eq.6.13: $(h + \mathbf{V}^2/2 + gz)_{in} = (h + \mathbf{V}^2/2 + gz)_{ex} + w_T$

Water states: $h_{in} \cong h_{ex}$; $v_{in} \cong v_{ex}$

Now the specific turbine work becomes

$$w_T = gz_{in} - gz_{ex} = 9.807 \times 200/1000 = 1.961 \text{ kJ/kg}$$

$$\dot{m} = \dot{W}_T/w_T = \frac{1300\times10^3 \text{ kW}}{1.961 \text{ kJ/kg}} = 6.63 \times10^5 \text{ kg/s}$$

$$\dot{V} = \dot{m}v = 6.63 \times10^5 \times 0.001001 = \mathbf{664\ m^3/s}$$

6.52

A windmill with rotor diameter of 30 m takes 40% of the kinetic energy out as shaft work on a day with 20^{o}C and wind speed of 30 km/h. What power is produced?

Solution:

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

Energy $\dot{m}\,(h_i + ½\mathbf{V}_i^2 + gZ_i) = \dot{m}(h_e + ½\mathbf{V}_e^2 + gZ_e) + \dot{W}$

Process information: $\dot{W} = \dot{m}½\mathbf{V}_i^2 \times 0.4$

$\dot{m} = \rho A\mathbf{V} = A\mathbf{V}_i / v_i$

$A = \frac{\pi}{4} D^2 = \frac{\pi}{4} 30^2 = 706.85 \text{ m}^2$

$v_i = RT_i/P_i = \frac{0.287 \times 293}{101.3} = 0.8301 \text{ m}^3\text{/kg}$

$\mathbf{V}_i = 30 \text{ km/h} = \frac{30 \times 1000}{3600} = 8.3333 \text{ m/s}$

$\dot{m} = A\mathbf{V}_i / v_i = \frac{706.85 \times 8.3333}{0.8301} = 7096 \text{ kg/s}$

$½\,\mathbf{V}_i^2 = ½\ 8.3333^2 \text{ m}^2/\text{s}^2 = 34.722 \text{ J/kg}$

$\dot{W} = 0.4\,\dot{m}½\,\mathbf{V}_i^2 = 0.4 \times 7096 \times 34.722 = 98\,555 \text{ W}$

$= \mathbf{98.56\ kW}$

6.53

A small turbine, shown in Fig. P 6.53, is operated at part load by throttling a 0.25 kg/s steam supply at 1.4 MPa, 250°C down to 1.1 MPa before it enters the turbine and the exhaust is at 10 kPa. If the turbine produces 110 kW, find the exhaust temperature (and quality if saturated).

Solution:

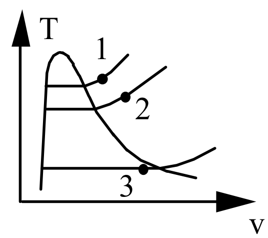
C.V. Throttle, Steady, $q = 0$ and $w = 0$. No change in kinetic or potential energy. The energy equation then reduces to

Energy Eq.6.13: $h_1 = h_2 = 2927.2$ kJ/kg from Table B.1.3

C.V. Turbine, Steady, no heat transfer, specific work: $w = \frac{110}{0.25} = 440$ kJ/kg

Energy Eq.: $h_1 = h_2 = h_3 + w = 2927.2$ kJ/kg

$\Rightarrow \quad h_3 = 2927.2 - 440 = 2487.2$ kJ/kg



State 3: (P, h) Table B.1.2 $h < h_g$

$2487.2 = 191.83 + x_3 \times 2392.8$

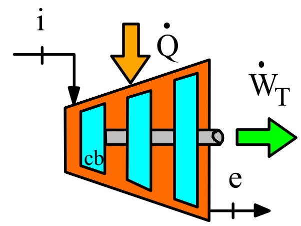
$\Rightarrow \quad T = \mathbf{45.8°C}, \quad x_3 = \mathbf{0.959}$

6.54

A small expander (a turbine with heat transfer) has 0.05 kg/s helium entering at 1000 kPa, 550 K and it leaves at 250 kPa, 300 K. The power output on the shaft is measured to 55 kW. Find the rate of heat transfer neglecting kinetic energies.

Solution:

C.V. Expander. Steady operation



Cont. $\dot{m}_i = \dot{m}_e = \dot{m}$

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

$$\dot{Q} = \dot{m}\,(h_e - h_i) + \dot{W}$$

Use heat capacity from tbl A.5: $C_{p\ He} = 5.193$ kJ/kg K

$$\dot{Q} = \dot{m}C_p\,(T_e - T_i) + \dot{W}$$
$$= 0.05 \times 5.193\,(300 - 550) + 55$$
$$= -64.91 + 55 = \mathbf{-9.9\ kW}$$

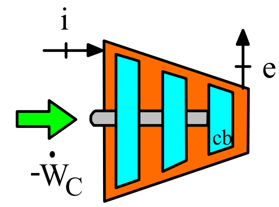
Compressors, fans

6.55

A compressor in a commercial refrigerator receives R-22 at -25$^{\mathrm{o}}$C, x = 1. The exit is at 800 kPa, 40$^{\mathrm{o}}$C. Neglect kinetic energies and find the specific work.

Solution:

C.V. Compressor, steady state, single inlet and exit flow. For this device we also assume no heat transfer and $Z_1 = Z_2$



From Table B.4.1 : $h_1 = 239.92$ kJ/kg

From Table B.4.2 : $h_2 = 274.24$ kJ/kg

Energy Eq.6.13 reduces to

$$w_c = h_1 - h_2 = (239.92 - 274.24) = \mathbf{-34.3\ kJ/kg}$$

6.56

The compressor of a large gas turbine receives air from the ambient at 95 kPa, 20°C, with a low velocity. At the compressor discharge, air exits at 1.52 MPa, 430°C, with velocity of 90 m/s. The power input to the compressor is 5000 kW. Determine the mass flow rate of air through the unit.

Solution:

C.V. Compressor, steady state, single inlet and exit flow.

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

Here we assume $q \cong 0$ and $\mathbf{V}_i \cong 0$ so using constant C_{Po} from A.5

$$-w = C_{Po}(T_e - T_i) + \mathbf{V}_e^2/2 = 1.004(430 - 20) + \frac{(90)^2}{2 \times 1000} = 415.5 \text{ kJ/kg}$$

Notice the kinetic energy is 1% of the work and can be neglected in most cases. The mass flow rate is then from the power and the specific work

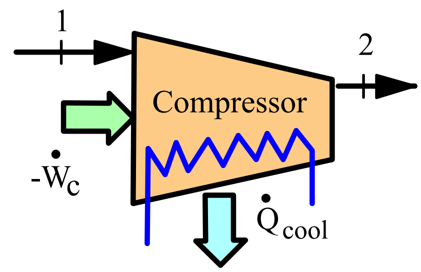
$$\dot{m} = \frac{\dot{W}_c}{-w} = \frac{5000}{415.5} = \mathbf{12.0\ kg/s}$$

6.57

A compressor brings R-134a from 150 kPa, -10°C to 1200 kPa, 50°C. It is water cooled with a heat loss estimated as 40 kW and the shaft work input is measured to be 150 kW. How much is the mass flow rate through the compressor?

Solution:

C.V Compressor. Steady flow.
Neglect kinetic and potential energies.



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

$$\dot{m} = (\dot{Q} - \dot{W})/(h_e - h_i)$$

Look in table B.5.2

$h_i = 393.84$ kJ/kg, $\qquad h_e = 426.84$ kJ/kg

$$\dot{m} = \frac{-40 - (-150)}{426.84 - 393.84} = \mathbf{3.333\ kg/s}$$

6.58

An ordinary portable fan blows 0.2 kg/s room air with a velocity of 18 m/s. What is the minimum power electric motor that can drive it? Hint: Are there any changes in P or T?

Solution:

C.V. Fan plus space out to near stagnant inlet room air.

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

Here $q \cong 0$, $\mathbf{V}_i \cong 0$ and $h_i = h_e$ same P and T

$-w = \mathbf{V}_e^2/2 = 18^2/2000 = 0.162$ kJ/kg

$-\dot{W} = -\dot{m}w = 0.2$ kg/s $\times$ 0.162 kJ/kg = **0.032 kW**

6.59

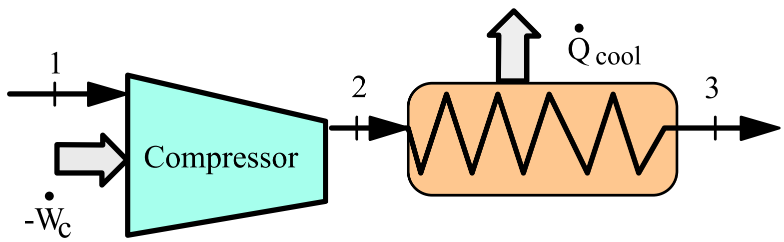
An air compressor takes in air at 100 kPa, 17°C and delivers it at 1 MPa, 600 K to a constant-pressure cooler, which it exits at 300 K. Find the specific compressor work and the specific heat transfer in the cooler.

Solution

C.V. air compressor $q = 0$

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

Energy Eq.6.13: $h_1 + w_c = h_2$



Compressor section Cooler section

Table A.7:

$w_{c\ in} = h_2 - h_1 = 607.02 - 290.17 =$ **316.85 kJ/kg**

C.V. cooler $w = \emptyset$

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

Energy Eq.6.13: $h_2 = q_{out} + h_3$

$q_{out} = h_2 - h_3 = 607.02 - 300.19 =$ **306.83 kJ/kg**

6.60

A 4 kg/s steady flow of ammonia runs through a device where it goes through a polytropic process. The inlet state is 150 kPa, -20^{o}C and the exit state is 400 kPa, 80^{o}C, where all kinetic and potential energies can be neglected. The specific work input has been found to be given as [n/(n-1)] Δ(Pv).

a) Find the polytropic exponent n

b) Find the specific work and the specific heat transfer.

Solution:

C.V. Steady state device. Single inlet and single exit flows.

Energy Eq.6.13: $h_1 + \frac{1}{2}\mathbf{V}_1^2 + gZ_1 + q = h_2 + \frac{1}{2}\mathbf{V}_2^2 + gZ_2 + w$

Process: Pv^n = constant and $Z_1 = Z_2$, $\mathbf{V}_1 = \mathbf{V}_2 = 0$

State 1: Table B.2.2 $v_1 = 0.79774$, $h_1 = 1422.9$

State 2: Table B.2.2 $v_2 = 0.4216$, $h_2 = 1636.7$

From the polytropic process equation and the two states we can find the exponent n:

$$n = \ln \frac{P_2}{P_1} / \ln \frac{v_1}{v_2} = \ln \frac{400}{150} / \ln \frac{0.79774}{0.4216} = \mathbf{1.538}$$

Before we can do the heat transfer we need the work term

$$w = -\frac{n}{n-1}(P_2v_2 - P_1v_1) = -2.8587(400\times0.4216 - 150\times0.79774)$$

$$= \mathbf{-140.0\ kJ/kg}$$

$$q = h_2 + w - h_1 = 1636.7 - 140.0 - 1422.9 = \mathbf{73.8\ kJ/kg}$$

6.61

An exhaust fan in a building should be able to move 2.5 kg/s air at 98 kPa, 20^{o}C through a 0.4 m diameter vent hole. How high a velocity must it generate and how much power is required to do that?

Solution:

C.V. Fan and vent hole. Steady state with uniform velocity out.

Continuity Eq.: $\dot{m}$ = constant = $\rho A\mathbf{V} = A\mathbf{V} / v = A\mathbf{V}P/RT$

Ideal gas : $Pv = RT$, and area is $A = \frac{\pi}{4} D^2$

Now the velocity is found

$$\mathbf{V} = \dot{m}\, RT/(\frac{\pi}{4} D^2 P) = 2.5 \times 0.287 \times 293.15 / (\frac{\pi}{4} \times 0.4^2 \times 98) = 17.1 \textbf{ m/s}$$

The kinetic energy out is

$$\frac{1}{2}\mathbf{V}_2^2 = \frac{1}{2} \times 17.1^2 / 1000 = 0.146 \text{ kJ/kg}$$

which is provided by the work (only two terms in energy equation that does not cancel, we assume $\mathbf{V}_1 = 0$)

$$\dot{W}_{in} = \dot{m}\ \frac{1}{2}\mathbf{V}_2^2 = 2.5 \times 0.146 = \mathbf{0.366\ kW}$$

6.62

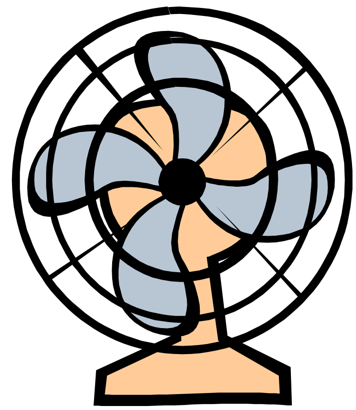
How much power is needed to run the fan in Problem 6.29?

A household fan of diameter 0.75 m takes air in at 98 kPa, 22°C and delivers it at 105 kPa, 23°C with a velocity of 1.5 m/s. What are the mass flow rate (kg/s), the inlet velocity and the outgoing volume flow rate in m^3/s?

Solution:

Continuity Eq. $\dot{m}_i = \dot{m}_e = A\mathbf{V}/ v$

Ideal gas $v = RT/P$



Area : $A = \frac{\pi}{4} D^2 = \frac{\pi}{4} \times 0.75^2 = 0.442 \text{ m}^2$

$\dot{V}_e = A\mathbf{V}_e = 0.442 \times 1.5 = \mathbf{0.6627\ m^3/s}$

$v_e = \frac{RT_e}{P_e} = \frac{0.287 \times 296}{105} = 0.8091 \text{m}^3\text{/kg}$

$\dot{m}_i = \dot{V}_e/v_e = 0.6627/0.8091 = \mathbf{0.819\ kg/s}$

$A\mathbf{V}_i / v_i = \dot{m}_i = A\mathbf{V}_e / v_e$

$\mathbf{V}_i = \mathbf{V}_e \times (v_i / v_e) = \mathbf{V}_e \times (RT_i)/(P_i v_e) = 1.5 \times \frac{0.287 \times (22 + 273)}{98 \times 0.8091} = \mathbf{1.6\ m/s}$

$\dot{m}\,(h_i + ½\mathbf{V}_i^2) = \dot{m}(h_e + ½\mathbf{V}_e^2) + \dot{W}$

$\dot{W} = \dot{m}(h_i + ½V_i^2 – h_e – ½V_e^2) = \dot{m}\,[C_p\,(T_i\text{-}T_e) + ½\,V_i^2 – ½V_e^2\,]$

$= 0.819\ [\ 1.004\ (-1) + \frac{1.6^2 - 1.5^2}{2000}] = 0.819\ [\ -1.004 + 0.000155]$

$= \mathbf{-\ 0.81\ kW}$

Heaters/Coolers

6.63

Carbon dioxide enters a steady-state, steady-flow heater at 300 kPa, 15^{o}C, and exits at 275 kPa, 1200^{o}C, as shown in Fig. P6.63. Changes in kinetic and potential energies are negligible. Calculate the required heat transfer per kilogram of carbon dioxide flowing through the heater.

Solution:

C.V. Heater Steady state single inlet and exit flow.

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

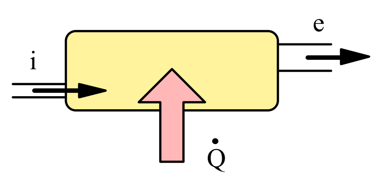


Table A.8: $q = h_e - h_i = 1579.2 – 204.6 =$ **1374.6 kJ/kg**

(If we use C_{p0} from A.5 then $q \cong 0.842(1200 - 15) = 997.8$ kJ/kg)

Too large ΔT, T_{ave} to use C_{p0} at room temperature.

6.64

A condenser (cooler) receives 0.05 kg/s R-22 at 800 kPa, 40^{o}C and cools it to 15^{o} C. There is a small pressure drop so the exit state is saturated liquid. What cooling capacity (kW) must the condenser have?

Solution:

C.V. R-22 condenser. Steady state single flow, heat transfer out and no work.

Energy Eq.6.12: $\dot{m}\, h_1 = \dot{m}\, h_2 + \dot{Q}_{out}$

Inlet state: Table B.4.2 $h_1 = 274.24$ kJ/kg,

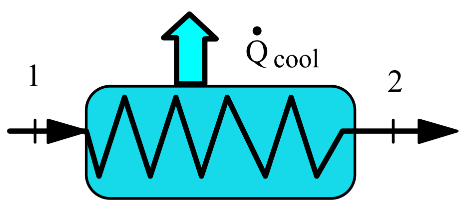
Exit state: Table B.4.1 $h_2 = 62.52$ kJ/kg

Process: Neglect kinetic and potential energy changes.

Cooling capacity is taken as the heat transfer out i.e. positive out so

$$\dot{Q}_{out} = \dot{m}\,(h_1 - h_2) = 0.05 \text{ kg/s } (274.24 - 62.52) \text{ kJ/kg}$$

$$= 10.586 \text{ kW} = \mathbf{10.6\ kW}$$



6.65

A chiller cools liquid water for air-conditioning purposes. Assume 2.5 kg/s water at 20^{o}C, 100 kPa is cooled to 5^{o}C in a chiller. How much heat transfer (kW) is needed?

Solution:

C.V. Chiller. Steady state single flow with heat transfer. Neglect changes in kinetic and potential energy and no work term.

Energy Eq.6.13: $q_{out} = h_i - h_e$

Properties from Table B.1.1:

$h_i = 83.94$ kJ/kg and $h_e = 20.98$ kJ/kg

Now the energy equation gives

$$q_{out} = 83.94 - 20.98 = 62.96 \text{ kJ/kg}$$

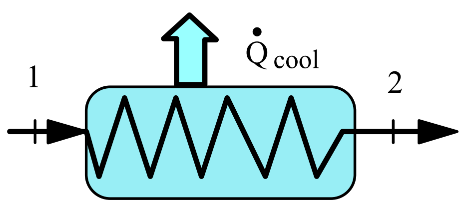
$$\dot{Q}_{out} = \dot{m}\, q_{out} = 2.5 \times 62.96 = \mathbf{157.4\ kW}$$

Alternative property treatment since single phase and small ΔT

If we take constant heat capacity for the liquid from Table A.4

$$q_{out} = h_i - h_e \cong C_p\,(T_i - T_e) = 4.18\,(20 - 5) = 62.7 \text{ kJ/kg}$$

$$\dot{Q}_{out} = \dot{m}\, q_{out} = 2.5 \times 62.7 = \mathbf{156.75\ kW}$$



6.66

Saturated liquid nitrogen at 500 kPa enters a boiler at a rate of 0.005 kg/s and exits as saturated vapor. It then flows into a super heater also at 500 kPa where it exits at 500 kPa, 275 K. Find the rate of heat transfer in the boiler and the super heater.

Solution:

C.V.: boiler steady single inlet and exit flow, neglect KE, PE energies in flow

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

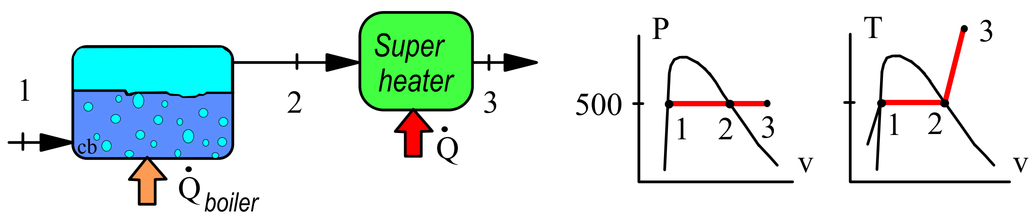


Table B.6.1: h_1 = -87.095 kJ/kg, h_2 = 86.15 kJ/kg,

Table B.6.2: h_3 = 284.06 kJ/kg

Energy Eq.6.13: $q_{boiler} = h_2 - h_1 = 86.15 - (- 87.095) = 173.25$ kJ/kg

$\dot{Q}_{boiler} = \dot{m}_1 q_{boiler} = 0.005 \times 173.25 = \mathbf{0.866\ kW}$

C.V. Superheater (same approximations as for boiler)

Energy Eq.6.13: $q_{sup\ heater} = h_3 - h_2 = 284.06 - 86.15 = 197.9$ kJ/kg

$\dot{Q}_{sup\ heater} = \dot{m}_2 q_{sup\ heater} = 0.005 \times 197.9 = \mathbf{0.99\ kW}$

6.67

In a steam generator, compressed liquid water at 10 MPa, 30°C, enters a 30-mm diameter tube at the rate of 3 L/s. Steam at 9 MPa, 400°C exits the tube. Find the rate of heat transfer to the water.

Solution:

C.V. Steam generator. Steady state single inlet and exit flow.

Constant diameter tube: $A_i = A_e = \frac{\pi}{4}(0.03)^2 = 0.0007068 \text{ m}^2$

Table B.1.4 $\dot{m} = \dot{V}_i/v_i = 0.003/0.0010003 = 3.0 \text{ kg/s}$

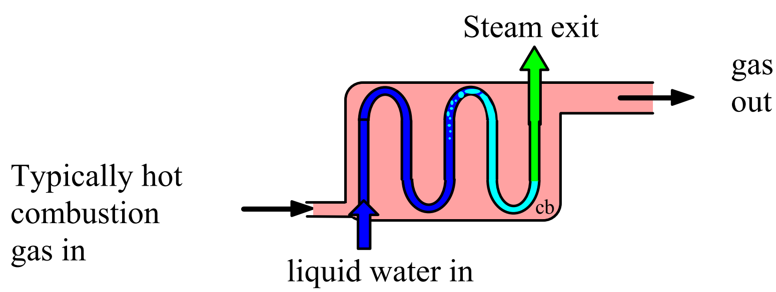
$\mathbf{V}_i = \dot{V}_i/A_i = 0.003/0.0007068 = 4.24 \text{ m/s}$

Exit state properties from Table B.1.3

$\mathbf{V}_e = \mathbf{V}_i \times v_e/v_i = 4.24 \times 0.02993/0.0010003 = 126.86 \text{ m/s}$

The energy equation Eq.6.12 is solved for the heat transfer as

$$\dot{Q} = \dot{m}\left[(h_e - h_i) + \left(\mathbf{V}_e^2 - \mathbf{V}_i^2\right)/2\right]$$
$$= 3.0\left[3117.8 - 134.86 + \frac{126.86^2 - 4.24^2}{2 \times 1000}\right] = \mathbf{8973\ kW}$$



6.68

The air conditioner in a house or a car has a cooler that brings atmospheric air from 30^{o}C to 10^{o}C both states at 101 kPa. If the flow rate is 0.5 kg/s find the rate of heat transfer.

Solution:

CV. Cooler. Steady state single flow with heat transfer.

Neglect changes in kinetic and potential energy and no work term.

Energy Eq.6.13: $q_{out} = h_i - h_e$

Use constant heat capacity from Table A.5 (T is around 300 K)

$$q_{out} = h_i - h_e = C_p\,(T_i - T_e)$$

$$= 1.004\,\frac{\text{kJ}}{\text{kg K}} \times (30 - 10)\text{ K} = 20.1\text{ kJ/kg}$$

$$\dot{Q}_{out} = \dot{m}\,q_{out} = 0.5 \times 20.1 = \mathbf{10\ kW}$$

6.69

A flow of liquid glycerine flows around an engine, cooling it as it absorbs energy. The glycerine enters the engine at 60°C and receives 9 kW of heat transfer. What is the required mass flow rate if the glycerine should come out at maximum 95° C?

Solution:

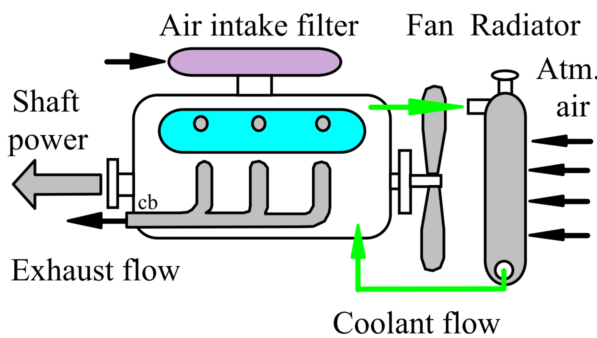
C.V. Liquid flow (glycerine is the coolant), steady flow. no work.

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

$$\dot{m} = \dot{Q}/(h_e - h_i) = \frac{\dot{Q}}{C_{gly}\,(T_e - T_i)}$$

From table A.4 $\quad C_{gly} = 2.42$ kJ/kg-K

$$\dot{m} = \frac{9}{2.42\,(95 - 60)} = \mathbf{0.106\ kg/s}$$



6.70

A cryogenic fluid as liquid nitrogen at 90 K, 400 kPa flows into a probe used in cryogenic surgery. In the return line the nitrogen is then at 160 K, 400 kPa. Find the specific heat transfer to the nitrogen. If the return line has a cross sectional area 100 times larger than the inlet line what is the ratio of the return velocity to the inlet velocity?

Solution:

C.V line with nitrogen. No kinetic or potential energy changes

Continuity Eq.: $\dot{m} = \text{constant} = \dot{m}_e = \dot{m}_i = A_e\mathbf{V}_e/v_e = A_i\mathbf{V}_i/v_i$

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

State i, Table B.6.1: $h_i = -95.58$ kJ/kg, $v_i = 0.001343$ m^3/kg

State e, Table B.6.2: $h_e = 162.96$ kJ/kg, $v_e = 0.11647$ m^3/kg

From the energy equation

$$q = h_e - h_i = 162.96 - (-95.58) = \mathbf{258.5\ kJ/kg}$$

From the continuity equation

$$\mathbf{V}_e/\mathbf{V}_i = A_i/A_e\ (v_e/v_i) = \frac{1}{100}\ \frac{0.11647}{0.001343} = \mathbf{0.867}$$

Pumps, pipe and channel flows

6.71

A small stream with 20^{o}C water runs out over a cliff creating a 100 m tall waterfall. Estimate the downstream temperature when you neglect the horizontal flow velocities upstream and downstream from the waterfall. How fast was the water dropping just before it splashed into the pool at the bottom of the waterfall?

Solution:

CV. Waterfall, steady state. Assume no $\dot{Q}$ nor $\dot{W}$

Energy Eq.6.13: $h + \frac{1}{2}V^2 + gZ = \text{const.}$

State 1: At the top zero velocity $Z_1 = 100$ m

State 2: At the bottom just before impact, $Z_2 = 0$

State 3: At the bottom after impact in the pool.

$$h_1 + 0 + gZ_1 = h_2 + \frac{1}{2}\mathbf{V}_2^2 + 0 = h_3 + 0 + 0$$

Properties: $h_1 \cong h_2$ same T, P

$$=> \quad \frac{1}{2}\mathbf{V}_2^2 = gZ_1$$

$$\mathbf{V}_2 = \sqrt{2gZ_1} = \sqrt{2 \times 9.806 \times 100} = \mathbf{44.3\ m/s}$$

Energy equation from state 1 to state 3

$$h_3 = h_1 + gZ_1$$

use $\Delta h = C_p\ \Delta T$ with value from Table A.4 (liquid water)

$$T_3 = T_1 + gZ_1 / C_p$$
$$= 20 + 9.806 \times 100 / 4180 = \mathbf{20.23\ °C}$$

6.72

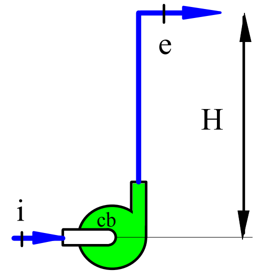
A small water pump is used in an irrigation system. The pump takes water in from a river at 10^{o}C, 100 kPa at a rate of 5 kg/s. The exit line enters a pipe that goes up to an elevation 20 m above the pump and river, where the water runs into an open channel. Assume the process is adiabatic and that the water stays at 10^{o}C. Find the required pump work.

Solution:

C.V. pump + pipe. Steady state , 1 inlet, 1 exit flow. Assume same velocity in and out, no heat transfer.

Continuity Eq.: $\dot{m}_{in} = \dot{m}_{ex} = \dot{m}$

Energy Eq.6.12:



$$\dot{m}(h_{in} + (1/2)\mathbf{V}_{in}^2 + gz_{in}) =$$

$$\dot{m}(h_{ex} + (1/2)\ \mathbf{V}_{ex}^2 + gz_{ex}) + \dot{W}$$

States: $h_{in} = h_{ex}$ same (T, P)

$$\dot{W} = \dot{m}\ g(z_{in} - z_{ex}) = 5 \times 9.807 \times (0 - 20)/1000 = \mathbf{-0.98\ kW}$$

I.E. 0.98 kW required input

6.73

A steam pipe for a 300-m tall building receives superheated steam at 200 kPa at ground level. At the top floor the pressure is 125 kPa and the heat loss in the pipe is 110 kJ/kg. What should the inlet temperature be so that no water will condense inside the pipe?

Solution:

C.V. Pipe from 0 to 300 m, no ΔKE, steady state, single inlet and exit flow. Neglect any changes in kinetic energy.

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

No condensation means: Table B.1.2, $h_e = h_g$ at 125 kPa = 2685.4 kJ/kg

$$h_i = h_e + gZ_e - q = 2685.4 + \frac{9.807 \times 300}{1000} - (-110) = 2810.1 \text{ kJ/kg}$$

At 200 kPa: T ~ **170°C** Table B.1.3

6.74

The main waterline into a tall building has a pressure of 600 kPa at 5 m below ground level. A pump brings the pressure up so the water can be delivered at 200 kPa at the top floor 150 m above ground level. Assume a flow rate of 10 kg/s liquid water at 10°C and neglect any difference in kinetic energy and internal energy u. Find the pump work.

Solution:

C.V. Pipe from inlet at -5 m up to exit at +150 m, 200 kPa.

Energy Eq.6.13: $h_i + \frac{1}{2}V_i^2 + gZ_i = h_e + \frac{1}{2}V_e^2 + gZ_e + w$

With the same u the difference in h's are the Pv terms

$$w = h_i - h_e + \frac{1}{2}(V_i^2 - V_e^2) + g(Z_i - Z_e)$$

$$= P_i v_i - P_e v_e + g(Z_i - Z_e)$$

$$= 600 \times 0.001 - 200 \times 0.001 + 9.806 \times (-5-150)/1000$$

$$= 0.4 - 1.52 = -1.12 \text{ kJ/kg}$$

$$\dot{W} = \dot{m}w = 10 \times (-1.12) = \mathbf{-11.2\ kW}$$

6.75

Consider a water pump that receives liquid water at 15^{o}C, 100 kPa and delivers it to a same diameter short pipe having a nozzle with exit diameter of 1 cm (0.01 m) to the atmosphere 100 kPa. Neglect the kinetic energy in the pipes and assume constant u for the water. Find the exit velocity and the mass flow rate if the pump draws a power of 1 kW.

Solution:

Continuity Eq.: $\dot{m}_i = \dot{m}_e = A\mathbf{V}/v$; $A = \frac{\pi}{4} D_e^2 = \frac{\pi}{4} \times 0.01^2 = 7.854 \times 10^{-5}$

Energy Eq.6.13: $h_i + \frac{1}{2}\mathbf{V}_i^2 + gZ_i = h_e + \frac{1}{2}\mathbf{V}_e^2 + gZ_e + w$

Properties: $h_i = u_i + P_i v_i = h_e = u_e + P_e v_e$; $P_i = P_e$; $v_i = v_e$

$$w = -\frac{1}{2}\mathbf{V}_e^2 \quad \Rightarrow \quad -\dot{W} = \dot{m}\,(\frac{1}{2}\mathbf{V}_e^2) = A \times \frac{1}{2}\mathbf{V}_e^3/v_e$$

$$\mathbf{V}_e = \left(\frac{-2\,\dot{W}\,v_e}{A}\right)^{1/3} = \left(\frac{2 \times 1000 \times 0.001001}{7.854\times10^{-5}}\right)^{1/3} = \mathbf{29.43\ m/s}$$

$$\dot{m} = A\mathbf{V}_e/v_e = 7.854\times 10^{-5} \times 29.43 / 0.001001 = \mathbf{2.31\ kg/s}$$

6.76

A cutting tool uses a nozzle that generates a high speed jet of liquid water. Assume an exit velocity of 1000 m/s of 20°C liquid water with a jet diameter of 2 mm (0.002 m). How much mass flow rate is this? What size (power) pump is needed to generate this from a steady supply of 20°C liquid water at 200 kPa?

Solution:

C.V. Nozzle. Steady state, single flow.

Continuity equation with a uniform velocity across A

$$\dot{m} = A\mathbf{V}/v = \frac{\pi}{4} D^2\ \mathbf{V} / v = \frac{\pi}{4} 0.002^2 \times 1000 / 0.001002 = \mathbf{3.135\ kg/s}$$

Assume $Z_i = Z_e = Ø$, $u_e = u_i$ and $\mathbf{V}_i = 0$ $P_e = 100$ kPa (atmospheric)

Energy Eq.6.13: $h_i + Ø + Ø = h_e + \frac{1}{2}\mathbf{V}_e^2 + Ø + w$

$$w = h_i - h_e - \frac{1}{2}\mathbf{V}_e^2 = u_i - u_e + P_i v_i - P_e v_e - \frac{1}{2}\mathbf{V}_e^2$$

$$= (P_i - P_e) v_i - \frac{1}{2}\mathbf{V}_e^2$$

$$= 0.001002 \times (200 - 100) - 0.5 \times (1000^2 / 1000)$$

$$= 0.1002 - 500 \cong -500 \text{ kJ/kg}$$

$$\dot{W} = \dot{m}w = 3.135\ (-500) = \mathbf{-1567.5\ kW}$$

6.77

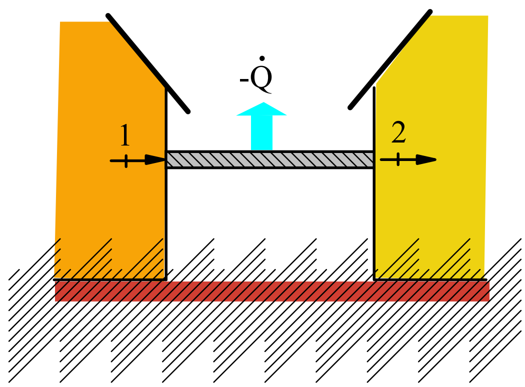
A pipe flows water at 15°C from one building to another. In the winter time the pipe loses an estimated 500 W of heat transfer. What is the minimum required mass flow rate that will ensure that the water does not freeze (i.e. reach 0°C)?

Solution:

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

Assume saturated liquid at given T from table B.1.1

$$\dot{m} = \frac{\dot{Q}}{h_e - h_i} = \frac{-500 \times 10^{-3}}{0 - 62.98} = \frac{0.5}{62.98} = \mathbf{0.007\ 94\ kg/s}$$



Multiple flow single device processes

Turbines, Compressors, Expanders

6.78

A steam turbine receives water at 15 MPa, 600°C at a rate of 100 kg/s, shown in Fig. P6.78. In the middle section 20 kg/s is withdrawn at 2 MPa, 350°C, and the rest exits the turbine at 75 kPa, and 95% quality. Assuming no heat transfer and no changes in kinetic energy, find the total turbine power output.

Solution:

C.V. Turbine Steady state, 1 inlet and 2 exit flows.

Continuity Eq.6.9: $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$; => $\dot{m}_3 = \dot{m}_1 - \dot{m}_2 = 80$ kg/s

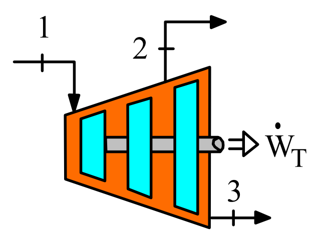
Energy Eq.6.10: $\dot{m}_1 h_1 = \dot{W}_T + \dot{m}_2 h_2 + \dot{m}_3 h_3$

Table B.1.3 $h_1 = 3582.3$ kJ/kg,

$h_2 = 3137$ kJ/kg

Table B.1.2 : $h_3 = h_f + x_3 h_{fg} = 384.3 + 0.95 \times 2278.6$

$= 2549.1$ kJ/kg



From the energy equation, Eq.6.10

$$\Rightarrow \quad \dot{W}_T = \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3 = \mathbf{91.565\ MW}$$

6.79

A steam turbine receives steam from two boilers. One flow is 5 kg/s at 3 MPa, 700°C and the other flow is 15 kg/s at 800 kPa, 500°C. The exit state is 10 kPa, with a quality of 96%. Find the total power out of the adiabatic turbine.

Solution:

C.V. whole turbine steady, 2 inlets, 1 exit, no heat transfer $\dot{Q} = 0$

Continuity Eq.6.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3 = 5 + 15 = 20$ kg/s

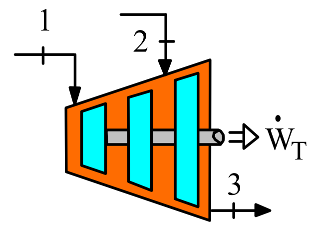
Energy Eq.6.10: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{W}_T$

Table B.1.3: $h_1 = 3911.7$ kJ/kg,

$h_2 = 3480.6$ kJ/kg

Table B.1.2: $h_3 = 191.8 + 0.96 \times 2392.8$

$= 2488.9$ kJ/kg



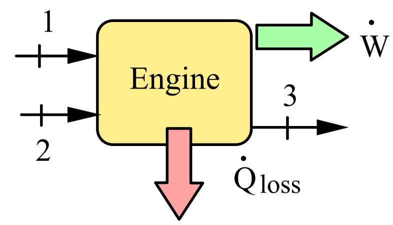
$\dot{W}_T = 5 \times 3911.7 + 15 \times 3480.6 - 20 \times 2488.9 = 21990$ kW = **22 MW**

6.80

Two steady flows of air enters a control volume, shown in Fig. P6.80. One is 0.025 kg/s flow at 350 kPa, 150°C, state 1, and the other enters at 450 kPa, 15°C, both flows with low velocity. A single flow of air exits at 100 kPa, –40°C, state 3. The control volume rejects 1 kW heat to the surroundings and produces 4 kW of power. Neglect kinetic energies and determine the mass flow rate at state 2.

Solution:

C.V. Steady device with two inlet and one exit flows, we neglect kinetic energies. Notice here the Q is rejected so it goes out.



Continuity Eq.6.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3 = 0.025 + \dot{m}_2$

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

Substitute the work and heat transfer into the energy equation and use constant heat capacity

$$0.025 \times 1.004 \times 423.2 + \dot{m}_2 \times 1.004 \times 288.2$$

$$= (0.025 + \dot{m}_2)\ 1.004 \times 233.2\ \ + 4.0 + 1.0$$

Now solve for $\dot{m}_2$.

$$\dot{m}_2 = \frac{4.0 + 1.0 + 0.025 \times 1.004 \times (233.2 - 423.2)}{1.004\ (288.2 - 233.2)}$$

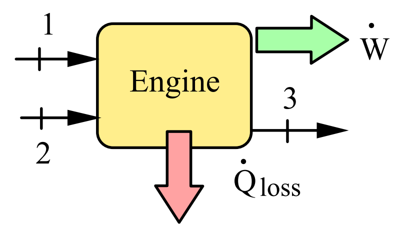
Solving, $\dot{m}_2$ = **0.0042 kg/s**

6.81

A large expansion engine has two low velocity flows of water entering. High pressure steam enters at point 1 with 2.0 kg/s at 2 MPa, 500°C and 0.5 kg/s cooling water at 120 kPa, 30°C enters at point 2. A single flow exits at point 3 with 150 kPa, 80% quality, through a 0.15 m diameter exhaust pipe. There is a heat loss of 300 kW. Find the exhaust velocity and the power output of the engine.

Solution:

C.V. : Engine (Steady state)



Constant rates of flow, $\dot{Q}_{loss}$ and $\dot{W}$

State 1: Table B.1.3: $h_1 = 3467.6$ kJ/kg

State 2: Table B.1.1: $h_2 = 125.77$ kJ/kg

$h_3 = 467.1 + 0.8 \times 2226.5 = 2248.3$ kJ/kg

$v_3 = 0.00105 + 0.8 \times 1.15825 = 0.92765$ m^3/kg

Continuity Eq.6.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3 = 2 + 0.5 = 2.5$ kg/s $= (AV/v) = (\pi/4)D^2V/v$

Energy Eq.6.10: $\dot{m}_1h_1 + \dot{m}_2h_2 = \dot{m}_3(h_3 + 0.5\ V^2) + \dot{Q}_{loss} + \dot{W}$

$\mathbf{V} = \dot{m}_3v_3 / [\frac{\pi}{4} D^2] = 2.5 \times 0.92765 / (0.7854 \times 0.15^2) =$ **131.2 m/s**

$0.5\ \mathbf{V}^2 = 0.5 \times 131.2^2 / 1000 = 8.6$ kJ/kg (remember units factor 1000)

$\dot{W} = 2 \times 3467.6 + 0.5 \times 125.77 - 2.5\ (2248.3 + 8.6) - 300 =$ **1056 kW**

6.82

Cogeneration is often used where a steam supply is needed for industrial process energy. Assume a supply of 5 kg/s steam at 0.5 MPa is needed. Rather than generating this from a pump and boiler, the setup in Fig. P6.82 is used so the supply is extracted from the high-pressure turbine. Find the power the turbine now cogenerates in this process.

Solution:

C.V. Turbine, steady state, 1 inlet and 2 exit flows, assume adiabatic, $\dot{Q}_{CV} = 0$

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

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

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

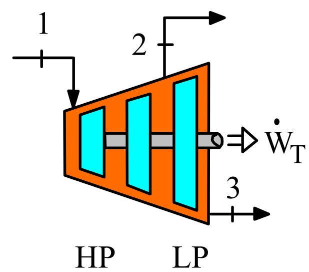
Process steam 2: 5 kg/s, 0.5 MPa, 155°C,

Exit state 3: 20 kPa, x = 0.9

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

Table B.1.2: $h_3 = 251.4 + 0.9 \times 2358.3$

$= 2373.9$ kJ/kg



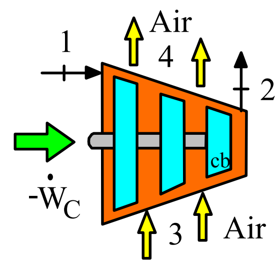
$\dot{W}_T = 20 \times 3373.7 - 5 \times 2755.9 - 15 \times 2373.9 =$ **18.084 MW**

6.83

A compressor receives 0.1 kg/s R-134a at 150 kPa, -10^{o}C and delivers it at 1000 kPa, 40^{o}C. The power input is measured to be 3 kW. The compressor has heat transfer to air at 100 kPa coming in at 20^{o}C and leaving at 25^{o}C. How much is the mass flow rate of air?

Solution:

C.V. Compressor, steady state, single inlet and exit flow. For this device we also have an air flow outside the compressor housing no changes in kenetic or potential energy.



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

Energy Eq. 6.12: $\dot{m}_1 h_1 + \dot{W}_{in} + \dot{m}_{air} h_3 = \dot{m}_2 h_2 + \dot{m}_{air} h_4$

Ideal gas for air and constant heat capacity: $h_4 - h_3 \sim C_{p\ air} (T_4 - T_3)$

$$\dot{m}_{air} = [\dot{m}_1 (h_1 - h_2) + \dot{W}_{in}] / C_{p\ air} (T_4 - T_3)$$

$$= \frac{0.1\ (393.84 - 420.25) + 3}{1.004\ (25\text{-}20)} = \frac{0.359}{5}$$

$$\mathbf{= 0.0715\ kg/s}$$

Heat Exchangers

6.84

A condenser (heat exchanger) brings 1 kg/s water flow at 10 kPa from 300°C to saturated liquid at 10 kPa, as shown in Fig. P6.84. The cooling is done by lake water at 20°C that returns to the lake at 30°C. For an insulated condenser, find the flow rate of cooling water.

Solution:

C.V. Heat exchanger

Energy Eq.6.10: $\dot{m}_{cool}h_{20} + \dot{m}_{H_2O}h_{300} = \dot{m}_{cool}h_{30} + \dot{m}_{H_2O}h_{f,\ 10\ kPa}$

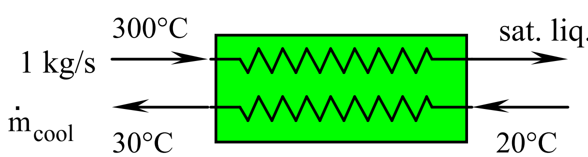


Table B.1.1: h_{20} = 83.96 kJ/kg , h_{30} = 125.79 kJ/kg

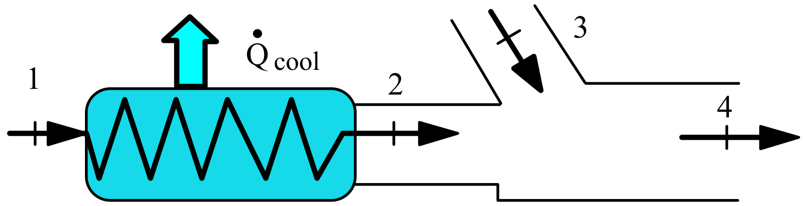
Table B.1.3: $h_{300,\ 10kPa}$ = 3076.5 kJ/kg, B.1.2: $h_{f,\ 10\ kPa}$ = 191.83 kJ/kg

$$\dot{m}_{cool} = \dot{m}_{H_2O}\frac{h_{300} - h_{f,\ 10kPa}}{h_{30} - h_{20}} = 1 \times \frac{3076.5 - 191.83}{125.79 - 83.96} = \mathbf{69\ kg/s}$$

6.85

A cooler in an air conditioner brings 0.5 kg/s air at 35^{o}C to 5^{o}C, both at 101 kPa and it then mix the output with a flow of 0.25 kg/s air at 20^{o}C, 101 kPa sending the combined flow into a duct. Find the total heat transfer in the cooler and the temperature in the duct flow.

Solution:



Cooler section Mixing section

C.V. Cooler section (no $\dot{W}$)

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

$\dot{Q}_{cool} = \dot{m}(h_1 - h_2) = \dot{m}\, C_p\, (T_1 - T_2) = 0.5 \times 1.004 \times (35\text{-}5) = 15.06 \text{ kW}$

C.V. mixing section (no $\dot{W}$, $\dot{Q}$)

Continuity Eq.: $\dot{m}_2 + \dot{m}_3 = \dot{m}_4$

Energy Eq.6.10: $\dot{m}_2h_2 + \dot{m}_3h_3 = \dot{m}_4h_4$

$\dot{m}_4 = \dot{m}_2 + \dot{m}_3 = 0.5 + 0.25 = 0.75 \text{ kg/s}$

$\dot{m}_4h_4 = (\dot{m}_2 + \dot{m}_3)h_4 = \dot{m}_2h_2 + \dot{m}_3h_3$

$\dot{m}_2\,(h_4 - h_2) + \dot{m}_3\,(h_4 - h_3) = \emptyset$

$\dot{m}_2\, C_p\, (T_4 - T_2) + \dot{m}_3\, C_p\, (T_4 - T_3) = \emptyset$

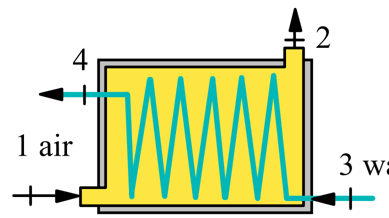
$T_4 = (\dot{m}_2 / \dot{m}_4)\, T_2 + (\dot{m}_3 / \dot{m}_4)\, T_3 = 5(0.5/0.75) + 20(0.25/0.75) = \mathbf{10°C}$

6.86

A heat exchanger, shown in Fig. P6.86, is used to cool an air flow from 800 K to 360 K, both states at 1 MPa. The coolant is a water flow at 15°C, 0.1 MPa. If the water leaves as saturated vapor, find the ratio of the flow rates $\dot{m}_{H_2O}/\dot{m}_{air}$

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.



Continuity Eqs.: Each line has a constant flow rate through it.

Energy Eq.6.10: $\dot{m}_{air}h_1 + \dot{m}_{H_2O}h_3 = \dot{m}_{air}h_2 + \dot{m}_{H_2O}h_4$

Process: Each line has a constant pressure.

Air states, Table A.7.1: $h_1 = 822.20$ kJ/kg, $h_2 = 360.86$ kJ/kg

Water states, Table B.1.1: $h_3 = 62.98$ kJ/kg (at 15°C),

Table B.1.2: $h_4 = 2675.5$ kJ/kg (at 100 kPa)

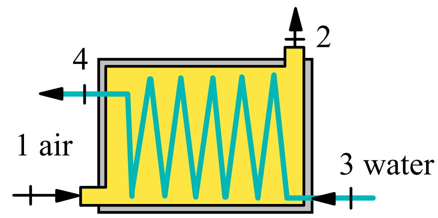
$$\dot{m}_{H_2O}/\dot{m}_{air} = \frac{h_1 - h_2}{h_4 - h_3} = \frac{822.20 - 360.86}{2675.5 - 62.99} = \mathbf{0.1766}$$

6.87

A superheater brings 2.5 kg/s saturated water vapor at 2 MPa to 450^{o}C. The energy is provided by hot air at 1200 K flowing outside the steam tube in the opposite direction as the water, which is a counter flowing heat exchanger. Find the smallest possible mass flow rate of the air so the air exit temperature is 20^{o}C larger than the incoming water temperature (so it can heat it).

Solution:

C.V. Superheater. Steady state with no external $\dot{Q}$ or any $\dot{W}$ the two flows exchanges energy inside the box. Neglect kinetic and potential energies at all states.



Energy Eq.6.10: $\dot{m}_{H_2O}\, h_3 + \dot{m}_{air}\, h_1 = \dot{m}_{H_2O}\, h_4 + \dot{m}_{air}\, h_2$

Process: Constant pressure in each line.

State 1: Table B.1.2 $\quad T_3 = 212.42°C, \;\; h_3 = 2799.51$ kJ/kg

State 2: Table B.1.3 $\quad h_4 = 3357.48$ kJ/kg

State 3: Table A.7 $\quad h_1 = 1277.81$ kJ/kg

State 4: $\quad T_2 = T_3 + 20 = 232.42°C = 505.57$ K

A.7 : $\quad h_2 = 503.36 + \dfrac{5.57}{20}\,(523.98 – 503.36) = 509.1$ kJ/kg

From the energy equation we get

$\dot{m}_{air} / \dot{m}_{H_2O} = (h_4 - h_3)/(h_1 - h_2)$

$= 2.5\,(3357.48 – 2799.51) / (1277.81 – 509.1) =$ **1.815 kg/s**

6.88

An automotive radiator has glycerine at 95^{o}C enter and return at 55^{o}C as shown in Fig. P6.88. Air flows in at 20^{o}C and leaves at 25^{o}C. If the radiator should transfer 25 kW what is the mass flow rate of the glycerine and what is the volume flow rate of air in at 100 kPa?

Solution:

If we take a control volume around the whole radiator then there is no external heat transfer - it is all between the glycerin and the air. So we take a control volume around each flow separately.

Glycerine: $\dot{m}h_i + (-\dot{Q}) = \dot{m}h_e$

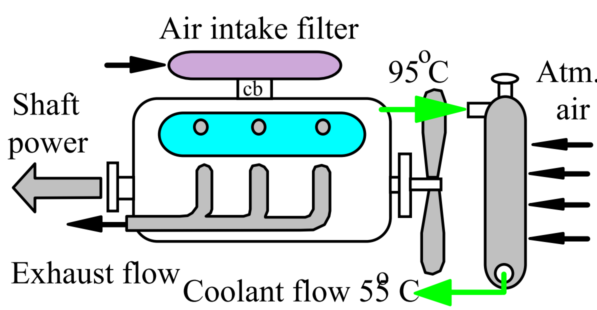
Table A.4: $\dot{m}_{gly} = \frac{-\dot{Q}}{h_e - h_i} = \frac{-\dot{Q}}{C_{gly}(T_e - T_i)} = \frac{-25}{2.42(55 - 95)} = \mathbf{0.258\ kg/s}$

Air $\dot{m}h_i + \dot{Q} = \dot{m}h_e$

Table A.5: $\dot{m}_{air} = \frac{\dot{Q}}{h_e - h_i} = \frac{\dot{Q}}{C_{air}(T_e - T_i)} = \frac{25}{1.004(25 - 20)} = 4.98$ kg/s

$$\dot{V} = \dot{m}v_i\ ; \quad v_i = \frac{RT_i}{P_i} = \frac{0.287 \times 293}{100} = 0.8409\ m^3/kg$$

$$\dot{V}_{air} = \dot{m}v_i = 4.98 \times 0.8409 = \mathbf{4.19\ m^3/s}$$



6.89

A two fluid heat exchanger has 2 kg/s liquid ammonia at 20°C, 1003 kPa entering state 3 and exiting at state 4. It is heated by a flow of 1 kg/s nitrogen at 1500 K, state 1, leaving at 600 K, state 2 similar to Fig. P6.86. Find the total rate of heat transfer inside the heat exchanger. Sketch the temperature versus distance for the ammonia and find state 4 (T, v) of the ammonia.

Solution:

CV: Nitrogen flow line, steady rates of flow, $\dot{Q}$ out and $\dot{W} = 0$

Continiuty: $\dot{m}_1 = \dot{m}_2 = 1$ kg/s ; Energy Eq: $\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{Q}_{out}$

Tbl. A.8: $h_1 = 1680.7$ kJ/kg; $h_2 = 627.24$ kJ/kg

$$\dot{Q}_{out} = \dot{m}_1(h_1 - h_2) = 1\ (1680.7 – 627.24) = \mathbf{1053.5\ kW}$$

If Tbl A.5 is used: Cp = 1.042 kJ/kg K

$$\dot{Q}_{out} = \dot{m}_1\ Cp\ (T_1 - T_2) = 1\times1.042\ (1500 - 600) = \mathbf{937.8\ kW}$$

CV The whole heat exchanger: No external $\dot{Q}$, constant pressure in each line.

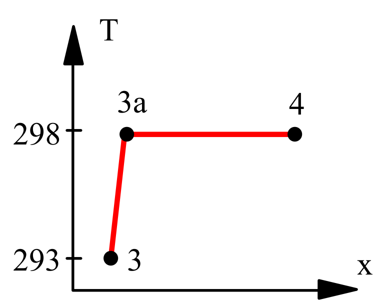
$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_1 h_2 + \dot{m}_3 h_4 \quad => \quad h_4 = h_3 + \dot{m}_1(h_1 - h_2)/\dot{m}_3$$

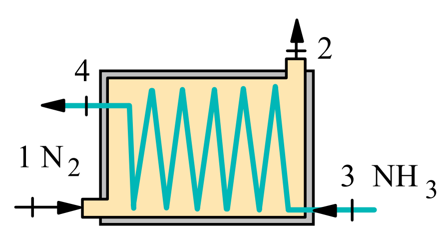
$$h_4 = 274.3 + 1053.5\ /2 = 801\ \text{kJ/kg} \ < \ h_g \quad => \quad \text{2-phase}$$

$$x_4 = (h_4 - h_f)/\ h_{fg} = (801 - 298.25)\ /\ 1165.2 = 0.43147$$

$$v_4 = v_f + x_4\ v_{fg} = 0.001658 + 0.43147\times0.12647 = 0.05623\ \text{m}^3\text{/kg}$$

$$T_4 = T_{3a} = 25^{o}\text{C} \quad \text{This is the boiling temperature for 1003 kPa.}$$





6.90

A copper wire has been heat treated to 1000 K and is now pulled into a cooling chamber that has 1.5 kg/s air coming in at 20^{o}C; the air leaves the other end at 60^{o}C. If the wire moves 0.25 kg/s copper, how hot is the copper as it comes out?

Solution:
C.V. Total chamber, no external heat transfer

Energy eq.: $\dot{m}_{cu}\, h_{\,icu} + \dot{m}_{air}\, h_{i\ air} = \dot{m}_{cu}\, h_{e\ cu} + \dot{m}_{air}\, h_{e\ air}$

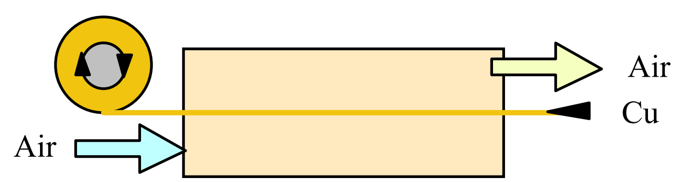
$$\dot{m}_{cu}\,(\, h_e - h_i\,)_{cu} = \dot{m}_{air}(\, h_i - h_e\,)_{air}$$

$$\dot{m}_{cu}\, C_{cu}\,(\, T_e - T_i\,)_{cu} = \dot{m}_{air}\, C_{p\ air}(\, T_e - T_i\,)_{air}$$

Heat capacities from A.3 for copper and A.5 for air

$$(\, T_e - T_i\,)_{cu} = \frac{\dot{m}_{air} C_{p\ air}}{\dot{m}_{cu} C_{cu}}\,(\, T_e - T_i\,)_{air} = \frac{1.5 \times 1.004}{0.25 \times 0.42}\,(20 - 60) = -\,573.7 \text{ K}$$

$$T_e = T_i - 573.7 = 1000 - 573.7 = \mathbf{426.3\ K}$$



Mixing processes

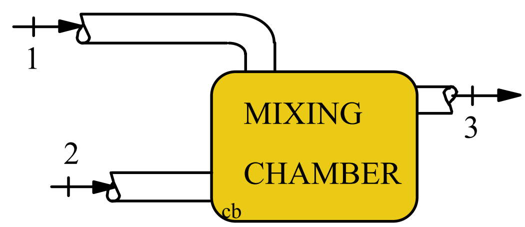
6.91

An open feedwater heater in a powerplant heats 4 kg/s water at 45$^{\mathrm{o}}$C, 100 kPa by mixing it with steam from the turbine at 100 kPa, 250$^{\mathrm{o}}$C. Assume the exit flow is saturated liquid at the given pressure and find the mass flow rate from the turbine.

Solution:

C.V. Feedwater heater.

No external $\dot{Q}$ or $\dot{W}$

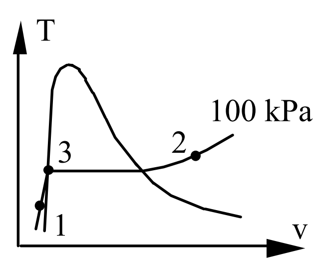


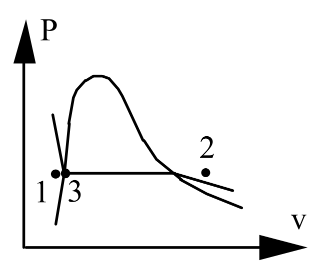
Continuity Eq.6.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

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

State 1:	Table B.1.1	$h = h_f = 188.42$ kJ/kg at 45$^{\mathrm{o}}$C
State 2:	Table B.1.3	$h_2 = 2974.33$ kJ/kg
State 3:	Table B.1.2	$h_3 = h_f = 417.44$ kJ/kg at 100 kPa

$$\dot{m}_2 = \dot{m}_1 \times \frac{h_1 - h_3}{h_3 - h_2} = 4 \times \frac{188.42 - 417.44}{417.44 - 2974.33} = \mathbf{0.358\ kg/s}$$

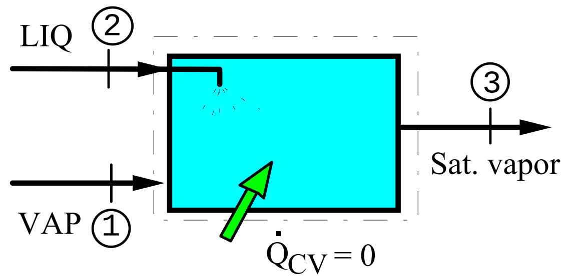




6.92

A desuperheater mixes superheated water vapor with liquid water in a ratio that produces saturated water vapor as output without any external heat transfer. A flow of 0.5 kg/s superheated vapor at 5 MPa, 400°C and a flow of liquid water at 5 MPa, 40°C enter a desuperheater. If saturated water vapor at 4.5 MPa is produced, determine the flow rate of the liquid water.

Solution:



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

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

Table B.1

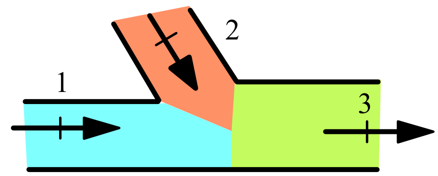
$$0.5 \times 3195.7 + \dot{m}_2 \times 171.97 = (0.5 + \dot{m}_2)\ 2797.9$$

$$=> \quad \dot{m}_2 = \mathbf{0.0757\ kg/s}$$

6.93

Two air flows are combined to a single flow. Flow one is 1 m^3/s at 20°C and the other is 2 m^3/s at 200°C both at 100 kPa. They mix without any heat transfer to produce an exit flow at 100 kPa. Neglect kinetic energies and find the exit temperature and volume flow rate.

Solution:



Mixing section

Cont. $\quad \dot{m}_i = \dot{m}_e = \dot{m}$

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

$$= (\dot{m}_1 + \dot{m}_2) h_3$$

$$\dot{m}_1 (h_3 - h_1) + \dot{m}_2 (h_3 - h_2) = 0$$

$$\dot{m}_1 C_p (T_3 - T_1) + \dot{m}_2 C_p (T_3 - T_2) = 0$$

$$T_3 = (\dot{m}_i/\dot{m}_3)/T_1 + (\dot{m}_2/\dot{m}_3) T_2$$

We need to find the mass flow rates

$$v_1 = RT_1/P_1 = (0.287 \times 293)/100 = 0.8409 \text{ m}^3/\text{kg}$$

$$v_2 = RT_2/P_2 = (0.287 \times 473)/100 = 1.3575 \text{ m}^3/\text{kg}$$

$$\dot{m}_1 = \frac{\dot{V}_1}{v_1} = \frac{1}{0.8409} = 1.1892 \frac{\text{kg}}{\text{s}}, \quad \dot{m}_2 = \frac{\dot{V}_2}{v_2} = \frac{2}{1.3575} = 1.4733 \frac{\text{kg}}{\text{s}}$$

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 = 2.6625 \text{ kg/s}$$

$$T_3 = \frac{1.1892}{2.6625} \times 20 + \frac{1.4733}{2.6625} \times 200 = \mathbf{119.6^o\ C}$$

$$v_3 = \frac{RT_3}{P_3} = \frac{0.287\ (119.6 + 273)}{100} = 1.1268 \text{ m}^3/\text{kg}$$

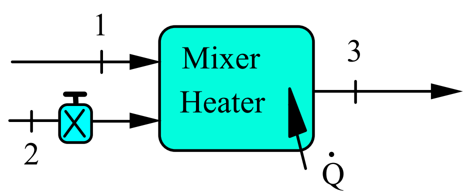
$$\dot{V}_3 = \dot{m}_3 v_3 = 2.6625 \times 1.1268 = \mathbf{3.0\ m^3/s}$$

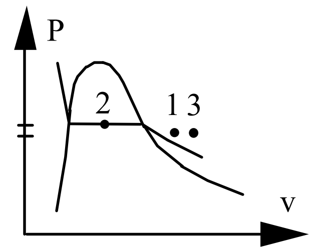
6.94

A mixing chamber with heat transfer receives 2 kg/s of R-22 at 1 MPa, 40°C in one line and 1 kg/s of R-22 at 30°C, quality 50% in a line with a valve. The outgoing flow is at 1 MPa, 60°C. Find the rate of heat transfer to the mixing chamber.

Solution:

C.V. Mixing chamber. Steady with 2 flows in and 1 out, heat transfer in.





Continuity Eq.6.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$; => $\dot{m}_3 = 2 + 1 = 3$ kg/s

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

Properties: Table B.4.2: $h_1 = 271.04$ kJ/kg, $h_3 = 286.97$ kJ/kg

Table B.4.1: $h_2 = 81.25 + 0.5 \times 177.87 = 170.18$ kJ/kg

Energy equation then gives the heat transfer as

$$\dot{Q} = 3 \times 286.973 - 2 \times 271.04 - 1 \times 170.18 = \mathbf{148.66\ kW}$$

6.95

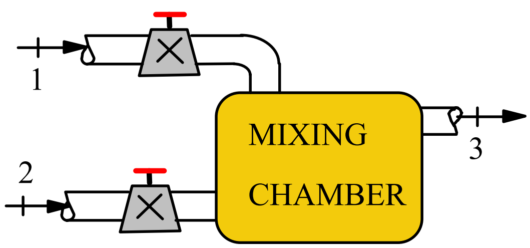
Two flows are mixed to form a single flow. Flow at state 1 is 1.5 kg/s water at 400 kPa, 200^{o}C and flow at state 2 is 500 kPa, 100^{o}C. Which mass flow rate at state 2 will produce an exit T_3 = 150^{o}C if the exit pressure is kept at 300 kPa?

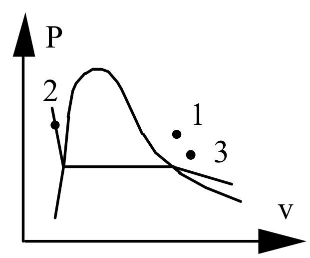
Solution:

C.V. Mixing chamber and valves. Steady state no heat transfer or work terms.

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

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





Properties Table B.1.3: h_1 = 2860.51 kJ/kg; h_3 = 2760.95 kJ/kg

Table B.1.4: h_2 = 419.32 kJ/kg

$$\dot{m}_2 = \dot{m}_1 \times \frac{h_1 - h_3}{h_3 - h_2} = 1.5 \times \frac{2860.51 - 2760.95}{2760.95 - 419.32} = \mathbf{0.0638\ kg/s}$$

6.96

An insulated mixing chamber receives 2 kg/s R-134a at 1 MPa, 100°C in a line with low velocity. Another line with R-134a as saturated liquid 60°C flows through a valve to the mixing chamber at 1 MPa after the valve. The exit flow is saturated vapor at 1 MPa flowing at 20 m/s. Find the flow rate for the second line.

Solution:

C.V. Mixing chamber. Steady state, 2 inlets and 1 exit flow.

Insulated $q = 0$, No shaft or boundary motion $w = 0$.

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

Energy Eq.6.10: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 (h_3 + \frac{1}{2}\mathbf{V}_3^2)$

$$\dot{m}_2 (h_2 - h_3 - \tfrac{1}{2}\mathbf{V}_3^2) = \dot{m}_1 (h_3 + \tfrac{1}{2}\mathbf{V}_3^2 - h_1)$$

1: Table B.5.2: 1 MPa, 100°C, $h_1 = 483.36$ kJ/kg

2: Table B.5.1: $x = \emptyset$, 60°C, $h_2 = 287.79$ kJ/kg

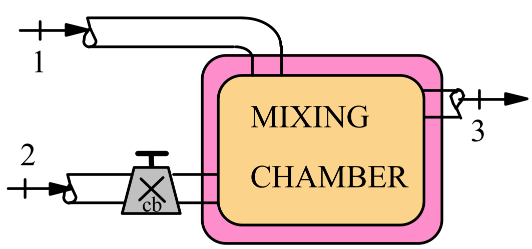
3: Table B.5.1: $x = 1$, 1 MPa, 20 m/s, $h_3 = 419.54$ kJ/kg

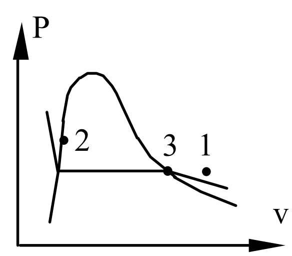
Now solve the energy equation for $\dot{m}_2$

$$\dot{m}_2 = 2 \times [419.54 + \tfrac{1}{2}\,20^2 \times \frac{1}{1000} - 483.36] \,/\, [287.79 - 419.54 - \tfrac{1}{2}\,\frac{20^2}{1000}]$$

$$= 2 \times (-63.82 + 0.2) / (-131.75 - 0.2) = \mathbf{0.964\ kg/s}$$

Notice how kinetic energy was insignificant.





6.97

To keep a jet engine cool some intake air bypasses the combustion chamber. Assume 2 kg/s hot air at 2000 K, 500 kPa is mixed with 1.5 kg/s air 500 K, 500 kPa without any external heat transfer. Find the exit temperature by using constant heat capacity from Table A.5.

Solution:

C.V. Mixing Section

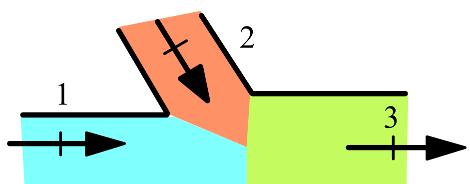
Continuity Eq.6.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \quad \Rightarrow \quad \dot{m}_3 = 2 + 1.5 = 3.5$ kg/s

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

$$h_3 = (\dot{m}_1 h_1 + \dot{m}_2 h_2) / \dot{m}_3 \;;$$

For a constant specific heat divide the equation for h_3 with C_p to get

$$T_3 = \frac{\dot{m}_1}{\dot{m}_3} T_1 + \frac{\dot{m}_2}{\dot{m}_3} T_2 = \frac{2}{3.5}\,2000 + \frac{1.5}{3.5}\,500 = \mathbf{1357\ K}$$



Mixing section

6.98

To keep a jet engine cool some intake air bypasses the combustion chamber. Assume 2 kg/s hot air at 2000 K, 500 kPa is mixed with 1.5 kg/s air 500 K, 500 kPa without any external heat transfer. Find the exit temperature by using values from Table A.7.

Solution:

C.V. Mixing Section

Continuity Eq.6.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3 \quad => \quad \dot{m}_3 = 2 + 1.5 = 3.5 \text{ kg/s}$

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

$$h_3 = (\dot{m}_1 h_1 + \dot{m}_2 h_2) / \dot{m}_3 \text{ ;}$$

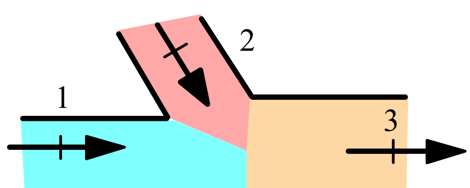
Using A.7 we look up the h at states 1 and 2 to calculate h_3

$$h_3 = \frac{\dot{m}_1}{\dot{m}_3} h_1 + \frac{\dot{m}_2}{\dot{m}_3} h_2 = \frac{2}{3.5} 2251.58 + \frac{1.5}{3.5} 503.36 = 1502 \text{ kJ/kg}$$

Now we can backinterpolate to find at what temperature do we have that h

$$T_3 = 1350 + 50 \frac{1502 - 1455.43}{1515.27 - 1455.43} = \mathbf{1389\ K}$$

This procedure is the most accurate.



Mixing section

Multiple Devices, Cycle Processes

6.99

The following data are for a simple steam power plant as shown in Fig. P6.99.

State	1	2	3	4	5	6	7
P MPa	6.2	6.1	5.9	5.7	5.5	0.01	0.009
T °C		45	175	500	490		40
h kJ/kg	-	194	744	3426	3404	-	168

State 6 has $x_6 = 0.92$, and velocity of 200 m/s. The rate of steam flow is 25 kg/s, with 300 kW power input to the pump. Piping diameters are 200 mm from steam generator to the turbine and 75 mm from the condenser to the steam generator. Determine the velocity at state 5 and the power output of the turbine.

Solution:

Turbine $A_5 = (\pi/4)(0.2)^2 = 0.031\ 42\ \text{m}^2$

$$\mathbf{V}_5 = \dot{m}v_5/A_5 = 25 \times 0.061\ 63 / 0.031\ 42 = \mathbf{49\ m/s}$$

$$h_6 = 191.83 + 0.92 \times 2392.8 = 2393.2\ \text{kJ/kg}$$

$$w_T = h_5 - h_6 + \frac{1}{2}(\mathbf{V}_5^2 - \mathbf{V}_6^2)$$

$$= 3404 - 2393.2 + (49^2 - 200^2)/(2 \times 1000) = 992\ \text{kJ/kg}$$

$$\dot{W}_T = \dot{m}w_T = 25 \times 992 = \mathbf{24\ 800\ kW}$$

Remark: Notice the kinetic energy change is small relative to enthalpy change.

6.100

For the same steam power plant as shown in Fig. P6.99 and Problem 6.99, assume the cooling water comes from a lake at 15°C and is returned at 25°C. Determine the rate of heat transfer in the condenser and the mass flow rate of cooling water from the lake.

Solution:

Condenser $A_7 = (\pi/4)(0.075)^2 = 0.004\,418\ \text{m}^2$, $v_7 = 0.001\,008\ \text{m}^3/\text{kg}$

$$\mathbf{V}_7 = \dot{m}v_7/A_7 = 25 \times 0.001\,008 / 0.004\,418 = 5.7\ \text{m/s}$$

$$h_6 = 191.83 + 0.92 \times 2392.8 = 2393.2\ \text{kJ/kg}$$

$$q_{COND} = h_7 - h_6 + \frac{1}{2}(\mathbf{V}_7^2 - \mathbf{V}_6^2)$$

$$= 168 - 2393.2 + (5.7^2 - 200^2)/(2\times1000) = -2245.2\ \text{kJ/kg}$$

$$\dot{Q}_{COND} = 25 \times (-2245.2) = \mathbf{-56\,130\ kW}$$

This rate of heat transfer is carried away by the cooling water so

$$-\dot{Q}_{COND} = \dot{m}_{H_2O}(h_{out} - h_{in})_{H_2O} = 56\,130\ \text{kW}$$

$$\Rightarrow \qquad \dot{m}_{H_2O} = \frac{56\,130}{104.9 - 63.0} = \mathbf{1339.6\ kg/s}$$

6.101

For the same steam power plant as shown in Fig. P6.99 and Problem 6.99, determine the rate of heat transfer in the economizer, which is a low temperature heat exchanger. Find also the rate of heat transfer needed in the steam generator.

Solution:

Economizer $A_7 = \pi D_7^2/4 = 0.004\ 418\ m^2$, $v_7 = 0.001\ 008\ m^3/kg$

$\mathbf{V}_2 = \mathbf{V}_7 = \dot{m}v_7/A_7 = 25 \times 0.001\ 008/0.004\ 418 = 5.7$ m/s,

$\mathbf{V}_3 = (v_3/v_2)\mathbf{V}_2 = (0.001\ 118 / 0.001\ 008)\ 5.7 = 6.3$ m/s $\approx \mathbf{V}_2$

so kinetic energy change unimportant

$q_{ECON} = h_3 - h_2 = 744 - 194 = 550.0$ kJ/kg

$\dot{Q}_{ECON} = \dot{m}q_{ECON} = 25\ (550.0) =$ **13 750 kW**

Generator $A_4 = \pi D_4^2/4 = 0.031\ 42\ m^2$, $v_4 = 0.060\ 23\ m^3/kg$

$\mathbf{V}_4 = \dot{m}v_4/A_4 = 25 \times 0.060\ 23/0.031\ 42 = 47.9$ m/s

$q_{GEN} = 3426 - 744 + (47.9^2 - 6.3^2)/(2{\times}1000) = 2683$ kJ/kg

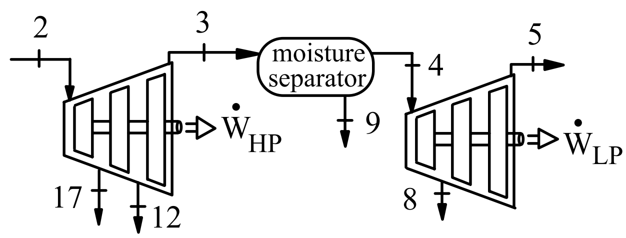
$\dot{Q}_{GEN} = \dot{m}q_{GEN} = 25 \times (2683) =$ **67 075 kW**

6.102

A somewhat simplified flow diagram for a nuclear power plant shown in Fig. 1.4 is given in Fig. P6.102. Mass flow rates and the various states in the cycle are shown in the accompanying table. The cycle includes a number of heaters in which heat is transferred from steam, taken out of the turbine at some intermediate pressure, to liquid water pumped from the condenser on its way to the steam drum. The heat exchanger in the reactor supplies 157 MW, and it may be assumed that there is no heat transfer in the turbines.

a. Assume the moisture separator has no heat transfer between the two turbinesections, determine the enthalpy and quality (h_4, x_4).
b. Determine the power output of the low-pressure turbine.
c. Determine the power output of the high-pressure turbine.
d. Find the ratio of the total power output of the two turbines to the total power delivered by the reactor.

Solution:



a) Moisture Separator, steady state, no heat transfer, no work

Mass: $\dot{m}_3 = \dot{m}_4 + \dot{m}_9$, Energy: $\dot{m}_3 h_3 = \dot{m}_4 h_4 + \dot{m}_9 h_9$;

$62.874 \times 2517 = 58.212 \times h_4 + 4.662 \times 558 \quad \Rightarrow \quad h_4 = 2673.9$ kJ/kg

$h_4 = 2673.9 = 566.18 + x_4 \times 2160.6 \quad => \quad x_4 = \mathbf{0.9755}$

b) Low Pressure Turbine, steady state no heat transfer

Energy Eq.: $\dot{m}_4 h_4 = \dot{m}_5 h_5 + \dot{m}_8 h_8 + \dot{W}_{CV(LP)}$

$\dot{W}_{CV(LP)} = \dot{m}_4 h_4 - \dot{m}_5 h_5 - \dot{m}_8 h_8$

$= 58.212 \times 2673.9 - 55.44 \times 2279 - 2.772 \times 2459$

$= 22\,489$ kW $=$ **22.489 MW**

c) High Pressure Turbine, steady state no heat transfer

Energy Eq.: $\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_{12} h_{12} + \dot{m}_{17} h_{17} + \dot{W}_{CV(HP)}$

$\dot{W}_{CV(HP)} = \dot{m}_2 h_2 - \dot{m}_3 h_3 - \dot{m}_{12} h_{12} - \dot{m}_{17} h_{17}$

$= 75.6 \times 2765 - 62.874 \times 2517 - 8.064 \times 2517 - 4.662 \times 2593$

$= 18\,394$ kW $=$ **18.394 MW**

d) $\eta = (\dot{W}_{HP} + \dot{W}_{LP})/\dot{Q}_{REACT} = 40.883/157 = \mathbf{0.26}$

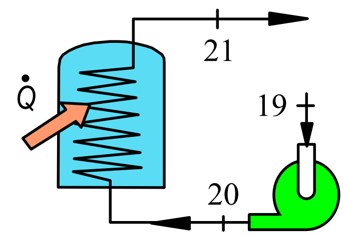
6.103

Consider the powerplant as described in the previous problem.

a. Determine the quality of the steam leaving the reactor.

b. What is the power to the pump that feeds water to the reactor?

Solution:



a) Reactor: Cont.: $\dot{m}_{20} = \dot{m}_{21}$; $\dot{Q}_{CV} = 157$ MW

Energy Eq.6.12: $\dot{Q}_{CV} + \dot{m}_{20}h_{20} = \dot{m}_{21}h_{21}$

$157\ 000 + 1386 \times 1221 = 1386 \times h_{21}$

$h_{21} = 1334.3 = 1282.4 + x_{21} \times 1458.3$

$\Rightarrow \quad x_{21} = \mathbf{0.0349}$

b) C.V. Reactor feedwater pump

Cont. $\dot{m}_{19} = \dot{m}_{20}$ Energy Eq.6.12: $\dot{m}_{19}h_{19} = \dot{m}_{19}h_{20} + \dot{W}_{Cv,P}$

Table B.1: $h_{19} = h(277°C, 7240 \text{ kPa}) = 1220$ kJ/kg, $h_{20} = 1221$ kJ/kg

$\dot{W}_{Cv,P} = \dot{m}_{19}(h_{19} - h_{20}) = 1386(1220 - 1221) = \mathbf{-1386\ kW}$

6.104

A gas turbine setup to produce power during peak demand is shown in Fig. P6.104. The turbine provides power to the air compressor and the electric generator. If the electric generator should provide 5 MW what is the needed air flow at state 1 and the combustion heat transfer between state 2 and 3?

Solution:

1: 90 kPa, 290 K ; 2: 900 kPa, 560 K ; 3: 900 kPa, 1400 K
4: 100 kPa, 850 K ;

$w_{c\ in} = h_2 - h_1 = 565.47 - 290.43 = 275.04$ kJ/kg
$w_{Tout} = h_3 - h_4 = 1515.27 - 877.4 = 637.87$ kJ/kg
$q_H = h_3 - h_2 = 1515.27 - 565.47 = 949.8$ kJ/kg

$\dot{W}_{el} = \dot{m}w_T - \dot{m}w_c$

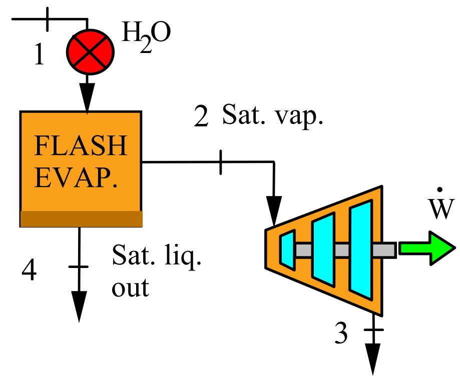
$\dot{m} = \dot{W}_{el} / (w_T - w_c) = \frac{5000}{637.87 - 275.04}$ **= 13.78 kg/s**

$\dot{Q}_H = \dot{m}q_H = 13.78 \times 949.8 = 13\ 088$ kW **= 13.1 MW**

6.105

A proposal is made to use a geothermal supply of hot water to operate a steam turbine, as shown in Fig. P6.105. The high-pressure water at 1.5 MPa, 180°C, is throttled into a flash evaporator chamber, which forms liquid and vapor at a lower pressure of 400 kPa. The liquid is discarded while the saturated vapor feeds the turbine and exits at 10 kPa, 90% quality. If the turbine should produce 1 MW, find the required mass flow rate of hot geothermal water in kilograms per hour.

Solution:



Separation of phases in flash-evaporator constant h in the valve flow so

Table B.1.3: $h_1 = 763.5$ kJ/kg

$h_1 = 763.5 = 604.74 + x \times 2133.8$

$\Rightarrow \quad x = 0.07439 = \dot{m}_2/\dot{m}_1$

Table B.1.2: $h_2 = 2738.6$ kJ/kg;

$h_3 = 191.83 + 0.9 \times 2392.8 = 2345.4$ kJ/kg

Energy Eq.6.12 for the turbine

$$\dot{W} = \dot{m}_2(h_2 - h_3) \quad => \quad \dot{m}_2 = \frac{1000}{2738.6 - 2345.4} = 2.543 \text{ kg/s}$$

$$\Rightarrow \quad \dot{m}_1 = \dot{m}_2/x = 34.19 \text{ kg/s} = \mathbf{123\ 075\ kg/h}$$

6.106

A R-12 heat pump cycle shown in Fig. P6.71 has a R-12 flow rate of 0.05 kg/s with 4 kW into the compressor. The following data are given

State	1	2	3	4	5	6
P kPa	1250	1230	1200	320	300	290
T °C	120	110	45		0	5
h kJ/kg	260	253	79.7	-	188	191

Calculate the heat transfer from the compressor, the heat transfer from the R-12 in the condenser and the heat transfer to the R-12 in the evaporator.

Solution:

CV: Compressor

$$\dot{Q}_{COMP} = \dot{m}(h_1 - h_e) + \dot{W}_{COMP}$$

$$= 0.05\ (260 - 191) - 4.0 = \mathbf{-0.55\ kW}$$

CV: Condenser

$$\dot{Q}_{COND} = \dot{m}\ (h_3 - h_2) = 0.05\ (79.7 - 253) = \mathbf{-8.665\ kW}$$

CV: Evaporator $\quad h_4 = h_3 = 79.7$ kJ/kg (from valve)

$$\dot{Q}_{EVAP} = \dot{m}\ (h_5 - h_4) = 0.05\ (188 - 79.7) = \mathbf{5.42\ kW}$$

6.107

A modern jet engine has a temperature after combustion of about 1500 K at 3200 kPa as it enters the turbine setion, see state 3 Fig. P.6.107. The compressor inlet is 80 kPa, 260 K state 1 and outlet state 2 is 3300 kPa, 780 K; the turbine outlet state 4 into the nozzle is 400 kPa, 900 K and nozzle exit state 5 at 80 kPa, 640 K. Neglect any heat transfer and neglect kinetic energy except out of the nozzle. Find the compressor and turbine specific work terms and the nozzle exit velocity.

Solution:

The compressor, turbine and nozzle are all steady state single flow devices and they are adiabatic.

We will use air properties from table A.7.1:

$h_1 = 260.32,\ h_2 = 800.28,\ h_3 = 1635.80,\ h_4 = 933.15, h_5 = 649.53$ kJ/kg

Energy equation for the compressor gives

$$w_{c\ in} = h_2 - h_1 = 800.28 - 260.32 = \mathbf{539.36\ kJ/kg}$$

Energy equation for the turbine gives

$$w_T = h_3 - h_4 = 1635.80 - 933.15 = \mathbf{702.65\ kJ/kg}$$

Energy equation for the nozzle gives

$$h_4 = h_5 + ½\, \mathbf{V}_5^2$$

$$½\, \mathbf{V}_5^2 = h_4 - h_5 = 933.15 - 649.53 = 283.62 \text{ kJ/kg}$$

$$\mathbf{V}_5 = [2(h_4 - h_5)]^{1/2} = (2\times 283.62 \times 1000)^{1/2} = \mathbf{753\ m/s}$$

Transient processes

6.108

A 1-m^3, 40-kg rigid steel tank contains air at 500 kPa, and both tank and air are at 20°C. The tank is connected to a line flowing air at 2 MPa, 20°C. The valve is opened, allowing air to flow into the tank until the pressure reaches 1.5 MPa and is then closed. Assume the air and tank are always at the same temperature and the final temperature is 35°C. Find the final air mass and the heat transfer.

Solution:

Control volume: Air and the steel tank.

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

Energy Eq.6.16: $(m_2u_2 - m_1u_1)_{AIR} + m_{ST}(u_2 - u_1)_{ST} = m_ih_i + {}_1Q_2$

$$m_{1\ AIR} = \frac{P_1V}{RT_1} = \frac{500 \times 1}{0.287 \times 293.2} = 5.94 \text{ kg}$$

$$m_{2\ AIR} = \frac{P_2V}{RT_2} = \frac{1500 \times 1}{0.287 \times 308.2} = \mathbf{16.96\ kg}$$

$$m_i = (m_2 - m_1)_{AIR} = 16.96 - 5.94 = 11.02 \text{ kg}$$

The energy equation now gives

$${}_1Q_2 = (m_2u_2 - m_1u_1)_{AIR} + m_{ST}(u_2 - u_1)_{ST} - m_ih_i$$
$$= m_1(u_2 - u_1) + m_i(u_2 - u_i - RT_i) + m_{ST}C_{ST}(T_2 - T_1)$$
$$\cong m_1C_v(T_2 - T_1) + m_i[C_v(T_2 - T_i) - RT_i] + m_{ST}C_{ST}(T_2 - T_1)$$
$$= 5.94 \times 0.717(35 - 20) + 11.02[0.717(35 - 20) - 0.287 \times 293.2]$$
$$+ 40 \times 0.46(35 - 20)$$
$$= 63.885 - 808.795 + 276$$
$$= \mathbf{-\ 468.9\ kJ}$$

6.109

An evacuated 150-L tank is connected to a line flowing air at room temperature, 25°C, and 8 MPa pressure. The valve is opened allowing air to flow into the tank until the pressure inside is 6 MPa. At this point the valve is closed. This filling process occurs rapidly and is essentially adiabatic. The tank is then placed in storage where it eventually returns to room temperature. What is the final pressure?

Solution:

C.V. Tank:

Continuity Eq.6.15: $m_i = m_2$

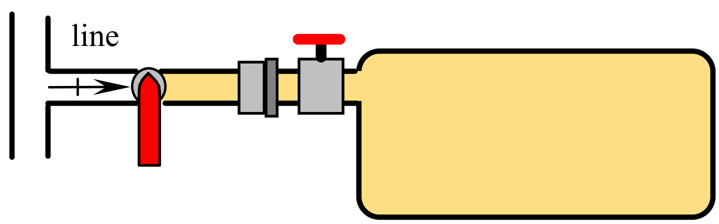
Energy Eq.6.16: $m_i h_i = m_2 u_2 \quad => \quad u_2 = h_i$

Use constant specific heat C_{Po} from table A.5 then energy equation:

$$T_2 = (C_P/C_V)\ T_i = kT_i = 1.4 \times 298.2 = 417.5 \text{ K}$$

Process: constant volume cooling to T_3:

$$P_3 = P_2 \times T_3/T_2 = 6.0 \times 298.15/\ 417.5 = \mathbf{4.29\ MPa}$$



6.110

An initially empty bottle is filled with water from a line at 0.8 MPa, 350^{o}C. Assume no heat transfer and that the bottle is closed when the pressure reaches the line pressure. If the final mass is 0.75 kg find the final temperature and the volume of the bottle.

Solution;

C.V. Bottle, transient process with no heat transfer or work.

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

Energy Eq.6.16: $m_2u_2 – m_1u_1 = - m_{in} h_{in}$

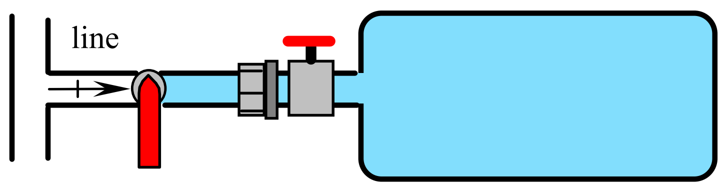
State 1: $m_1 = 0$ => $m_2 = m_{in}$ and $u_2 = h_{in}$

Line state: Table B.1.3: $h_{in} = 3161.68$ kJ/kg

State 2: $P_2 = P_{line} = 800$ kPa, $u_2 = 3161.68$ kJ/kg from Table B.1.3

$T_2 = \mathbf{520^{o}C}$ and $v_2 = 0.4554$ m^3/kg

$V_2 = m_2v_2 = 0.75 \times 0.4554 = 0\mathbf{.342\ m^3}$

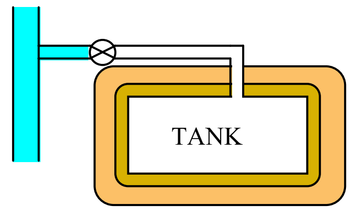


6.111

A 25-L tank, shown in Fig. P6.111, that is initially evacuated is connected by a valve to an air supply line flowing air at 20°C, 800 kPa. The valve is opened, and air flows into the tank until the pressure reaches 600 kPa.Determine the final temperature and mass inside the tank, assuming the process is adiabatic. Develop an expression for the relation between the line temperature and the final temperature using constant specific heats.

Solution:

C.V. Tank:



Continuity Eq.6.15: $m_2 = m_i$

Energy Eq.6.16: $m_2u_2 = m_ih_i$

Table A.7: $u_2 = h_i = 293.64$ kJ/kg

$\Rightarrow T_2 = \mathbf{410.0\ K}$

$$m_2 = \frac{P_2V}{RT_2} = \frac{600 \times 0.025}{0.287 \times 410} = \mathbf{0.1275\ kg}$$

Assuming constant specific heat,

$$h_i = u_i + RT_i = u_2\ , \quad RT_i = u_2 - u_i = C_{vo}(T_2 - T_i)$$

$$C_{vo}T_2 = (\ C_{vo} + R\ )T_i = C_{Po}T_i\ \ , \quad T_2 = \left(\frac{C_{Po}}{C_{vo}}\right) T_i = kT_i$$

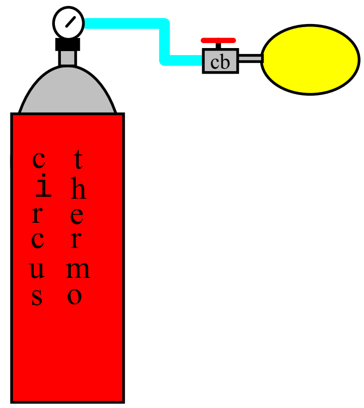
For $T_i = 293.2$K & constant C_{Po}, $\quad T_2 = 1.40{\times}293.2 = \mathbf{410.5\ K}$

6.112

Helium in a steel tank is at 250 kPa, 300 K with a volume of 0.1 m^3. It is used to fill a balloon. When the tank pressure drops to 150 kPa the flow of helium stops by itself. If all the helium still is at 300 K how big a balloon did I get? Assume the pressure in the balloon varies linearly with volume from 100 kPa (V = 0) to the final 150 kPa. How much heat transfer did take place?

Solution:

Take a C.V. of all the helium.
This is a control mass, the tank mass changes density and pressure.



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

Process Eq.: $P = 100 + CV$

State 1: P_1, T_1, V_1

State 2: $P_2, T_2, V_2 = ?$

Ideal gas:

$$P_2 V_2 = mRT_2 = mRT_1 = P_1V_1$$

$$V_2 = V_1(P_1/P_2) = 0.1\times (250/150) = 0.16667 \text{ m}^3$$

$$V_{bal} = V_2 - V_1 = 0.16667 - 0.1 = 0.06667 \text{ m}^3$$

$$_1W_2 = \int P\, dV = \text{AREA} = ½\,(P_1 + P_2)(V_2 - V_1)$$

$$= ½(250 + 150) \times 0.06667 = 13.334 \text{ kJ}$$

$$U_2 - U_1 = {}_1Q_2 - {}_1W_2 = m\,(u_2 - u_1) = mC_v\,(T_2 - T_1) = 0$$

so $\quad {}_1Q_2 = {}_1W_2 = \mathbf{13.334\ kJ}$

Remark: The process is transient, but you only see the flow mass if you select the tank or the balloon as a control volume. That analysis leads to more terms that must be elliminated between the tank control volume and the balloon control volume.

6.113

A rigid 100-L tank contains air at 1 MPa, 200°C. A valve on the tank is now opened and air flows out until the pressure drops to 100 kPa. During this process, heat is transferred from a heat source at 200°C, such that when the valve is closed, the temperature inside the tank is 50°C. What is the heat transfer?

Solution:

1 : 1 MPa, 200°C, $m_1 = P_1V_1/RT_1 = 1000 \times 0.1/(0.287 \times 473.1) = 0.736$ kg

2 : 100 kPa, 50°C, $m_2 = P_2V_2/RT_2 = 100 \times 0.1/(0.287 \times 323.1) = 0.1078$ kg

Continuity Eq.6.15: $m_{ex} = m_1 - m_2 = 0.628$ kg,

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

Table A.7: $u_1 = 340.0$ kJ/kg, $u_2 = 231.0$ kJ/kg,

$h_{e\ ave} = (h_1 + h_2)/2 = (475.8 + 323.75)/2 = 399.8$ kJ/kg

${}_1Q_2 = 0.1078 \times 231.0 - 0.736 \times 340.0 + 0.628 \times 399.8 = $ **+25.7 kJ**

6.114

A 1-m^3 tank contains ammonia at 150 kPa, 25°C. The tank is attached to a line flowing ammonia at 1200 kPa, 60°C. The valve is opened, and mass flows in until the tank is half full of liquid, by volume at 25°C. Calculate the heat transferred from the tank during this process.

Solution:

C.V. Tank. Transient process as flow comes in.

State 1 Table B.2.2 interpolate between 20 °C and 30°C:

$v_1 = 0.9552 \text{ m}^3/\text{kg}; \;\; u_1 = 1380.6 \text{ kJ/kg}$

$m_1 = V/v_1 = 1/0.9552 = 1.047 \text{ kg}$

State 2: 0.5 m^3 liquid and 0.5 m^3 vapor from Table B.2.1 at 25°C

$v_f = 0.001658 \text{ m}^3/\text{kg}; \;\; v_g = 0.12813 \text{ m}^3/\text{kg}$

$m_{LIQ2} = 0.5/0.001658 = 301.57 \text{ kg}, \;\; m_{VAP2} = 0.5/0.12813 = 3.902 \text{ kg}$

$m_2 = 305.47 \text{ kg}, \;\; x_2 = m_{VAP2}/m_2 = 0.01277,$

From continuity equation

$m_i = m_2 - m_1 = 304.42 \text{ kg}$

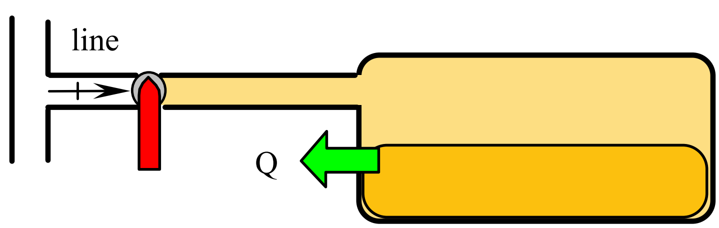
Table B.2.1: $u_2 = 296.6 + 0.01277 \times 1038.4 = 309.9 \text{ kJ/kg}$

State inlet: Table B.2.2 $h_i = 1553.3 \text{ kJ/kg}$

Energy Eq.6.16:

$Q_{CV} + m_i h_i = m_2 u_2 - m_1 u_1$

$Q_{CV} = 305.47 \times 309.9 - 1.047 \times 1380.6 - 304.42 \times 1553.3 = \mathbf{-379\ 636\ kJ}$



6.115

An empty cannister of volume 1 L is filled with R-134a from a line flowing saturated liquid R-134a at $0^{o}C$. The filling is done quickly so it is adiabatic. How much mass of R-134a is there after filling? The cannister is placed on a storage shelf where it slowly heats up to room temperature $20^{o}C$. What is the final pressure?

C.V. cannister, no work and no heat transfer.

Continuity Eq.6.15: $m_2 = m_i$

Energy Eq.6.16: $m_2u_2 - 0 = m_ih_i = m_ih_{line}$

Table B.5.1: $h_{line} = 200.0$ kJ/kg, $P_{line} = 294$ kPa

From the energy equation we get

$u_2 = h_{line} = 200 \text{ kJ/kg} > u_f = 199.77 \text{ kJ/kg}$

State 2 is two-phase $P_2 = P_{line} = 294$ kPa and $T_2 = 0°C$

$$x_2 = \frac{u_2 - u_f}{u_{fg}} = \frac{200 - 199.77}{178.24} = 0.00129$$

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

$m_2 = V/v_2 = 0.01/0.000861 = \mathbf{11.61\ kg}$

At 20°C: $v_f = 0.000817\ m^3/kg < v_2$ so still two-phase

$P = P_{sat} = \mathbf{572.8\ kPa}$

6.116

A piston cylinder contains 1 kg water at 20$^{\text{o}}$C with a constant load on the piston such that the pressure is 250 kPa. A nozzle in a line to the cylinder is opened to enable a flow to the outside atmosphere at 100 kPa. The process continues to half the mass has flowed out and there is no heat transfer. Assume constant water temperature and find the exit velocity and total work done in the process.

Solution:

C.V. The cylinder and the nozzle.

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

Energy Eq.6.16: $m_2u_2 - m_1u_1 = - m_e(h_e + \frac{1}{2}\mathbf{V}_e^2) - {}_1W_2$

Process: $P = C \quad => \quad {}_1W_2 = \int P\, dV = P(V_2 - V_1)$

State 1: Table B.1.1, 20$^{\text{o}}$C => $v_1 = 0.001002$, $u_1 = 83.94$ kJ/kg

State 2: Table B.1.1, 20$^{\text{o}}$C => $v_2 = v_1$, $u_2 = u_1$;

$m_2 = m_1/2 = 0.5$ kg => $V_2 = V_1/2$

${}_1W_2 = P(V_2 - V_1) = 250\ (0.5 - 1)\ 0.001002 = \mathbf{-0.125\ kJ}$

Exit state: Table B.1.1, 20$^{\text{o}}$C => $h_e = 83.94$ kJ/kg

Solve for the kinetic energy in the energy equation

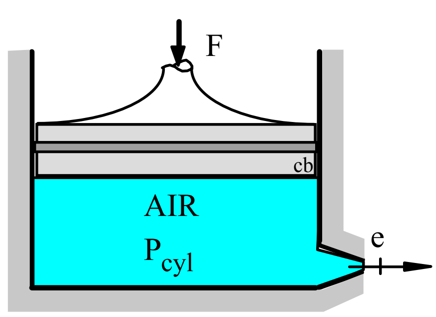
$$\frac{1}{2}\mathbf{V}_e^2 = [m_1u_1 - m_2u_2 - m_eh_e - {}_1W_2]/m_e$$

$$= [1 \times 83.94 - 0.5 \times 83.94 - 0.5 \times 83.94 + 0.125] / 0.5$$

$$= 0.125/0.5 = 0.25 \text{ kJ/kg}$$

$$\mathbf{V} = \sqrt{2 \times 0.25 \times 1000} = \mathbf{22.36\ m/s}$$

All the work ended up as kinetic energy in the exit flow.

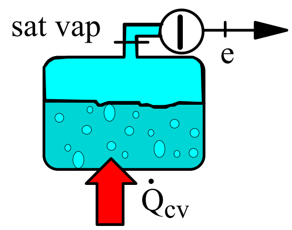


6.117

A 200 liter tank initially contains water at 100 kPa and a quality of 1%. Heat is transferred to the water thereby raising its pressure and temperature. At a pressure of 2 MPa a safety valve opens and saturated vapor at 2 MPa flows out. The process continues, maintaining 2 MPa inside until the quality in the tank is 90%, then stops. Determine the total mass of water that flowed out and the total heat transfer.

Solution:

C.V. Tank, no work but heat transfer in and flow out. Denoting State 1: initial state, State 2: valve opens, State 3: final state.



Continuity Eq.: $m_3 - m_1 = - m_e$

Energy Eq.: $m_3u_3 - m_1u_1 = - m_eh_e + {}_1Q_3$

State 1 Table B.1.2: $v_1 = v_f + x_1v_{fg} = 0.001043 + 0.01 \times 1.69296$
$= 0.01797 \text{ m}^3\text{/kg}$
$u_1 = u_f + x_1u_{fg} = 417.33 + 0.01 \times 2088.72 = 438.22 \text{ kJ/kg}$
$m_1 = V/v_1 = 0.2 \text{ m}^3/(0.01797 \text{ m}^3\text{/kg}) = 11.13 \text{ kg}$

State 3 (2MPa): $v_3 = v_f + x_3v_{fg} = 0.001177 + 0.9 \times 0.09845 = 0.8978 \text{ m}^3\text{/kg}$
$u_3 = u_f + x_3u_{fg} = 906.42 + 0.9 \times 1693.84 = 2430.88 \text{ kJ/kg}$
$m_3 = V/v_3 = 0.2 \text{ m}^3/(0.08978 \text{ m}^3\text{/kg}) = 2.23 \text{ kg}$

Exit state (2MPa): $h_e = h_g = 2799.51 \text{ kJ/kg}$

Hence: $m_e = m_1 - m_3 = 11.13 \text{ kg} - 2.23 \text{ kg} = \mathbf{8.90 \text{ kg}}$

Applying the 1st law between state 1 and state 3

$${}_1Q_3 = m_3u_3 - m_1u_1 + m_eh_e$$
$$= 2.23 \times 2430.88 - 11.13 \times 438.22 + 8.90 \times 2799.51$$
$$= 25\,459 \text{ kJ} = \mathbf{25.46 \text{ MJ}}$$

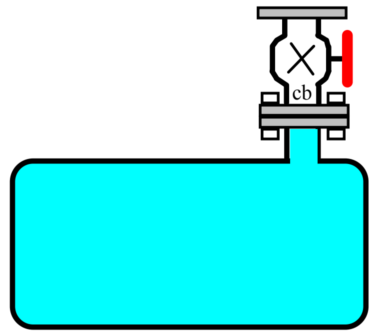
6.118

A 100-L rigid tank contains carbon dioxide gas at 1 MPa, 300 K. A valve is cracked open, and carbon dioxide escapes slowly until the tank pressure has dropped to 500 kPa. At this point the valve is closed. The gas remaining inside the tank may be assumed to have undergone a polytropic expansion, with polytropic exponent *n* = 1.15. Find the final mass inside and the heat transferred to the tank during the process.

Solution:

Ideal gas law and value from table A.5

$$m_1 = \frac{P_1V}{RT_1} = \frac{1000 \times 0.1}{0.18892 \times 300} = 1.764 \text{ kg}$$



Polytropic process and ideal gas law gives

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{(n-1)/n} = 300 \left(\frac{500}{1000}\right)^{(0.15/1.15)} = 274 \text{ K}$$

$$m_2 = \frac{P_2V}{RT_2} = \frac{500 \times 0.1}{0.18892 \times 274} = \mathbf{0.966\ kg}$$

Energy Eq.6.16:

$$Q_{CV} = m_2u_2 - m_1u_1 + m_eh_{e\ avg}$$

$$= m_2C_{vo}T_2 - m_1C_{vo}T_1 + (m_1 - m_2)C_{Po}(T_1 + T_2)/2$$

$$= 0.966 \times 0.6529 \times 274 - 1.764 \times 0.6529 \times 300$$

$$+ (1.764 - 0.966) \times 0.8418 \times (300 + 274)/2 = \mathbf{+20.1\ kJ}$$

6.119

A nitrogen line, 300 K and 0.5 MPa, shown in Fig. P6.119, is connected to a turbine that exhausts to a closed initially empty tank of 50 m^3. The turbine operates to a tank pressure of 0.5 MPa, at which point the temperature is 250 K. Assuming the entire process is adiabatic, determine the turbine work.

Solution:

C.V. turbine & tank $\Rightarrow$ Transient process

Conservation of mass Eq.6.15: $m_i = m_2 \Rightarrow m$

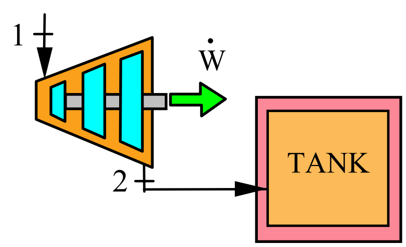
Energy Eq.6.16: $m_i h_i = m_2 u_2 + W_{CV}$; $W_{CV} = m(h_i - u_2)$

Table B.6.2: $P_i = 0.5$ MPa, $T_i = 300$ K, Nitrogen; $h_i = 310.28$ kJ/kg

2: $P_2 = 0.5$ MPa, $T_2 = 250$ K, $u_2 = 183.89$ kJ/kg, $v_2 = 0.154$ m^3/kg

$m_2 = V/v_2 = 50/0.154 = 324.7$ kg

$W_{CV} = 324.7\ (310.28 - 183.89) = 41\ 039$ kJ = **41.04 MJ**



We could with good accuracy have solved using ideal gas and Table A.5

6.120

A 2 m tall cylinder has a small hole in the bottom. It is filled with liquid water 1 m high, on top of which is 1 m high air column at atmospheric pressure of 100 kPa. As the liquid water near the hole has a higher P than 100 kPa it runs out. Assume a slow process with constant T. Will the flow ever stop? When?
New fig.
Solution:

$$P_{bot} = P_{air} + \rho g L_{liq}$$

For the air PV = mRT

$P_{air} = mRT/V_{air}$; $V_{air} = A\ L_{air} = A\ (H\text{-}L_{liq})$

$$P_{bot} = \frac{m_a R_a T_a}{A(H\text{-}L_{liq})} + \rho_f g\ L_f = \frac{P_{a1}V_{a1}}{A(H\text{-}L_{liq})} + \rho_{liq}\ gL_f = \frac{P_{a1}L_{a1}}{H\text{-}L_f} + \rho_{liq}\ gL_f \geq P_o$$

Solve for L_{liq} ; $\rho_{liq} = 1/(v_f) = 1/0.0021002 = 998\ kg/m^3$

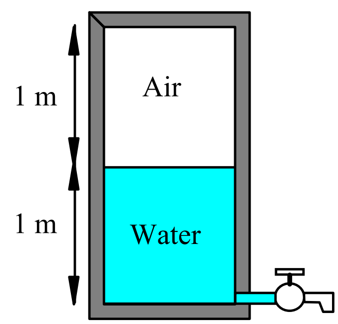
$$P_{a1}\ L_{a1} + \rho g\ L_f\ (H - L_f) \geq P\ (H - L_f)$$

$$(\rho g H + P_o)\ L_f - \rho g L^2_f = P_o\ H + P_{a1}\ L_{a1} \geq 0$$

Put in numbers and solve quadratic eq.

$$L^2_f - (H + (P_o/\rho g))\ L_f + \frac{P_o H\text{-}P_{a1}L_{a1}}{\rho g} = \varnothing$$

$$L^2_f - 12.217\ L_f + 10.217 = 0$$



$$(P_o/\rho g) = \frac{100\ kPa\ m^3\ s^3}{998 \times 9.807\ kg\ m} = 10.217\ m$$

$$\frac{P_o H + P_{a1}L_{a1}}{\rho g} = \frac{100\ (2\text{-}1)}{998 \times 9.807} = 10.217\ m$$

$$L_f = \frac{12.217}{2} \times [\frac{12.217^3}{4} - \frac{12.217}{4}]^{1/2} = 6.1085 \times 5.2055$$

$$=> 11.314 \quad \text{or} \quad 0.903\ m$$

Verify

$$P_{a2} = P_{a1} \cdot \frac{L_{a1}}{H\text{-}L_f} = 100\ \frac{1}{2 - 0.903} = 91.158\ kPa$$

$$\rho g L_f = 998 \times 9.807 \times 0.903 = 8838\ Pa = 8.838\ kPa$$

$$P_{bot} = P_{a2} + \rho g L_f = 91.158 + 8.838 = 99.996\ kPa \quad \text{OK}$$

6.121

A 2-m^3 insulated vessel, shown in Fig. P6.121, contains saturated vapor steam at 4 MPa. A valve on the top of the tank is opened, and steam is allowed to escape. During the process any liquid formed collects at the bottom of the vessel, so that only saturated vapor exits. Calculate the total mass that has escaped when the pressure inside reaches 1 MPa.

Solution:

C.V. Vessel: Mass flows out.

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

Energy Eq.6.16: $m_2u_2 - m_1u_1 = -(m_1-m_2)h_e$ or $m_2(h_e-u_2) = m_1(h_e-u_1)$

Average exit enthalpy $h_e \approx (h_{G1}+h_{G2})/2 = (2801.4+2778.1)/2 = 2789.8$

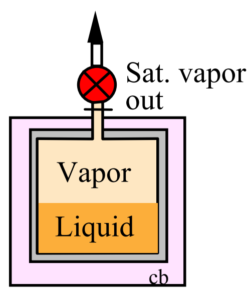
State 1: $m_1 = V/v_1 = 40.177$ kg, $m_2 = V/v_2$

Energy equation $\Rightarrow$ $\frac{2}{v_2}(2789.8-u_2) = 40.177(2789.8-2602.3) = 7533.19$

But $v_2 = .001\,127 + .193\,313\,x_2$ and $u_2 = 761.7 + 1822\,x_2$

Substituting and solving, $x_2 = 0.7936$

$\Rightarrow m_2 = V/v_2 = 12.94$ kg, $m_e =$ **27.24 kg**



6.122

A 750-L rigid tank, shown in Fig. P6.122, initially contains water at 250°C, 50% liquid and 50% vapor, by volume. A valve at the bottom of the tank is opened, and liquid is slowly withdrawn. Heat transfer takes place such that the temperature remains constant. Find the amount of heat transfer required to the state where half the initial mass is withdrawn.

Solution:

C.V. vessel

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

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

State 1: $m_{LIQ1} = \frac{0.375}{0.001251} = 299.76$ kg; $m_{VAP1} = \frac{0.375}{0.05013} = 7.48$ kg

$m_1u_1 = 299.76 \times 1080.37 + 7.48 \times 2602.4 = 343\ 318$ kJ

$m_1 = 307.24$ kg; $m_e = m_2 = 153.62$ kg

State 2: $v_2 = \frac{0.75}{153.62} = 0.004882 = 0.001251 + x_2 \times 0.04888$

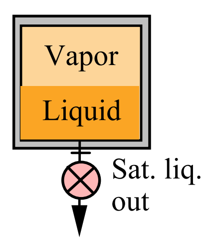
$x_2 = 0.07428$; $u_2 = 1080.37 + 0.07428 \times 1522 = 1193.45$ kJ/kg

Exit state: $h_e = h_f = 1085.34$ kJ/kg

Energy equation now gives the heat transfer as

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

$= 153.62 \times 1193.45 - 343\ 318 + 153.62 \times 1085.34$ = **6750 kJ**



6.123

Consider the previous problem but let the line and valve be located in the top of the tank. Now saturated vapor is slowly withdrawn while heat transfer keeps the temperature inside constant. Find the heat transfer required to reach a state where half the original mass is withdrawn.

Solution:

C.V. vessel

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

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

State 1: $m_{LIQ1} = \frac{0.375}{0.001251} = 299.76$ kg; $m_{VAP1} = \frac{0.375}{0.05013} = 7.48$ kg

$m_1u_1 = 299.76 \times 1080.37 + 7.48 \times 2602.4 = 343\,318$ kJ

$m_1 = 307.24$ kg; $m_e = m_2 = 153.62$ kg

State 2: $v_2 = \frac{0.75}{153.62} = 0.004882 = 0.001251 + x_2 \times 0.04888$

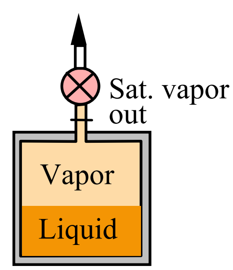
$x_2 = 0.07428$; $u_2 = 1080.37 + 0.07428 \times 1522 = 1193.45$ kJ/kg

Exit state: $h_e = h_g = 2801.52$ kJ/kg

Energy equation now gives the heat transfer as

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

$= 153.62 \times 1193.45 - 343\,318 + 153.62 \times 2801.52 = \mathbf{270\,389\ kJ}$



Review Problems

6.124

Two kg of water at 500 kPa, 20^{o}C is heated in a constant pressure process to 1700^{o}C. Find the best estimate for the heat transfer.

Solution:

C.V. Heater; steady state 1 inlet and exit, no work term, no ΔKE, ΔPE .

Continuity Eq.: $\dot{m}_{in} = \dot{m}_{ex} = \dot{m}$,

Energy Eq.6.13: $q + h_{in} = h_{ex} \Rightarrow q = h_{ex} - h_{in}$

steam tables only go up to 1300^{o}C so use an intermediate state at lowest pressure (closest to ideal gas) h_X(1300^{o}C, 10 kPa) from Table B.1.3 and table A.8 for the high T change Δh

$$h_{ex} - h_{in} = (h_{ex} - h_X) + (h_X - h_{in})$$

$$= (71\ 423 - 51\ 629)/18.015 + 5409.7 - 83.96 = 6424.5 \text{ kJ/kg}$$

$$Q = m(h_{ex} - h_{in}) = 2 \times 6424.5 = \mathbf{12\ 849\ kJ}$$

6.125

In a glass factory a 2 m wide sheet of glass at 1500 K comes out of the final rollers that fix the thickness at 5 mm with a speed of 0.5 m/s. Cooling air in the amount of 20 kg/s comes in at 17^{o}C from a slot 2 m wide and flows parallel with the glass. Suppose this setup is very long so the glass and air comes to nearly the same temperature (a co-flowing heat exchanger) what is the exit temperature?

Solution:

Energy Eq.: $\dot{m}_{glass}h_{glass\ 1} + \dot{m}_{air}h_{air\ 2} = \dot{m}_{glass}h_{glass\ 3} + \dot{m}_{air}h_{air\ 4}$

$\dot{m}_{glass} = \rho\dot{V} = \rho AV = 2500\times 2 \times 0.005\times 0.5 = 12.5$ kg/s

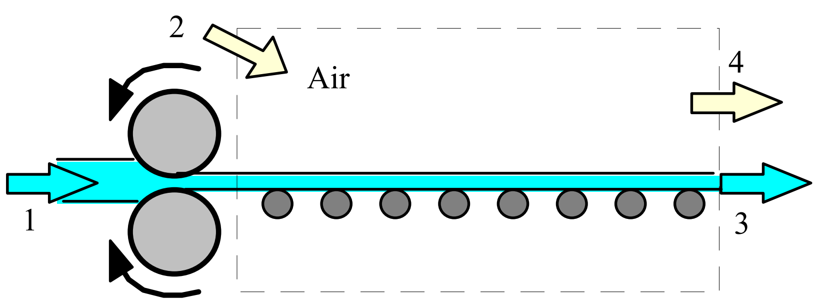
$\dot{m}_{glass}C_{glass} (T_3 - T_1) + \dot{m}_{air}\ C_{Pa} (T_4 - T_2) = \varnothing$

$T_4 = T_3$, $C_{glass} = 0.80$ kJ/kg K, $C_{Pa} = 1.004$ kJ/kg K

$$T_3 = \frac{\dot{m}_{glass}C_{glass}\ T_1 + \dot{m}_{air}C_{Pa}\ T_2}{\dot{m}_{glass}C_{glass} + \dot{m}_{air}C_{Pa}} = \frac{12.5\times0.80\times1500 + 20\times1.004\times290}{12.5\times0.80 + 20\times1.004}$$

$= \mathbf{692.3\ K}$

We could use table A.7.1 for air, but then it will be trial and error



6.126

Assume a setup similar to the previous problem but the air flows in the opposite direction of the glass, it comes in where the glass goes out. How much air flow at 17^oC is required to cool the glass to 450 K assuming the air must be at least 120 K cooler than the glass at any location?

Solution:

Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_4 h_4 = \dot{m}_3 h_3 + \dot{m}_2 h_2$

$T_4 = 290$ K and $T_3 = 450$ K

$\dot{m}_{glass} = \rho\dot{V} = \rho AV = 2500\times 2 \times 0.005\times 0.5 = 12.5$ kg/s

$T_2 \le T_1 - 120 \text{ K} = 1380 \text{ K}$

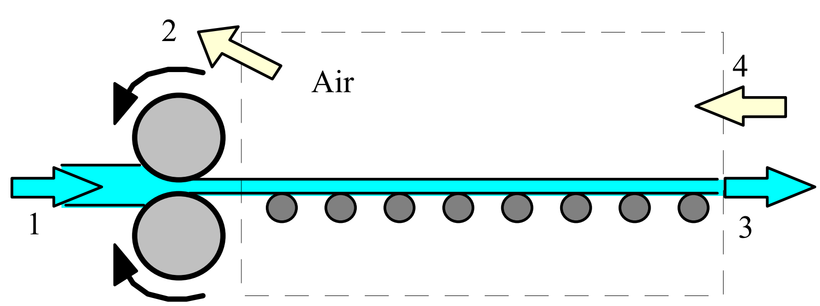
$$\dot{m} = \dot{m}_4 = \dot{m}_2 = \dot{m}_1 \frac{h_1\text{-}h_3}{h_2\text{-}h_4}$$

Let us check the limit and since T is high use table A.7.1 for air.

$h_4 = 290.43$ kJ/kg, $h_2 = 1491.33$ kJ/kg

$$\dot{m} = \dot{m}_4 = \dot{m}_2 = \dot{m}_1 \frac{h_1\text{-}h_3}{h_2\text{-}h_4} = \dot{m}_1 \frac{C_{glass}(T_1\text{-}T_3)}{h_2\text{-}h_4}$$

$$\dot{m} = 12.5 \frac{0.8\ (1500\text{-}450)}{1491.33 - 290.43} = \mathbf{8.743\ kg/s}$$



6.127

Three air flows all at 200 kPa are connected to the same exit duct and mix without external heat transfer. Flow one has 1 kg/s at 400 K, flow two has 3 kg/s at 290 K and flow three has 2 kg/s at 700 K. Neglect kinetic energies and find the volume flow rate in the exit flow.

Solution:

Continuity Eq. $\dot{m}_1 + \dot{m}_2 + \dot{m}_3 = \dot{m}_4 h_4$

Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_4 h_4$

$\dot{V}_4 = \dot{m}\, v_4$

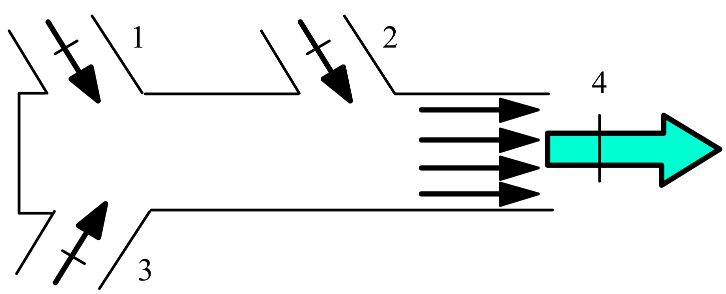
$$h_4 = \frac{\dot{m}_1}{\dot{m}_4} h_1 + \frac{\dot{m}_2}{\dot{m}_4} h_2 + \frac{\dot{m}_3}{\dot{m}_4} h_3 = \frac{1}{6} \times 401.3 + \frac{3}{6} \times 290.43 + \frac{2}{6} \times 713.56$$

$= 449.95$ kJ/kg

$$T_4 = 440 + 20\,\frac{449.95 - 441.93}{462.34 - 441.93} = 447.86 \text{ K}$$

$v_4 = RT_4 / P_4 = 0.287 \times 447.86/200 = \mathbf{0.643\ m^3/kg}$

$\dot{V}_4 = \dot{m}_4 v_4 = 6 \times 0.643 = \mathbf{3.858\ m^3/s}$



6.128

Consider the power plant as described in Problem 6.102.

a. Determine the temperature of the water leaving the intermediate pressure heater, T_{13}, assuming no heat transfer to the surroundings.

b. Determine the pump work, between states 13 and 16.

Solution:

a) Intermediate Pressure Heater

Energy Eq.6.10: $\dot{m}_{11}h_{11} + \dot{m}_{12}h_{12} + \dot{m}_{15}h_{15} = \dot{m}_{13}h_{13} + \dot{m}_{14}h_{14}$

$75.6\times284.6 + 8.064\times2517 + 4.662\times584 = 75.6\times h_{13} + 12.726\times349$

$h_{13} = 530.35 \rightarrow T_{13} = \mathbf{126.3°C}$

b) The high pressure pump

Energy Eq.6.12: $\dot{m}_{13}h_{13} = \dot{m}_{16}h_{16} + \dot{W}_{Cv,P}$

$\dot{W}_{Cv,P} = \dot{m}_{13}(h_{13} - h_{16}) = 75.6(530.35 - 565) = \mathbf{-2620\ kW}$

6.129

Consider the powerplant as described in Problem 6.102.

a. Find the power removed in the condenser by the cooling water (not shown).

b. Find the power to the condensate pump.

c. Do the energy terms balance for the low pressure heater or is there a heat transfer not shown?

Solution:

a) Condenser:

Energy Eq.6.10: $\dot{Q}_{CV} + \dot{m}_5 h_5 + \dot{m}_{10} h_{10} = \dot{m}_6 h_6$

$$\dot{Q}_{CV} + 55.44 \times 2279 + 20.16 \times 142.51 = 75.6 \times 138.3$$

$$\dot{Q}_{CV} = -118\ 765 \text{ kW} = \mathbf{-118.77\ MW}$$

b) The condensate pump

$$\dot{W}_{Cv,P} = \dot{m}_6(h_6 - h_7) = 75.6(138.31 - 140) = \mathbf{-127.8\ kW}$$

c) Low pressure heater   Assume no heat transfer

$$\dot{m}_{14} h_{14} + \dot{m}_8 h_8 + \dot{m}_7 h_7 + \dot{m}_9 h_9 = \dot{m}_{10} h_{10} + \dot{m}_{11} h_{11}$$

LHS = 12.726×349 + 2.772×2459 + 75.6×140 + 4.662×558 = 24 443 kW

RHS = (12.726 + 2.772 + 4.662) × 142.51 + 75.6 × 284.87 = 24 409 kW

A slight imbalance, but OK.

6.130

A 500-L insulated tank contains air at 40°C, 2 MPa. A valve on the tank is opened, and air escapes until half the original mass is gone, at which point the valve is closed. What is the pressure inside then?

Solution:

State 1: ideal gas $\quad m_1 = P_1V/RT_1 = \dfrac{2000 \times 0.5}{0.287 \times 313.2} = 11.125 \text{ kg}$

Continuity eq.6.15: $\quad m_e = m_1 - m_2,\ \ m_2 = m_1/2 \ \Rightarrow\ m_e = m_2 = 5.5625 \text{ kg}$

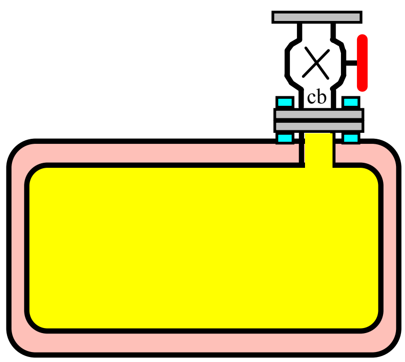
Energy Eq.6.16: $\quad m_2u_2 - m_1u_1 = - m_eh_{e\ AV}$

Substitute constant specific heat from table A.5 and evaluate the exit enthalpy as the average between the beginning and the end values

$$5.5625{\times}0.717\ T_2 - 11.125{\times}0.717{\times}313.2 = -\ 5.5625{\times}1.004\ (313.2 + T_2)/2$$

Solving, $T_2 = 239.4$ K

$$P_2 = \frac{m_2RT_2}{V} = \frac{5.5625 \times 0.287 \times 239.4}{0.5} = \mathbf{764\ kPa}$$



6.131

A steam engine based on a turbine is shown in Fig. P6.131. The boiler tank has a volume of 100 L and initially contains saturated liquid with a very small amount of vapor at 100 kPa. Heat is now added by the burner, and the pressure regulator does not open before the boiler pressure reaches 700 kPa, which it keeps constant. The saturated vapor enters the turbine at 700 kPa and is discharged to the atmosphere as saturated vapor at 100 kPa. The burner is turned off when no more liquid is present in the as boiler. Find the total turbine work and the total heat transfer to the boiler for this process.

Solution:

C.V. Boiler tank. Heat transfer, no work and flow out.

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

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

State 1: Table B.1.1, 100 kPa => $v_1 = 0.001\ 043$, $u_1 = 417.36$ kJ/kg

=> $m_1 = V/v_1 = 0.1/0.001\ 043 = 95.877$ kg

State 2: Table B.1.1, 700 kPa => $v_2 = v_g = 0.2729$, $u_2 = 2572.5$ kJ/kg

=> $m_2 = V/v_g = 0.1/0.2729 = 0.366$ kg,

Exit state: Table B.1.1, 700 kPa => $h_e = 2763.5$ kJ/kg

From continuity eq.: $m_e = m_1 - m_2 = 95.511$ kg

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

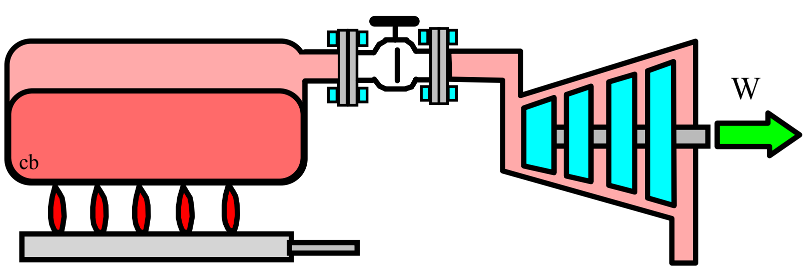
$= 0.366 \times 2572.5 - 95.877 \times 417.36 + 95.511 \times 2763.5$

$= 224\ 871$ kJ = **224.9 MJ**

C.V. Turbine, steady state, inlet state is boiler tank exit state.

Turbine exit state: Table B.1.1, 100 kPa => $h_e = 2675.5$ kJ/kg

$W_{turb} = m_e\ (h_{in} - h_{ex}) = 95.511 \times (2763.5 - 2675.5) =$ **8405 kJ**



6.132

An insulated spring-loaded piston/cylinder, shown in Fig. P6.132, is connected to an air line flowing air at 600 kPa, 700 K by a valve. Initially the cylinder is empty and the spring force is zero. The valve is then opened until the cylinder pressure reaches 300 kPa. By noting that $u_2 = u_{line} + C_V(T_2 - T_{line})$ and $h_{line} - u_{line} = RT_{line}$ find an expression for T_2 as a function of P_2, P_o, T_{line}. With P = 100 kPa, find T_2.

Solution:

C.V. Air in cylinder, insulated so $_1Q_2 = 0$

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

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

$$m_1 = 0 \;\Rightarrow\; m_{in} = m_2\;;\;\; m_2u_2 = m_2h_{line} - \frac{1}{2}(P_0 + P_2)m_2v_2$$

$$\Rightarrow \qquad u_2 + \frac{1}{2}(P_0 + P_2)v_2 = h_{line}$$

Use constant specific heat in the energy equation

$$C_V(T_2 - T_{line}) + u_{line} + \frac{1}{2}(P_0 + P_2)RT_2/P_2 = h_{line}$$

$$\boldsymbol{\left[C_V + \frac{1}{2}\frac{P_0 + P_2}{P_2}R\right]T_2 = (R + C_V)T_{line}}$$

with #'s: $T_2 = \dfrac{R + C_V}{\frac{2}{3}R + C_V}T_{line}\;;\quad C_V/R = 1/(k\text{-}1)\,,\quad k = 1.4$

$$T_2 = \frac{k - 1 + 1}{\frac{2}{3}k - \frac{2}{3} + 1}T_{line} = \frac{3k}{2k + 1}T_{line} = 1.105\ T_{line} = \mathbf{773.7\ K}$$

6.133

A mass-loaded piston/cylinder, shown in Fig. P6.133, containing air is at 300 kPa, 17°C with a volume of 0.25 m^3, while at the stops $V = 1\ m^3$. An air line, 500 kPa, 600 K, is connected by a valve that is then opened until a final inside pressure of 400 kPa is reached, at which point $T = 350$ K. Find the air mass that enters, the work, and heat transfer.

Solution:

C.V. Cylinder volume.

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

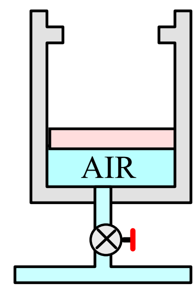
Energy Eq.6.16: $m_2u_2 - m_1u_1 = m_{in}h_{line} + Q_{CV} - {}_1W_2$

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

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

State 2:

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



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

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

Only work while constant P

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

Energy Eq.: $\quad Q_{CV} + m_ih_i = m_2u_2 - m_1u_1 + {}_1W_2$

$$Q_{CV} = 3.982 \times 0.717 \times 350 - 0.90 \times 0.717 \times 290.2 + 225$$
$$- 3.082 \times 1.004 \times 600 = \mathbf{-819.2\ kJ}$$

We could also have used the air tables A.7.1 for the u's and h_i.

6.134

A 2-m^3 storage tank contains 95% liquid and 5% vapor by volume of liquified natural gas (LNG) at 160 K, as shown in Fig. P6.65. It may be assumed that LNG has the same properties as pure methane. Heat is transferred to the tank and saturated vapor at 160 K flows into the a steady flow heater which it leaves at 300 K. The process continues until all the liquid in the storage tank is gone. Calculate the total amount of heat transfer to the tank and the total amount of heat transferred to the heater.

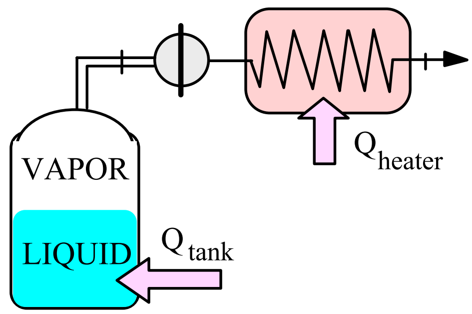
Solution:

CV: Tank, flow out, transient.

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

Energy Eq.:

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



At 160 K, from Table B.7:

$$m_f = V_f/v_f = \frac{0.95 \times 2}{0.00297} = 639.73 \text{ kg}, \quad m_g = V_g/v_g = \frac{0.05 \times 2}{0.03935} = 2.541 \text{ kg}$$

$m_1 = 642.271$ kg, $\quad m_2 = V/v_{g2} = 2/0.03935 = 50.826$ kg

$$m_1u_1 = 639.73(-106.35) + 2.541(207.7) = -67507 \text{ kJ}$$

$$m_e = m_1 - m_2 = 591.445 \text{ kg}$$

$$Q_{Tank} = 50.826 \times 207.7 - (-67\,507) + 591.445 \times 270.3$$

$$= \mathbf{+237\,931 \text{ kJ}}$$

CV: Heater, steady flow, $P = P_{G\ 160\ K} = 1593$ kPa

$$Q_{Heater} = m_{e\ Tank}(h_e - h_i)_{Heater}$$

$$= 591.445(612.9 - 270.3) = \mathbf{202\,629 \text{ kJ}}$$

Heat transfer problems

6.135

Liquid water at 80^{o}C flows with 0.2 kg/s inside a square duct, side 2 cm insulated with a 1 cm thick layer of foam k = 0.1 W/m K. If the outside foam surface is at 25^{o}C how much has the water temperature dropped for 10 m length of duct? Neglect the duct material and any corner effects (A = 4sL).

Solution:

Conduction heat transfer

$$\dot{Q}_{out} = kA \frac{dT}{dx} = k\ 4\ sL \frac{\Delta T}{\Delta x} = 0.1\times 4\times 0.02\times 10\times(80\text{-}25)/0.01 = 440\ \text{W}$$

Energy equation: $\dot{m}_1 h_1 = \dot{m} h_e + \dot{Q}_{out}$

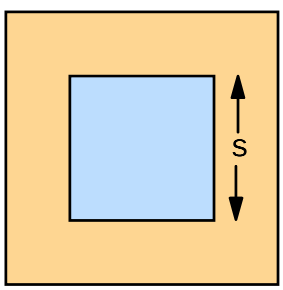
$h_e - h_i = -\dot{Q}/\dot{m} = -\ (440/0.2) = -2200$ J/kg $= -\ 2.2$ kJ/kg

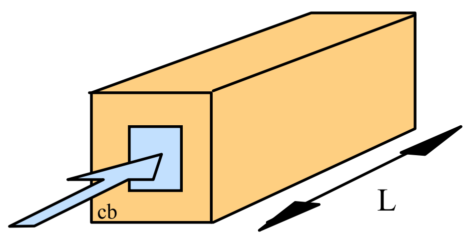
$h_e = h_i$ -2.2 kJ/kg = 334.88 – 2.2 = 332.68 kJ/kg

$$T_e = 80 - \frac{2.2}{334.88\text{-}313.91}\ 5 = 79.48^{o}\text{C}$$

$\Delta T = \mathbf{0.52^{o}C}$

We could also have used $h_e - h_i = C_p \Delta T$





6.136

A counter-flowing heat exchanger conserves energy by heating cold outside fresh air at 10°C with the outgoing combustion gas (air) at 100°C. Assume both flows are 1 kg/s and the temperature difference between the flows at any point is 50°C. What is the incoming fresh air temperature after the heat exchanger? What is the equivalent (single) convective heat transfer coefficient between the flows if the interface area is 2 m^2?

Solution:

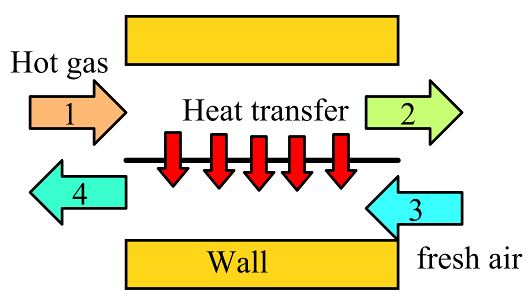
The outside fresh air is heated up to T_4 = 50°C (100 – 50), the heat transfer needed is

$$\dot{Q} = \dot{m}\Delta h = \dot{m}C_p\Delta T = 1 \text{ kg/s} \times 1.004 \frac{\text{kJ}}{\text{kg K}} \times (50 - 10) \text{ K} = 40 \text{ kW}$$

This heat transfer takes place with a temperature difference of 50°C throughout

$$\dot{Q} = h\, A\, \Delta T \quad \Rightarrow \quad h = \frac{\dot{Q}}{A\Delta T} = \frac{40\,000}{2 \times 50} \frac{\text{W}}{\text{m}^2 \text{ K}} = \mathbf{400} \; \mathbf{\frac{W}{m^2 K}}$$

Often the flows may be concentric as a smaller pipe inside a larger pipe.



6.137

Saturated liquid water at 1000 kPa flows at 2 kg/s inside a 10 cm outer diameter steel pipe and outside of the pipe is a flow of hot gases at 1000 K with a convection coefficient of h = 150 W/m^2 K. Neglect any ΔT in the steel and any inside convection h and find the length of pipe needed to bring the water to saturated vapor.

Solution:

Energy Eq. water: $\dot{Q} = \dot{m}\,(h_e - h_i) = \dot{m}\,h_{fg}$

Table B.1.2: h_{fg} = 2015.29 kJ/kg, $T = T_{sat}$ = 179.91^{o}C = 453.1 K

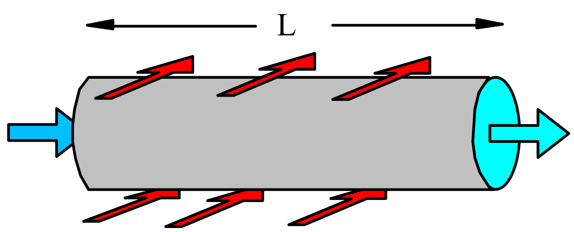
The energy is transferred by heat transfer so

$$\dot{Q} = h\,A\,\Delta T = h\,\pi D\,L\,\Delta T$$

Equate the two expressions for the heat transfer and solve for the length L

$$L = \frac{\dot{Q}}{h\,\pi D\,\Delta T} = \frac{\dot{m}h_{fg}}{h\,\pi D\,\Delta T} = \frac{2 \times 2015.29 \times 1000}{150 \times \pi \times 0.1 \times (1000 - 453.1)}$$

$= \mathbf{156.4\ m}$



6.138

A flow of 1000 K, 100 kPa air with 0.5 kg/s in a furnace flows over a steel plate of surface temperature 400 K. The flow is such that the convective heat transfer coefficient is h = 125 W/m^2 K. How much of a surface area does the air have to flow over to exit with a temperature of 800 K? How about 600 K?

Solution:

Convection heat transfer

$\dot{Q} = hA\ \Delta T$

Inlet: $\Delta T_i = 1000 - 400 = 600$ K

a)

Exit: $\Delta T_e = 800 - 400 = 400$ K,

so we can use an average of $\Delta T = 500$ K for heat transfer

$\dot{Q} = \dot{m}_a\ (h_i - h_e) = 0.5(1046.22 - 822.2) = 112$ kW

$$A = \frac{\dot{Q}}{h\ \Delta T} = \frac{112 \times 1000}{125 \times 500} = \mathbf{1.79\ m^2}$$

b)

$\dot{Q} = \dot{m}_a\ (h_i - h_e) = 0.5\ (1046.22 - 607.32) = 219.45$ kW

Exit: $\Delta T_{out} = 600 - 400 = 200$ K,

so we have an average of $\Delta T = 400$ K for heat transfer

$$A = \frac{\dot{Q}}{h\Delta T} = \frac{219.45 \times 1000}{125 \times 400} = \mathbf{4.39\ m^2}$$