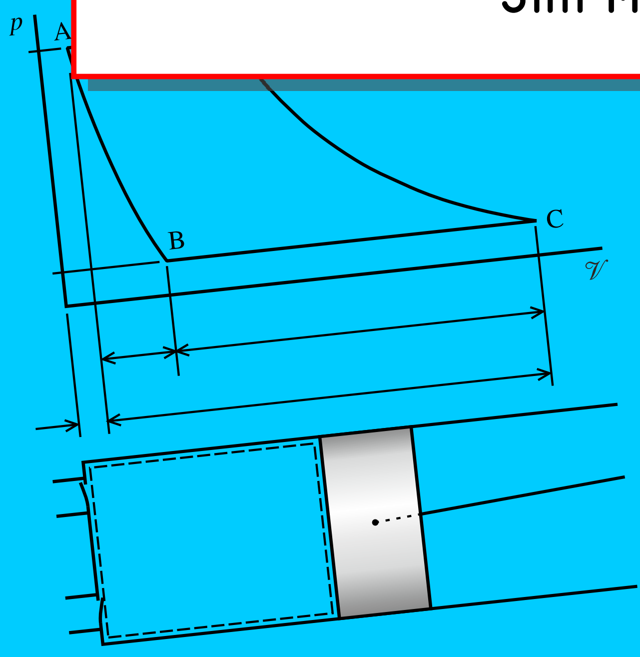
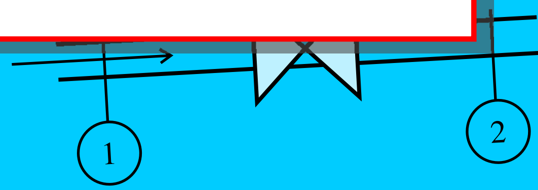
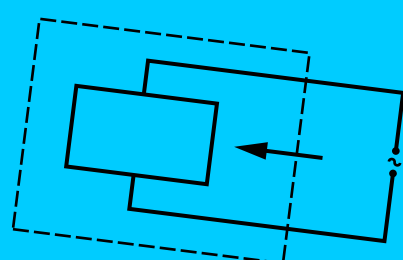
Applied Energy Systems — Rudimentary Thermodynamics

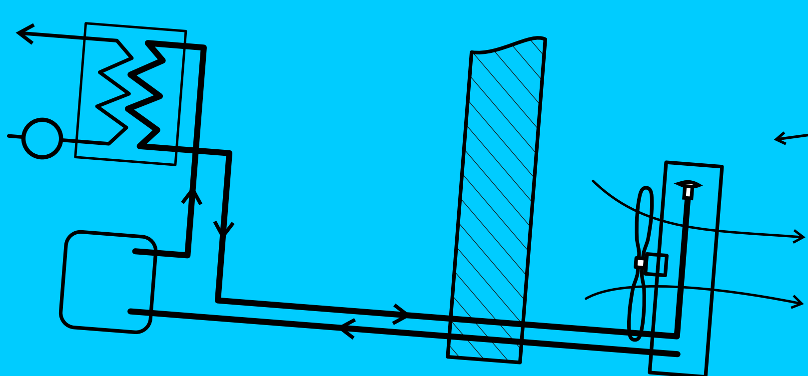
Solutions Manual

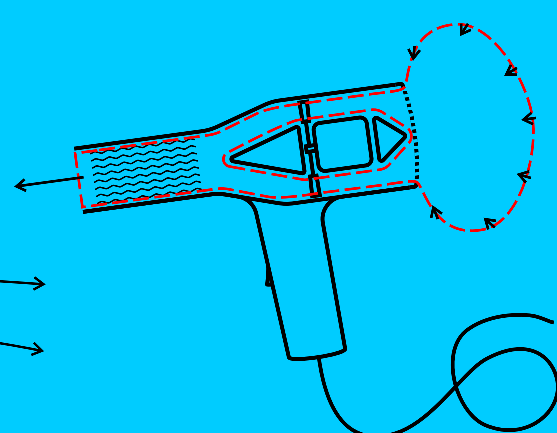
Jim McGovern











SI Units 2014 Edition

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Preface

This document contains complete worked solutions for all of the end-of-chapter problems in the associated textbook. Some instructors might wonder why these solutions have been made publicly available, rather than making them available to instructors only. Some learners may mistakenly assume that if they have read the solutions they will have acquired the ability to solve such problems. Nonetheless, for a textbook that is made freely available on a Creative Commons license, the author felt this was the best approach. There are caveats for instructors and for learners.

In general, it would not be appropriate for instructors to use the problems in an unmodified form for grading learners. However, they are free to modify and adapt them, as appropriate, to meet their assessment needs and to offer learners problems for which worked solutions are not available.

The caveat for learners is that they should resist any temptation to read the solutions before they have attempted the problems themselves. There are sufficient worked examples in the textbook itself for the purpose of studying how solutions can be set out. Learning must be an active process and the way to learn how to solve problems is to solve problems ourselves. Effective learners have tenacity and should manage to obtain answers themselves to all, or almost all, of the problems they attempt. Having worked through a problem and obtained a solution or answers, the learner can get confirmation of the correctness of their approach by referring to the solutions in this manual. This is effective learning.

Chapter 1 Quantities, Units and Dimensions

1-1 Indicate which of the following statements are true and which are false.

Solution

		Answ.	**Comment**
A	A know mass of a specified gas at a specified constant temperature and constant pressure within a container of a specified volume possesses internal energy.	True	Internal energy is a property that is possessed by the system consisting of the gas.
B	Kinetic energy and potential energy at the macroscopic level can be used directly to produce mechanical work.	True	
C	Heat and work are the same because they are both energy transfer.	False	They are not the same, because they are different modes of energy transfer.

		Answ.	Comment
D	All of the internal energy of a system or substance can be used directly to produce mechanical work.	False	It is not possible to use all of the internal energy, which is at the molecular level, to mechanical work at the macroscopic level.
E	Work is a manner or occurrence by which energy can leave an amount of substance.	True	
F	Ice has less heat than liquid water.	False	Heat is energy transfer, which is not a property that a substance can have.
G	1 kg of compressed air at ambient temperature has more work than 1 kg of air at ambient temperature and pressure.	False	Work is energy transfer, which is not a property that a substance can have.
H	Heat transfer is a manner or occurrence by which energy can enter a system.	True	

1-2 Match the physical quantities on the left with the base SI units on the right.

Solution

	Physical quantity		SI base units
A	power	10	W or $\mathrm{N\,m\,s^{-1}}$

B	volume per unit mass	1	$m^3 kg^{-1}$
C	angle	7	rad
D	energy per unit mass	5	$J kg^{-1}$
E	temperature (absolute)	2	K
F	volume	13	m^3
G	pressure	9	Pa or $N m^{-2}$
H	volume flow rate	6	$m^3 s^{-1}$
I	density	8	$kg m^{-3}$
J	mass flow rate	11	$kg s^{-1}$
K	mass	12	kg
L	amount of substance	4	mol
M	temperature (conventional)	3	°C

1-3 Match the symbols in the left column below with the numbers and units in the right column.

Solution

	Symbol		**Number and unit**
A	hPa or mbar	6	100 Pa
B	kPa	4	1000 Pa
C	MPa	2	1,000,000 Pa
D	bar	5	10^5 Pa
E	kJ	3	1000 J
F	MJ	7	1,000,000 J
G	L or litre	12	10^{-3} m^3
H	g or gram	8	10^{-3} kg

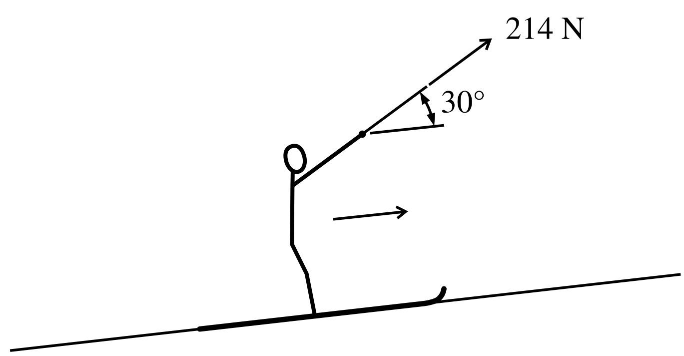
	Symbol		Number and unit
I	mL or millilitre or cc or cubic centimetre	1	10^{-6} m^3
J	MW	10	1,000,000 W
K	kW	11	1000 W
L	GW or gigawatt	9	10^9 W

1-4 Match the quantities in the left column below with dimensions in the right column.

Solution

	Quantity		Dimensions
A	pressure	3	$\mathrm{M\,L^{-1}\,T^{-2}}$
B	temperature	5	Θ
C	volume	2	$\mathrm{L^3}$
D	heat transfer	7	$\mathrm{M\,L^2\,T^{-2}}$
E	work per unit time	1	$\mathrm{M\,L^2\,T^{-3}}$
F	density	8	$\mathrm{M\,L^{-3}}$
G	acceleration	4	$\mathrm{L\,T^{-2}}$
H	force	6	$\mathrm{M\,L\,T^{-2}}$

1-5



A skier advances up a smooth incline due to a pulling force from a ski tow of 214 N that is at an angle of 30° to the slope, as shown in the diagram. The skier covers a distance of 150 m up the slope in 43 seconds. Calculate the work done on the skier by the ski tow and the rate at which the work is done.

Solution

$$W = F\,s\cos\theta$$

$$= 214\ [\text{N}]\ 150\ [\text{m}]\cos 30°$$

$$= 26.80 \times 10^3\ \text{J}$$

$$= 26.8\ \text{kJ}$$

$$\dot{W} = \frac{W}{t} = \frac{26.80 \times 10^3 [\text{J}]}{43\ [\text{s}]}$$

$$= 0.623 \times 10^3\ \text{W}$$

$$623\ \text{W}$$

1-6 A mass of 2.3 kg is raised through a height of 3.7 m in the Earth's gravitational field and its original velocity of 1.2 m/s is increased by 1.6 m/s. By how much does the energy of the mass increase?

Solution

$$\Delta E_\text{p} = mgh$$

$$= 2.3\ [\text{kg}]\ 9.81\ \left[\text{m/s}^2\right]\ 3.7\ [\text{m}]$$

$$= 83.45\ \text{J}$$

$$V_2 = V_1 + \Delta V = (1.2 + 1.6)\ [\text{m s}^{-1}] = 2.8\ \text{m s}^{-1}$$

$$\Delta E_\text{k} = \frac{mV_2^2}{2} - \frac{mV_1^2}{2}$$

$$= \frac{m\left(V_2^2 - V_1^2\right)}{2}$$

$$= \frac{2.3\ [\text{kg}] \left(2.8^2 - 1.2^2\right) [\text{m}^2/\text{s}^2]}{2}$$

$$= 7.36\ \text{J}$$

$$\Delta E = (83.48 + 7.36)\ [\text{J}]$$

$$= 90.8\ \text{J}$$

1-7 A boulder with a mass of 251 kg has fallen off a cliff. It has a velocity of 15 m/s and is at a height of 60 m from the ground below. Evaluate its kinetic energy and its potential energy. What is the maximum of kinetic plus potential energy that the rock could have when it hits the ground? Explain your answer.

Solution

$$E_\text{p} = mgz$$

$$= 251\ [\text{kg}]\ 9.81 \left[\frac{\text{m}}{\text{s}^2}\right] 60\ [\text{m}]$$

$$= 147{,}739\ \text{J} = 147.7\ \text{kJ}$$

$$E_\text{k} = \frac{m\,V^2}{2}$$

$$= \frac{251\,[\text{kg}]\ \ 15^2 \left[\frac{\text{m}^2}{\text{s}^2}\right]}{2}$$

$$= 28{,}238\ \text{J} = 28.2\ \text{kJ}$$

$$E_\text{tot} = (147.7 + 28.2)\ \text{kJ} = 176\ \text{kJ}$$

1-8 Is there heat transfer between Venus and Earth and if so what is its direction? As a (big) simplification assume that Venus, which is 30% nearer the Sun than the Earth, has a higher effective temperature for radiation exchange than the Earth.

Solution

Radiation can occur between Venus and the Earth as the two planets normally have a line of sight through the vacuum of space. As net heat transfer by radiation occurs from the higher to the lower temperature, its direction is from Venus to Earth.

1-9 A cuckoo clock is powered by an elevated mass of 0.32 kg that descends 1.60 m in 24 hours. Calculate the average power provided to the clock in microwatts.

Solution

Calculate the work done by the descending mass.

$$W = mgh$$

$$0.32\ [\text{kg}] \times 9.81 \left[\frac{\text{m}}{\text{s}^2}\right] \times 1.6\ [\text{m}]$$

$$= 5.023\ \text{J}$$

Express the time in seconds

$$t = 24 \times 60 \times 60\ [\text{s}] = 86{,}400\ \text{s}$$

Evaluate the average power

$$\dot{W} = \frac{W}{t} = \frac{5.023\ [\text{J}]}{86{,}400\ [\text{s}]} = 58.13 \times 10^{-6}\ \text{W} = 58.13\ \mu\text{W}$$

Chapter 2 Properties of Substances

2-1 Express 56 °C, 431.6 °C and −186.2 °C in absolute units.

Solution

$$56\ [°C] + 273.15\ [K] = 329.15\ K$$
$$431.6\ [°C] + 273.15\ [K] = 704.75\ K$$
$$-186.2\ [°C] + 273.15\ [K] = 86.95\ K$$

2-2 Match the physical quantities on the left with the base SI units on the right.

Solution

	Physical Quantity		**Base Unit**
A	pressure	3	Pa
B	molar mass	1	$kg\,mol^{-1}$
C	absolute temperature	7	Kelvin
D	specific heat	8	$J\,kg^{-1}\,K^{-1}$
E	density	11	$kg\,m^{-3}$
F	conventional temperature	9	°C
G	universal or molar gas constant	2	$J\,mol^{-1}\,K^{-1}$
H	rate of heat transfer	6	W
I	work	4	J
J	specific volume	10	$m^3\,kg^{-1}$
K	amount of substance	12	mole
L	specific energy	5	$J\,kg^{-1}$

2-3 If the atmospheric pressure is 1010 hPa and the pressure in a tyre is 240 kPa gauge what is the absolute pressure in the tyre?

Solution

$$p_{\text{tyre}} = p_{\text{atm}} + p_{\text{tyre, gauge}}$$

$$= 1010 \times 100\ [\text{Pa}] + 240 \times 10^3\ [\text{Pa}]$$

$$= (101{,}000 + 240{,}000)\ \text{Pa}$$

$$= 341{,}000\ \text{Pa absolute}$$

$$= 341\ \text{kPa absolute}$$

2-4 An iron casting with a mass of 29.1 kg and at 156 °C is cooled to 18.2 °C by immersion in a tank that contains 1.62 m^3 of water. If the specific heat of the iron is 0.448 kJ/kg K, calculate the energy loss from the casting. Also, assuming that all of the energy lost by the iron is gained by the water, calculate the increase in temperature of the water. Take the specific volume of water as 0.001 m^3/kg and take its specific heat as 4.18 kJ/kgK.

Solution

Calculate the energy loss from the casting

$$E_{\text{loss}} = -\Delta U = -m\Delta u = mc_{\text{iron}}(T_1 - T_2)$$

$$= 29.1\ [\text{kg}] \times 0.448\ [\text{kJ/kg K}] \times (156 - 18.2)\ [\text{K}]$$

$$= 1796\ \text{kJ}$$

The energy gained by the water equals the energy lost by the casting. Hence,

$$E_{\text{gain}} = \Delta U_{\text{water}} = m_{\text{water}}\, c_{\text{water}}\, \Delta T_{\text{water}} = E_{\text{loss}}$$

$$\Delta T_{\text{water}} = \frac{E_{\text{loss}}}{m_{\text{water}}\, c_{\text{water}}}$$

$$= \frac{1796\ [\text{kJ}]}{\dfrac{1.62\ [\text{m}^3]}{0.001\ [\text{m}^3/\text{kg}]} \times 4.18\ [\text{kJ/kgK}]} = 0.265\ \text{K}$$

2-5 What is the mass of hydrogen in a balloon that has a volume of 90 m^3 if the pressure is 0.0989 MPa absolute and the temperature is 14 °C? What would be the mass if air were to replace the hydrogen?

Solution

$$p\mathscr{V} = mRT$$

$$p = 0.0989 \times 10^6\ \text{Pa}$$

$$\mathscr{V} = 90\ \text{m}^3$$

$$T_1 = (14 + 273.15)\ \text{K} = 287.15\ \text{K}$$

$$R_{\text{H}_2} = 4.124 \times 10^3\ \frac{\text{J}}{\text{kgK}}$$

$$= 4124\ \frac{\text{J}}{\text{kgK}}$$

$$m_{\text{H}_2} = \frac{p\mathscr{V}}{RT}$$

$$= \frac{0.0989 \times 10^6\ [\text{Pa}]\ 90\ [\text{m}^3]}{4124\ \left[\frac{\text{J}}{\text{kgK}}\right]\ 287.15\ [\text{K}]}$$

$$= 7.516\ \text{kg}$$

If the balloon is filled with air instead

$$R_{\text{air}} = 0.2871 \times 10^3\ \frac{\text{J}}{\text{kgK}}$$

$$= 287.1\ \frac{\text{J}}{\text{kgK}}$$

$$m_{\text{air}} = \frac{p\mathscr{V}}{RT}$$

$$= \frac{0.0989 \times 10^6 \text{ [Pa] } 90 \text{ [m}^3\text{]}}{287.1 \left[\frac{\text{J}}{\text{kgK}}\right] 287.15 \text{ [K]}}$$

$$= 108.0 \text{ kg}$$

2-6 Find the mass of carbon dioxide in a container of volume 1.2×10^{-3} m^3 if the pressure is 730 kPa and the temperature is -5 °C.

Solution

$$p\mathcal{V} = mRT$$

$$R_{CO_2} = 0.1889 \text{ kJ/kgK}$$

$$m = \frac{p\mathcal{V}}{R_{CO_2}T}$$

$$= \frac{730 \times 10^3 \left[\text{Nm}^{-2}\right] \times 1.2 \times 10^{-3} \left[\text{m}^3\right]}{0.1889 \times 10^3 \text{ [J/kgK] } \times (-5 + 273.15)\text{[K]}}$$

$$= 0.0173 \text{ kg}$$

2-7 A fixed mass of an ideal gas has a volume of 5.2 m^3 at a pressure of 1 bar absolute. What volume will it have at the same temperature if the pressure is increased to 4 bar absolute?

Solution

$$\frac{p_1\mathcal{V}_1}{T_1} = \frac{p_2\mathcal{V}_2}{T_2}$$

and

$$T_1 = T_2$$

Hence,

$$p_1\mathcal{V}_1 = p_2\mathcal{V}_2$$

and

$$\mathcal{V}_2 = \mathcal{V}_1\frac{p_1}{p_2}$$

$$= 5.2\ \left[\text{m}^3\right] \times \frac{1\,[\text{bar}]}{4\,[\text{bar}]}$$

$$\mathscr{V} = 1.30\ \text{m}^3$$

2-8 A container of volume 4.2 m^3 holds an unknown gas at a pressure of 1.4 MPa absolute and a temperature of 135 °C. If the mass of the gas is 69 kg, what is its specific gas constant?

Solution

$$p\mathscr{V} = \text{m}RT$$

$$R = \frac{p\mathscr{V}}{mT}$$

$$= \frac{1.4 \times 10^6\ \left[\text{Nm}^{-2}\right] \times 4.2\ \left[\text{m}^3\right]}{69\ [\text{kg}] \times (135 + 273.15)\ [\text{K}]}$$

$$= 208.8\ \text{J/kgK}$$

2-9 A container holds a mixture of 2.3 kg of nitrogen gas and 2.7 kg of carbon dioxide gas. Determine the amount of substance of each gas present in kmol and in mol. Hence, briefly discuss the question ‘is there more nitrogen or carbon dioxide in the container?’

Solution

From Table A-3, the molar masses of nitrogen and carbon dioxide are

$$\overline{m}_{\text{N}_2} = 28.01\ \frac{\text{kg}}{\text{kmol}}$$

$$\overline{m}_{\text{CO}_2} = 44.01\ \frac{\text{kg}}{\text{kmol}}$$

Hence,

$$n_{\text{N}_2} = \frac{m}{\overline{m}} = \frac{2.3\ [\text{kg}]}{28.01\ [\text{kg}\,\text{kmol}^{-1}]}$$

$$= 0.0821\ \text{kmol} = 82.1\ \text{mol}$$

$$n_{CO_2} = \frac{m}{\overline{m}} = \frac{2.7\ [\text{kg}]}{44.01\ [\text{kg kmol}^{-1}]}$$
$$= 0.0613\ \text{kmol} = 61.3\ \text{mol}$$

By amount of substance there is more nitrogen than carbon dioxide in the container, while by mass there is more carbon dioxide than nitrogen. Hence in such a case the word ‘more’ could be ambiguous unless the basis of comparison is specified.

2-10 In a vehicle repair garage compressed air is stored in a pressure vessel called an air receiver at a pressure of 700 kPa gauge. The compressed air is used for inflating tyres and for operating pneumatic tools. Briefly describe four ways in which the compressed air within or coming from this vessel could cause failure, damage or personal injury.

Solution

If air is charged into the receiver at too high a pressure the vessel could rupture. If air is released from the receiver suddenly through a valve it could cause physical damage or injury to personnel. If the vessel is heated to a high temperature the pressure within it could rise to a dangerous level; this could arise if the garage went on fire. If an air hose coming from the receiver were to rupture, air at high pressure would escape and this could cause physical damage or personal injury.

Chapter 3 Non-flow Processes

3-1 Given that for a polytropic process

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}}$$

calculate the final temperature of a gas if it is compressed from atmospheric pressure of 1013 hPa and a temperature of 25 °C to 0.3 MPa gauge with a polytropic index of 1.6.

Solution

$$p_1 = 0.1013 \text{ MPa}$$

$$p_2 = (0.33 + 0.1013) \text{ [MPa]} = 0.4013 \text{ MPa}$$

$$T_1 = (25 + 273.15)\text{[K]} = 298.15 \text{ K}$$

$$T_2 = 298.15 \text{ [K]} \left(\frac{0.4013}{0.1013} \right)^{\frac{1.6-1}{1.6}}$$

$$= 499.6 \text{ K}$$

3-2 A 15 kg mass of carbon dioxide gas ($R = 188.9$ J/kg K) is compressed from 200 kPa gauge and 20 °C to 20% of its original volume and 1700 kPa gauge. It is then cooled back to 20 °C at constant volume. Take atmospheric pressure as 100 kPa. Determine:

a) the temperature after compression.

b) the pressure drop due to the cooling.

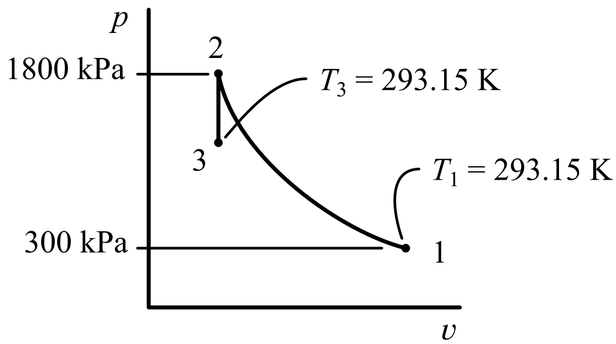
c) the final specific volume of the gas.

Solution

Atmospheric pressure is 100 kPa. Hence,

$$p_1 = 300 \text{ kPa}$$

$$p_2 = 1800 \text{ kPa}$$



a)

$$\frac{v_2}{v_1} = 0.2$$

$$T_1 = T_3 = 293.15 \text{ K}$$

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

Hence

$$T_2 = T_1 \frac{p_2 v_2}{p_1 v_1}$$

$$= 293.15 \text{ [K]} \ \frac{1800}{300} \times 0.2 = 351.78 \text{ K}$$

This temperature can be expressed in Celsius units as

$$t_2 = (351.78 - 273.15) \text{ °C} = 78.63 \text{ °C}$$

b)

$$\frac{p_3 v_3}{T_3} = \frac{p_2 v_2}{T_2} \text{ and } v_3 = v_2$$

Hence

$$\frac{p_3}{T_3} = \frac{p_2}{T_2}$$

Therefore

$$p_3 = p_2 \frac{T_3}{T_2}$$

$$p_3 = 1800\ [\text{kPa}]\ \frac{293.15}{351.78}$$

$$= 1500\ \text{kPa}$$

The pressure drop due to the cooling is therefore

$$\Delta p = p_2 - p_3 = (1800 - 1500)\ [\text{kPa}] = 300\ \text{kPa}$$

c)

$$pv = RT$$

Hence

$$v_3 = \frac{RT_3}{p_3}$$

$$= \frac{188.9\ \left[\frac{\text{J}}{\text{kg K}}\right] \times 293.15\ [\text{K}]}{1.5 \times 10^6\ \left[\frac{\text{N}}{\text{m}^2}\right]}$$

$$= 0.0369\ \frac{\text{m}^3}{\text{kg}}$$

3-3 Dry air within a closed system is compressed from a temperature of 300 K and a pressure of 0.100 MPa to one tenth of its original volume. Assuming the process is polytropic, calculate the final temperature of the air if the polytropic exponent is (a) 1.2 and (b) 1.4. The following equation can be used:

$$\frac{T_2}{T_1} = \left(\frac{\mathscr{V}_1}{\mathscr{V}_2}\right)^{n-1}.$$

Solution

$$T_2 = T_1 \left(\frac{\mathscr{V}_1}{\mathscr{V}_2} \right)^{n-1}$$

$$= 300 \text{ [K] } 10^{n-1}$$

With $n = 1.2$

$$T_2 = 300 \times 10^{0.2} \text{ [K]} = 475.5 \text{ K}$$

With $n = 1.4$

$$T_2 = 300 \times 10^{0.4} \text{ [K]} = 753.6 \text{ K}$$

3-4 Sketch the following processes on diagrams of pressure versus specific volume for a closed system containing an ideal gas. In each case indicate the directions of the processes by means of arrowheads.

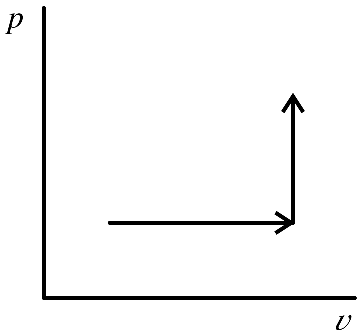
(i) Constant pressure with volume increase followed by constant volume with pressure increase

(ii) Polytropic compression followed by constant volume heat addition, followed by polytropic expansion, followed by constant volume heat rejection thereby arriving at the original state

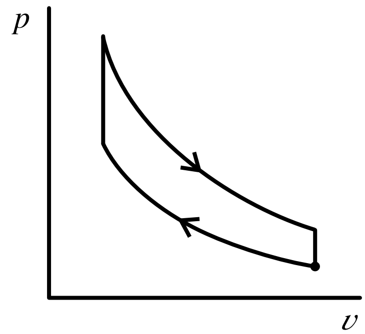
(iii) Isothermal and adiabatic processes, both ending at the same pressure and specific volume and both involving the same reduction in specific volume

(iv) Constant pressure with cooling followed by constant volume with heating followed by polytropic expansion

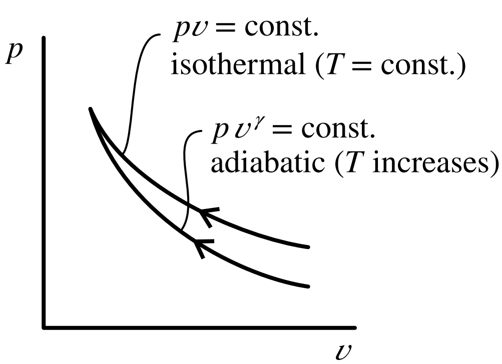
Solution



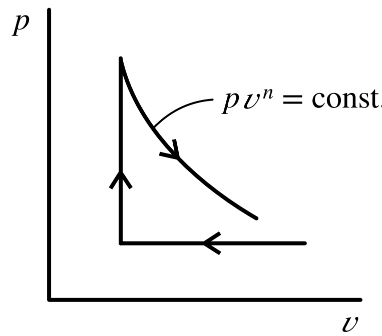
(i)



(ii)



(iii)



(iv)

3-5 Calculate the increase in the enthalpy and the increase in the specific enthalpy of 3.2 kg of air when it is brought from 0.11 MPa and 18 °C to 0.17 MPa and 43.5 °C

Solution

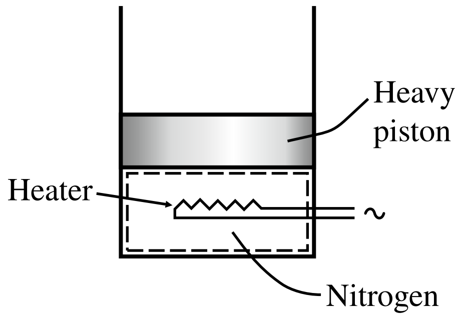
$$\Delta H = m\, c_p\, (T_2 - T_1)$$

$$= 3.22\ [\text{kg}] \times 1.0042 \left[\frac{\text{kJ}}{\text{kg K}}\right] \times (43.5 - 18)\ [\text{K}] = 81.9\ \text{kJ}$$

$$\Delta h = c_p\, (T_2 - T_1)$$

$$= 1.0042 \left[\frac{\text{kJ}}{\text{kg K}}\right] \times (43.5 - 18)\ [\text{K}] = 18.3\ \text{kJ/kg}$$

3-6



The volume occupied by 0.1 kg of nitrogen in the system shown above is to be increased by 25% through the use of an electric heater. The gas system is assumed to be perfectly insulated and the piston is assumed to be leak tight and frictionless. The initial temperature of the gas is 17 °C and the pressure is 0.121 MPa absolute. What amount of work is done on the piston? What energy input must be supplied to the electric heater? The following equations can be used:

$$p\mathscr{V} = mRT$$

$$W_{\text{out, displ,}1\to 2}\Big|_{p\,=\,\text{const}} = p(\mathscr{V}_2 - \mathscr{V}_1)$$

$$W_{\text{in, elec,}1\to 2} = m(u_2 - u_1) + p(\mathscr{V}_2 - \mathscr{V}_1)$$

$$= m(h_2 - h_1) = mc_p(T_2 - T_1).$$

Solution

From Table D-1 for nitrogen

$$R = 0.2968\ \frac{\text{kJ}}{\text{kg K}}$$

$$c_p = 1.0395\ \frac{\text{kJ}}{\text{kg K}}$$

Calculate the initial volume

$$\mathscr{V}_1 = \frac{mRT_1}{p_1} = \frac{0.1\,[\text{kg}]\ 296.8\left[\frac{\text{J}}{\text{kgK}}\right] 290.15\ [\text{K}]}{121 \times 10^3\,[\text{Pa}]}$$

$$= 71.17 \times 10^{-3}\ \text{m}^3$$

Calculate the displacement work

$$\mathscr{V}_2 - \mathscr{V}_1 = 0.25\ \mathscr{V}_1$$

Hence

$$W_{\text{out, displ},1\rightarrow 2}\Big|_{p\,=\,\text{const}} = 121 \times 10^3\,[\text{Pa}] \times 0.25 \times 71.17 \times 10^{-3}\ \left[\text{m}^3\right]$$

$$= 2153\ \text{J}$$

Find the final temperature

$$\frac{\mathscr{V}_1}{T_1} = \frac{\mathscr{V}_2}{T_2}$$

Hence

$$T_2 = T_1 \frac{\mathscr{V}_2}{\mathscr{V}_1} = 290.15[\text{K}] \times 1.25 = 362.69\ \text{K}$$

Now find the energy input as electric energy to the heater

$$W_{\text{in, elec}} = mc_p\,(T_2 - T_1)$$

$$= 0.1\,[\text{kg}] \times 1039.5\left[\frac{\text{J}}{\text{kgK}}\right] \times (362.69 - 290.15)\ [\text{K}]$$

$$= 7540\ \text{J}$$

Chapter 4 The Reciprocating Compressor

4-1 Within the cylinder of a reciprocating air compressor 1.26 L of air at a pressure of 0.135 MPa gauge is compressed to a volume of 0.17 L, at which point the pressure is measured as 3.0 MPa gauge. Atmospheric pressure is 0.1020 MPa. If the temperature of the air is 18 °C at the first state, what is it at the second state?

Solution

$$p_1 = (0.135 + 0.1020)\ \text{MPa abs.} = 0.237\ \text{MPa abs.}$$

$$p_2 = (3.0 + 0.1020)\ \text{MPa abs.} = 3.102\ \text{MPa abs.}$$

$$\mathscr{V}_1 = 1.26\ \text{L}$$

$$V_2 = 0.17\ \text{L}$$

$$T_1 = (18 + 273.15)\ \text{K} = 291.15\ \text{K}$$

$$\frac{p_1 \mathscr{V}_1}{T_1} = \frac{p_2 \mathscr{V}_2}{T_2}$$

$$T_2 = T_1 \frac{p_2 \mathscr{V}_2}{p_1 \mathscr{V}_1}$$

$$= 291.15\ [\text{K}]\ \frac{3.102}{0.237} \times \frac{0.17}{1.26}$$

$$= 514.19\ \text{K}$$

$$t_2 = (514.19 - 273.15)\ °\text{C} = 241.04\ °\text{C}$$

This can be rounded to 241 °C.

4-2 An ideal reciprocating compressor has a bore of 75 mm and a stroke of 70 mm and operates at 1450 cycles per minute. Air is taken in at 17 °C and 0.1 MPa and discharged at 0.9 MPa. The clearance ratio is 2% and the polytropic exponent is 1.35.

Determine the average volume flow rate of air in the inlet pipe in L/min. The formulae below are provided.

$$E_{\text{vol, ideal}} = 1 - r_{\text{cl}}\left[\left(\frac{p_2}{p_1}\right)^{1/n} - 1\right]$$

$$r_{\text{cl}} = \frac{\mathscr{V}_{\text{cl}}}{\mathscr{V}_{\text{sw}}}$$

Solution

Calculate the swept volume rate.

$$\dot{\mathscr{V}}_{\text{sw}} = \left(\pi\frac{0.075^2}{4}\right)\left[\text{m}^2\right] \times 0.07[\text{m}] \times 1450\ \left[\text{min}^{-1}\right]$$

$$= 448.4 \times 10^{-3}\ \left[\frac{\text{m}^3}{\text{min}}\right] = 448.4\ \frac{\text{L}}{\text{min}}$$

Calculate the volumetric efficieny.

$$E_{\text{vol, ideal}} = 1 - r_{\text{cl}}\left[\left(\frac{p_2}{p_1}\right)^{1/n} - 1\right]$$

$$= 1 - 0.02\left[(9)^{1/1.35} - 1\right] = 0.9182$$

$$= 94.6\%$$

Hence, calculate the volume flow rate in the inlet pipe.

$$\dot{\mathscr{V}}_{\text{sw}} = 0.946 \times 448.4\left[\frac{\text{L}}{\text{min}}\right] = 424\ \frac{\text{L}}{\text{min}}$$

4-3 If a compressor takes in oxygen at 101.3 kPa absolute and 11 °C at the rate of 92.6×10^{-3} m^3/s, determine the intake mass flow rate in kg/s.

Solution

$$T = (11 + 273.15)\ \text{K} = 284.15\ \text{K}$$

$$p = 101.3 \times 10^3\ \text{Nm}^{-2}$$

From table D-1, the specific gas constant for oxygen is

$$R = 259.8 \text{ J/kgK}$$

The specific volume is given by

$$v = \frac{RT}{p} = \frac{259.8 \left[\frac{\text{J}}{\text{kgK}}\right] \times 284.15 \text{ [K]}}{101.3 \times 10^3 \left[\frac{\text{N}}{\text{m}^2}\right]}$$

$$= 728.7 \times 10^{-3} \ \frac{\text{m}^3}{\text{kg}}$$

The mass flow rate is given by

$$\dot{m} = \frac{\dot{\mathscr{V}}}{v} = \frac{92.6 \times 10^{-3} \left[\frac{\text{m}^3}{\text{s}}\right]}{728.7 \times 10^{-3} \left[\frac{\text{m}^3}{\text{kg}}\right]}$$

$$= 132 \times 10^{-3} \ \frac{\text{kg}}{\text{s}}$$

4-4 Nitrogen at a pressure of 0.11 MPa and a temperature of 12 °C is to be compressed to 2 MPa in an ideal compressor for which the polytropic index is 1.29. Determine the final temperature of the air (a) if it is compressed in a single stage and (b) if it is compressed to 0.47 MPa, cooled to 30 °C and then compressed to 2 MPa in a second stage.

Solution

For direct compression from 0.11 MPa to 2 MPa

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}}$$

$$= 285.15 \text{ [K]} \left(\frac{2.0}{0.11} \right)^{\frac{1.29-1}{1.29}}$$

$$= 547.33 \text{ K}$$

$$t_2 = (547.33 - 273.15) \text{ [°C]} = 274 \text{ °C}$$

For the second stage of compression from the intermediate pressure 0.11 MPa

$$T_{2'} = 303.15\ [\text{K}] \left(\frac{2.0}{0.47} \right)^{\frac{1.29-1}{1.29}}$$

$$= 419.80\ \text{K}$$

$$t_{2'} = (419.80\ - 273.15)\ [°\text{C}] = 147\ °\text{C}$$

Chapter 5 The Steady Flow Energy Equation

5-1 $\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) + \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$

With regard to the equation above, match the correct meaning and the correct base SI units to each symbol in the table below.

Solution

Symb.		Meaning		Base Units
$\dot{m}$	B	flow rate	3	kg s^{-1}
h	C	specific enthalpy	1	J kg^{-1}
V	E	velocity	6	ms^{-1}
g	F	acceleration due to gravity	2	ms^{-2}
$\dot{Q}$	D	net heat transfer rate	5	W
z	A	elevation	4	m

5-2 Water enters a boiler at ground level at a rate of 4.6 kg/s, with a velocity of 3.7 m/s and with a specific enthalpy of 81.5 kJ/kg. Steam leaves the boiler at the same mass flow rate with a specific enthalpy of 2571 kJ/kg. The elevation of the outlet is 20 m above ground level and the exit velocity is 9.2 m/s. Calculate the rate of heat transfer to the water substance in the boiler. Comment on the significance of the kinetic and potential energy terms in this case.

Solution

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) + \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

$$\dot{W}_{\text{in}} = 0$$

$$3.7\left[\frac{\text{kg}}{\text{s}}\right]\left(81.5\times10^3+\frac{3.7^2}{2}+0\right)\left[\frac{\text{J}}{\text{kg}}\right]+\dot{Q}_{\text{in}}$$

$$=3.7\left[\frac{\text{kg}}{\text{s}}\right]\left(2571\times10^3+\frac{9.2^2}{2}+9.81\times20\right)\left[\frac{\text{J}}{\text{kg}}\right]$$

Hence,

$$\begin{aligned}\dot{Q}_{\text{in}} &= 3.7\,(2{,}571{,}000 + 42.32 + 196.2 - 81{,}500 - 6.85)\ [\text{W}]\\ &= 9{,}212{,}007\ \text{W}\\ &= 9212\ \text{kW or } 9.21\ \text{MW}\end{aligned}$$

It can be seen that the kinetic and potential energy terms are negligible in comparison to enthalpy terms.

5-3 Water passes through a steady-flow electric water heater at the rate of 2.16 L/min and its temperature increases from 18 °C to 55 °C. The average specific heat of the water is 4.2 kJ/kgK and the average specific volume is 0.001007 m^3/kg. Calculate the electric power input to the heater and state any assumptions made.

Solution

Assume no energy loss from the heater to the surroundings.

$$\dot{W}_{\text{in, elec}} = \dot{m}(h_2 - h_1) = \dot{m}c_p(t_2 - t_1)$$

$$= \frac{\dot{\mathscr{V}}}{v}\,c_p(t_2 - t_1)$$

$$= \frac{2.16\times10^3\left[\frac{\text{m}^3}{\text{min}}\right]\times\frac{1}{60}\left[\frac{\text{min}}{\text{sec}}\right]}{0.001007\left[\frac{\text{m}^3}{\text{kg}}\right]}\times4.2\left[\frac{\text{kJ}}{\text{kgK}}\right](55-18)\ [\text{K}]$$

5.56 kW

5-4 Water enters a pressure washer machine with negligible velocity at atmospheric pressure and 14.5 °C. It exits from a nozzle with a velocity of 81 m/s at atmospheric pressure and at a temperature of 14.8 °C. The mass flow rate of the water is 0.106 kg/s. Estimate the electric power consumption of the machine on the assumption that all electric energy supplied to the machine is transferred to the water. If the machine were to be fitted with a heater to raise the temperature of the water to 45 °C, how much additional electric power would be required? Take the specific heat of water as 4.2 kJ/kgK.

Solution

Start with the steady flow equation.

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) + \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

There is no heat transfer and the inlet kinetic energy is negligible. Changes in potential energy are also negligible. Hence,

$$\dot{m}h_1 + \dot{W}_{\text{in, elec}} = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right)$$

$$\dot{W}_{\text{in, elec}} = \dot{m}\left(c_p(t_2 - t_2) + \frac{V_2^2}{2}\right)$$

$$= 0.106\ \left[\frac{\text{kg}}{\text{s}}\right]\left\{\begin{matrix} 4.2\left[\frac{\text{kJ}}{\text{kgK}}\right](14.8 - 14.5)\,[\text{K}] \\ + \frac{81^2}{2}\left[\frac{\text{J}}{\text{kg}}\right] \times 10^{-3}\left[\frac{\text{kJ}}{\text{J}}\right] \end{matrix}\right\}$$

$$= 0.106\ \left[\frac{\text{kg}}{\text{s}}\right]\left\{1.260\left[\frac{\text{kJ}}{\text{kg}}\right] + 3.281\left[\frac{\text{kJ}}{\text{kg}}\right]\right\}$$

$$= 0.481\ \text{kW}$$

With the higher water outlet temperature the same equation as above can be used.

$$\dot{W}_{\text{in, elec}} = 0.106 \left[\frac{\text{kg}}{\text{s}}\right] \left\{4.2 \left[\frac{\text{kJ}}{\text{kg K}}\right] (45 - 14.5)[\text{K}] + 3.281 \left[\frac{\text{kJ}}{\text{kg}}\right]\right\}$$

$$= 0.106 \left[\frac{\text{kg}}{\text{s}}\right] \left\{128.1 \left[\frac{\text{kJ}}{\text{kg}}\right] + 3.281 \left[\frac{\text{kJ}}{\text{kg}}\right]\right\}$$

$$= 13.9 \text{ kW}$$

It can be seen that the extra power required is given by

$$\dot{W}_{\text{in, elec}} = \dot{m}c_p\left(t_{2,\text{ heater}} - t_2\right)$$

$$= 0.106 \left[\frac{\text{kg}}{\text{s}}\right] 4.2 \left[\frac{\text{kJ}}{\text{kg K}}\right] (45 - 14.8)\,[\text{K}]$$

$$= 13.4 \text{ kW}$$

Chapter 6 Properties of Water Substance

6-1 Match the physical quantities on the left with the SI units on the right.

Solution

A	entropy	5	$\mathrm{kJ\,K^{-1}}$
B	specific entropy (also specific heat capacity, specific gas constant)	6	$\mathrm{kJ\,kg^{-1}K^{-1}}$
C	specific volume	9	$\mathrm{m^3kg^{-1}}$
D	pressure	7	MPa
E	conventional temperature	1	°C
F	dryness fraction	2	no units
G	enthalpy, internal energy	8	J
H	specific enthalpy, specific internal energy	4	$\mathrm{kJ\,kg^{-1}}$
I	absolute temperature, temperature difference	3	K

6-2 (a) Find the specific volume of dry saturated steam at 700 kPa absolute.

(b) Find the specific internal energy of saturated liquid water at 190 °C.

(c) Find the specific enthalpy of dry saturated steam at 165 °C.

(d) Find the specific entropy of saturated liquid water at 1 MPa absolute.

(e) What is the saturation temperature of steam at 20 bar?

(f) What is the saturation pressure of water substance at 190 °C?

Solution

(a) 0.2728 m^3/kg

(b) 806.1 kJ/kg

(c) 2762.7 kJ/kg

(d) 2.138 kJ/kgK

(e) 212.4 °C

(f) 1.255 MPa

6-3 Calculate the specific enthalpy of saturated water and steam at 1 MPa if the dryness fraction is 82%.

Solution

$$h_{\mathrm{f}} = 762.7 \frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$h_{\mathrm{fg}} = 2014.4 \text{ kJ/kg}$$

$$h = h_{\mathrm{f}} + x h_{\mathrm{fg}}$$

$$= (762.7 + 0.82 \times 2014.4\,) \frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$= 2414.5 \text{ kJ/kg}$$

6-4 A saturated mixture of liquid water and steam at 900 kPa has a specific enthalpy of 1574 kJ/kg. What is its dryness fraction?

Solution

$$h = h_{\mathrm{f}} + x h_{\mathrm{fg}}$$

$$x = \frac{h - h_{\mathrm{f}}}{h_{\mathrm{fg}}}$$

$$h = 1574 \text{ kJ/kg}$$

$$h_f = 742.7 \text{ kJ/kg}$$

$$h_{fg} = 2030.3 \text{ kJ/kg}$$

$$x = \frac{1574 - 742.7}{2030.3} = 40.9\%$$

6-5 A steady flow of water substance passes through a boiler drum in which the pressure is 0.8 MPa gauge at the rate of 1.74×10^{-2} kg/s. If it enters as saturated liquid and leaves as wet steam with a dryness fraction of 98%, calculate the rate of heat transfer to the water substance within the boiler. Take atmospheric pressure to be 0.1 MPa. The steady flow energy equation, below, applies.

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) + \dot{Q}_{in} + \dot{W}_{in} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

Solution

$$\dot{Q} = \dot{m}(h_2 - h_1) = \dot{m}\left(h_f + xh_{fg} - h_f\right) = \dot{m}xh_{fg}$$

$$p = (0.8 + 0.1) \text{ MPa absolute} = 0.9 \text{ MPa}$$

From the saturation table at 0.9 MPa

$$h_{fg} = 2030.3 \frac{\text{kJ}}{\text{kg}}$$

Hence,

$$\dot{Q} = 1.74 \times 10^{-2} \left[\frac{\text{kg}}{\text{s}}\right] \times 0.98 \times 2030.3 \left[\frac{\text{kJ}}{\text{kg}}\right] = 34.6 \text{ kW}$$

Chapter 7 Use of Tables for Water Substance

7-1 If wet steam has a specific enthalpy of 2762 kJ/kg and a pressure of 10 bar what is its dryness fraction? ($h = h_f + xh_{fg}$)

Solution

$$h = h_f + xh_{fg}$$

$$x = \frac{h - h_f}{h_{fg}}$$

$$h = 2762 \text{ kJ/kg}$$

$$h_f = 762.7 \text{ kJ/kg}$$

$$h_{fg} = 2014.4 \text{ kJ/kg}$$

$$x = \frac{2762 - 762.7}{2014.4} = 99.3\%$$

7-2 Calculate the specific volume of a saturated mixture of water and steam at 1.5 MPa given that the vapour fraction is 6.2%.

Solution

At 1.3 MPa

$$t_s = 198.3 \text{ °C}$$

Usually $v_f \cong 0.001 \text{m}^3/\text{kg}$. However in this case the temperature is high so the value should be read from the saturation table

$$v_f = 0.001154 \text{ m}^3/\text{kg}$$

$$v_g = 0.1317 \text{ m}^3/\text{kg}$$

$$v_{fg} = 0.1305 \text{ m}^3/\text{kg}$$

$$v = v_f + xv_{fg} = 0.001154 \left[\text{m}^3/\text{kg}\right] + 0.062 \times 0.1305 \left[\text{m}^3/\text{kg}\right]$$

$$= 0.00925 \text{ m}^3/\text{kg}$$

7-3 Calculate the specific volume of wet steam at 190 °C, given that the dryness fraction is 98.5%.

Solution

At 190 °C

$$v_{\mathrm{f}} = 0.001141\ \mathrm{m^3/kg}$$

$$v_{\mathrm{fg}} = 0.1553\ \mathrm{m^3/kg}$$

(Note: for liquid water $v_{\mathrm{f}} \cong 0.001\ \mathrm{m^3/kg}$)

The average specific volume of the mixture of water and steam is given by

$$v = v_{\mathrm{f}} + x v_{\mathrm{fg}}$$

$$= (0.001141 + 0.985 \times 0.1553)\ \mathrm{m^3/kg}$$

$$= 0.1541\ \mathrm{m^3/kg}$$

7-4 Find (a) the saturation pressure for water at 160 °C and (b) the specific enthalpy of steam at 1.5 MPa and 362.5 °C.

Solution

(a) From the saturation tables at 160 °C, $p_{\mathrm{s}} = 0.6181$ MPa

(b) From the superheat tables at 1.5 MPa and 350 °C $h = 3148.0$ kJ/kg and at 1.5 MPa and 400 °C $h = 3256.4$ kJ/kg. Therefore at 362.5 °C

$$h = \left[3148.0 + \frac{362.5 - 350}{400 - 350}(3256.4 - 3148.0)\right]\ \mathrm{kJ/kg}$$

$$= (3148.0 + 27.1)\ \mathrm{kJ/kg} = 3175.1\ \mathrm{kJ/kg}$$

7-5 Find the specific internal energy, the specific entropy and the specific enthalpy of liquid water at 1.5 MPa and 165 °C. ($h = h_{\mathrm{f}\,@\,T} + (p - p_{\mathrm{s}}) v_{\mathrm{f}\,@\,T}$)

Solution

At 1.5 MPa $t_s = 198.3$ °C. Therefore the water is subcooled. For subcooled water the properties of saturated liquid water at the same temperature can be used in the case of specific internal energy and specific entropy.

$$u = u_{\mathrm{f\ @\ 165\ °C}} = 696.4\,\frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$s = s_{\mathrm{f\ @\ 165\ °C}} = 1.992\,\frac{\mathrm{kJ}}{\mathrm{kgK}}$$

For subcooled water, the specific enthalpy of saturated liquid water at the same temperature can be used together with a correction for pressure, as follows:

$$p_{\mathrm{s\ @\ 165\ °C}} = 0.7\ \mathrm{MPa}$$

$$h_{\mathrm{f\ @\ 165\ °C}} = 697.1\,\frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$v_{\mathrm{f\ @\ 165\ °C}} = 0.001108\ \frac{\mathrm{m^3}}{\mathrm{kg}}$$

$$h = h_{\mathrm{f\ @\ 165\ °C}} + (p - p_{\mathrm{s}})v_{\mathrm{f}}$$

$$= 697.1\left[\frac{\mathrm{kJ}}{\mathrm{kg}}\right] + (1500 - 700)\left[\frac{\mathrm{kN}}{\mathrm{m^2}}\right] \times 0.001108\left[\frac{\mathrm{m^3}}{\mathrm{kg}}\right]$$

$$= 697.1\left[\frac{\mathrm{kJ}}{\mathrm{kg}}\right] + 0.8864\left[\frac{\mathrm{kJ}}{\mathrm{kg}}\right]$$

$$= 698.0\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

7-6 (a) Find the specific volume of steam at 2 MPa and 350 °C.

(b) Find the specific internal energy of superheated steam at 250 °C and 3 MPa.

(c) If superheated steam has a specific enthalpy of 2924 kJ/kg and a pressure of 1.5 MPa, what is its temperature?

Solution

(a) From the superheat table

$$v = 0.1386 \ \frac{\text{m}^3}{\text{kg}}$$

(b) From the superheat table

$$u = 2644.7 \ \frac{\text{kJ}}{\text{kg}}$$

(c) From the superheat table at 1.5 MPa, looking across the values for specific enthalpy, the value of 2924 kJ/kg is found at a temperature of 250 °C.

(Note: If the exact value is not found, seek a value below the desired value and a value higher than it and work out the corresponding temperature by interpolation.)

Chapter 8 The Steam Power Plant

8-1 In a steam power plant operating with a thermal efficiency of 39% the net electric power production is 105 MW. Calculate the rate of heat transfer in the boiler and superheater, stating any assumptions made.

Solution

Assume that

$$E_{th} = \frac{\dot{W}_{net,\ out}}{\dot{Q}_{H,\ in}}$$

where $\dot{Q}_{H,\ in}$ is the rate of heat transfer in the boiler and superheater and $\dot{W}_{net,\ out}$ is the net electric power production.

Hence,

$$\dot{Q}_{H,\ in} = \frac{\dot{W}_{net,\ out}}{E_{th}}$$

$$= \frac{105\ [\text{MW}]}{0.39} = 269.2\ \text{MW}$$

8-2 Feed water enters a boiler at 3 MPa and 150 °C. It leaves as superheated steam at a temperature of 450 °C. Determine the heat transfer per unit mass of steam and the rate of heat transfer if the mass flow rate is 23.2 kg/s. The formula below can be used in calculating the specific enthalpy of the feed water.

$$h_{\text{subcooled liquid}} = h_{f\ @\ T} + (p - p_{s\ @\ T})\, v_{f\ @\ T}$$

Solution

At 3 MPa $t_s = 233.9$ °C. Therefore the water entering the boiler is subcooled.

Find h_{in} at 150 °C and 3 MPa:

h_f at 150 °C = 632.3 kJ/kg

p_s at 150 °C = 0.4762 MPa

v_f at 150 °C = 0.001091 m^3/kg

Therefore

$$h_{in} = 632.3 \left[\frac{\text{kJ}}{\text{kg}}\right] + (3 - 0.4762) \times 10^3 \ [\text{kPa}] \ \times 0.001091 \left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$= (632.3 + 2.75) \ \frac{\text{kJ}}{\text{kg}} = 635.1 \ \frac{\text{kJ}}{\text{kg}}$$

Find h_{out} at 450 °C and 3 MPa:

$$h_{out} = 3344.8 \text{ kJ/kg}$$

Therefore the heat transfer per unit mass of steam is

$$q_{in} = h_{out} - h_{in}$$

$$= (3344.8 - 635.1) \frac{\text{kJ}}{\text{kg}} = 2709.7 \ \frac{\text{kJ}}{\text{kg}}$$

The rate of heat transfer is

$$\dot{Q}_{in} = \dot{m}\,(h_{out} - h_{in}) = \dot{m}\,q_{in}$$

$$= 23.2 \left[\frac{\text{kg}}{\text{s}}\right] \times 2709.7 \left[\frac{\text{kJ}}{\text{kg}}\right] = 62.9 \times 10^3 \text{ kW} = 62.9 \text{ MW}$$

8-3 Wet steam, with a quality of 0.985 condenses at 0.045 MPa absolute. Determine:

(a) the absolute temperature of the steam,

(b) the rate of heat rejection in the condenser if the mass flow rate of the condensate is 4.23 tonne/hour.

Solution

(a) From the saturation table

$p/$[MPa]	$t_s/$[°C]
0.04	75.9
0.0474	80.0

Hence,

$$t_s = \left[75.9 + \frac{0.045 - 0.04}{0.0474 - 0.04}(80.0 - 75.9)\right] [°C]$$
$$= 78.7 \text{ °C}$$
$$T_s = [273.15 + 78.7][K] = 351.8 \text{ K}$$

(b)

$$q_{\text{cond, out}} = h_{\text{in}} - h_{\text{out}}$$

where $h_{\text{in}} = h_f + xh_{fg}$ and $h_{\text{out}} = h_f$. Hence

$$q_{\text{cond, out}} = h_f + xh_{fg} - h_f = xh_{fg}$$

From the saturation table

$p/$[MPa]	$h_{fg}/$[kJ/kg]
0.04	2318.5
0.0474	2308.0

Hence,

$$h_{fg} = \left[2318.5 + \frac{0.045 - 0.04}{0.0474 - 0.04}(2308.0 - 2318.5)\right] [\text{kJ/kg}]$$
$$= 2311.4 \text{ kJ/kg}$$

Hence

$$q_{\text{cond, out}} = 0.95 \times 2311.4 \left[\frac{\text{kJ}}{\text{kg}}\right] = 2276.7 \frac{\text{kJ}}{\text{kg}}$$

$$\dot{q}_{\text{cond, out}} = \dot{m}\, q_{\text{cond, out}}$$

$$= 4.23 \left[\frac{\text{tonne}}{\text{hour}}\right] \times 10^3 \left[\frac{\text{kg}}{\text{tonne}}\right] \times \frac{1}{3600}\left[\frac{\text{hour}}{\text{sec}}\right] \times 2276.7 \left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$= 2675 \text{ kW} = 2.675 \text{ MW}$$

8-4 Dry saturated steam enters a superheater at 3 MPa at the rate of 22.1 kg/s and leaves as superheated steam at 500 °C. Determine the rate of heat transfer to the steam in the superheater.

Solution

$$\dot{Q}_{\text{superheater, in}} = \dot{m}\,(h_{\text{out}} - h_{\text{in}})$$

From the tables at 3 MPa

$$h_{\text{in}} = h_{\text{g}} = 2803.2 \ \frac{\text{kJ}}{\text{kg}}$$

$$h_{\text{out}} = h_{500\ °\text{C}} = 3457.2 \ \frac{\text{kJ}}{\text{kg}}$$

Hence

$$\dot{Q}_{\text{superheater, in}} = 22.1 \left[\frac{\text{kg}}{\text{s}}\right] (3457.2 - 2803.2) \left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$= 14.45 \times 10^3 \text{ kW} = 14.45 \text{ MW}$$

8-5 Liquid water enters a boiler at a pressure of 9 MPa and a temperature of 200 °C. Steam leaves the boiler and flows through a superheater, leaving with a temperature of 550 °C. Calculate the specific enthalpy of the liquid water that enters the boiler and that of the superheated steam that leaves the superheater. The following expression may be used to find the specific enthalpy of subcooled liquid water:

$$h_{\text{subcooled liquid}} = h_{\text{f @ }T} + (p - p_{\text{s @ }T})\, v_{\text{f @ }T}.$$

If the rate of heat transfer in the boiler and superheater is 47.3 MW, calculate the mass flow rate of the water substance. State any assumptions made.

Solution

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) + \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

As $\dot{W}_{\text{in}} = 0$ and neglecting changes in potential and kinetic energy

$$\dot{Q}_{\text{in}} = \dot{m}\,(h_2 - \text{h}_1) = \Delta h.$$

Hence

$$\dot{m} \;=\; \dot{Q}_{\text{in}}/\Delta h.$$

At 9 MPa $t_{\text{s}} = 303.3$ °C. Therefore the liquid entering the boiler is subcooled.

t/[°C]	p_{s}/[MPa]	h_{f}/[kJ/kg]	v_{f}/[m^3/kg]
200	1.555	852.3	0.001157

Find h_1 at 200 °C and 9 MPa:

$$h_1 \;=\; h_{\text{f @ }T} \;+\; (p \;-\; p_{\text{s @ }T})\, v_{\text{f @ }T}$$

$$=\; 852.3\left[\frac{\text{kJ}}{\text{kg}}\right] + (9\; - 1.555) \times 10^3\ [\text{kPa}] \times 0.001157\left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$= 860.9\ \frac{\text{kJ}}{\text{kg}}$$

The specific enthalpy at exit from the superheater is found from the tables at 9 MPa and 550 °C:

$$h_2 = \;3512.0\ \text{kJ/kg}$$

Hence,

$$\Delta h = h_2 - h_1$$

$$= (3512.0 - 860.9)\left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$= 2651.1\ \frac{\text{kJ}}{\text{kg}}$$

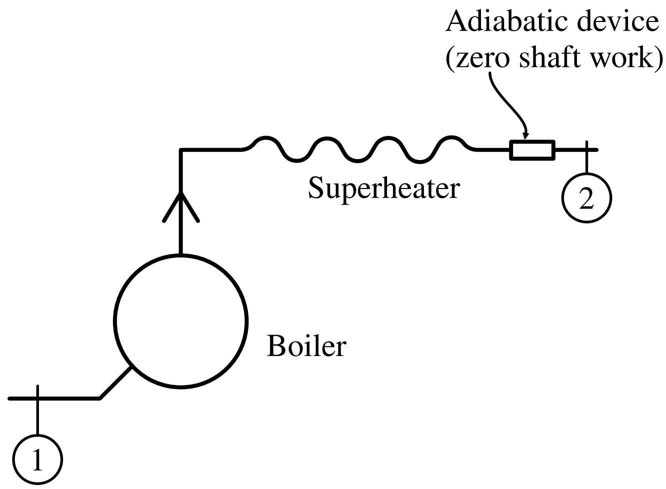
The mass flow rate can now be calculated as

$$\dot{m}\ =\ \frac{47.3 \times 10^3\ [\text{kW}]}{2651.1\left[\frac{\text{kJ}}{\text{kg}}\right]}$$

$$= 17.84\ \frac{\text{kg}}{\text{s}}$$

8-6 Water enters a boiler at ground level at a rate of 3.1 kg/s, with a velocity of 4 m/s. The boiler operates at a pressure of 4 MPa and the inlet temperature is 30 °C. The boiler is followed by a superheater and then by an adiabatic device that has no input or output of shaft work. The elevation of the outlet from the adiabatic device is 75 m relative to the boiler inlet and the exit velocity at this position is 394 m/s, while the exit specific enthalpy is 2883.9 kJ/kg. Calculate the rate of heat transfer to the water substance in the boiler and superheater. Comment on the significance of the changes in the kinetic energy per unit mass and in the potential energy per unit mass in this case.

Solution



$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) + \dot{Q}_{\text{in}} + \dot{W}_{\text{in}} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

As $\dot{W}_{\text{in}} = 0$,

$$\dot{Q}_{\text{in}} = \dot{m}\left[(h_2 - \text{h}_1) + \left(\frac{V_2^2}{2} - \frac{V_1^2}{2}\right) + g(z_2 - z_2)\right]$$

$$= \dot{m}\,(\Delta h + \Delta e_{\text{k}} + \Delta e_{\text{p}})$$

At 4 MPa $t_{\text{s}} = 250.4$ °C. Therefore the liquid entering the boiler is subcooled.

t/[°C]	p_{s}/[MPa]	h_{f}/[kJ/kg]	v_{f}/[m^3/kg]
30.0	0.00425	125.7	0.001004

Find h_1 at 30 °C and 4 MPa:

$$h_1 = h_{\text{f @ }T} + (p - p_{\text{s @ }T})\,v_{\text{f @ }T}$$

$$= 125.7\left[\frac{\text{kJ}}{\text{kg}}\right] + (4 - 0.00425) \times 10^3\ [\text{kPa}] \times 0.001004\left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$= 129.7\ \frac{\text{kJ}}{\text{kg}}$$

The specific enthalpy at exit from the adiabatic device is given:

$$h_2 = 2883.9 \text{ kJ/kg}$$

Hence,

$$\Delta h = h_2 - h_1$$

$$= (2883.9 - 129.7) \left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$= 2754.2 \ \frac{\text{kJ}}{\text{kg}}$$

The increase in kinetic energy per unit mass is calculated as:

$$\Delta e_\text{k} = \frac{V_2^2}{2} - \frac{V_1^2}{2}$$

$$= \left(\frac{394^2}{2} - \frac{4^2}{2}\right) \left[\frac{\text{m}^2}{\text{s}^2}\right] \times 10^{-3} \left[\frac{\text{kJ}}{\text{J}}\right]$$

$$= 77.61 \frac{\text{kJ}}{\text{kg}}$$

The increase in potential energy per unit mass is calculated as:

$$\Delta e_\text{p} = g(z_2 - z_2)$$

$$= 9.81 \left[\frac{\text{m}}{\text{s}^2}\right] \times 75 \text{ [m]} \times 10^{-3} \text{ [kJ/J]}$$

$$= 0.736 \ \frac{\text{kJ}}{\text{kg}}$$

The rate of heat transfer can now be calculated as

$$\dot{Q}_\text{in} = 3.1 \left[\frac{\text{kg}}{\text{s}}\right] \times (2754.2 + 77.61 + 0.736) \left[\frac{\text{kJ}}{\text{kg}}\right]$$

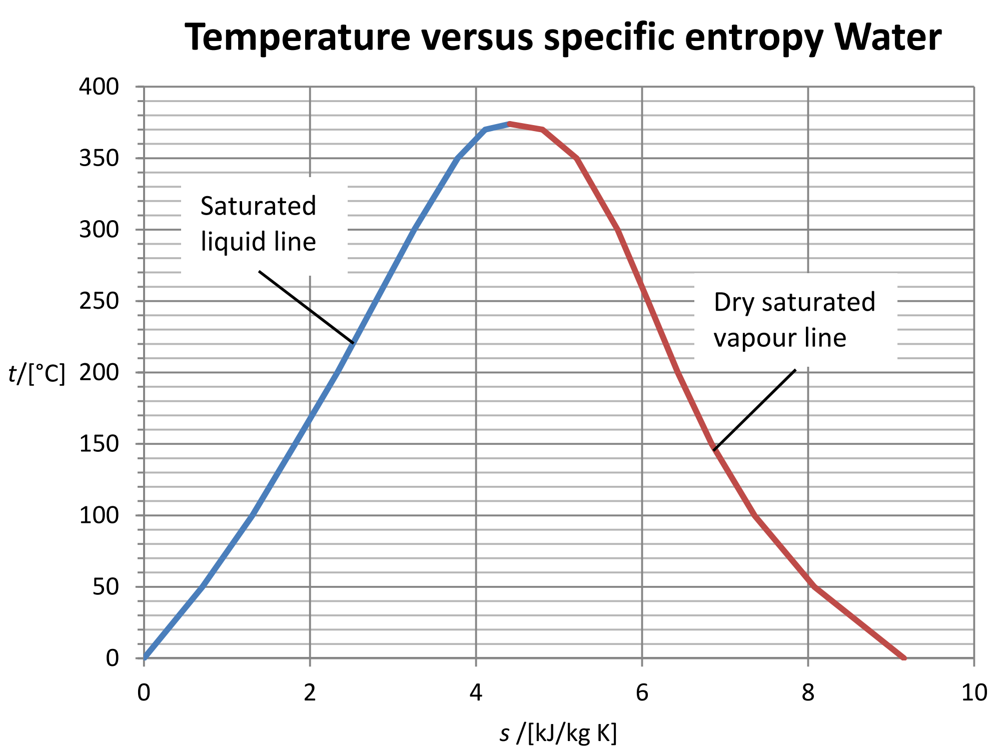
$$= 8780.9 \text{ kW}$$

$$= 8.781 \text{ MW}$$

It can be seen that the change in kinetic energy per unit mass is about 2.8% of the change in specific enthalpy, while the change in potential energy per unit mass is only about 0.027% of the change in specific enthalpy. The change in potential energy per unit mass is therefore negligible, while the change in kinetic energy needs to be taken into account.

8-7 Using a spreadsheet application prepare a diagram, like Figure 6-3, showing only the saturated liquid line and the dry saturated vapour line as a graph of temperature versus specific entropy. Use data values from Table E-1, Appendix E. Plot only sufficient points to obtain a reasonably smooth outline. Use a temperature scale with a range from 0 °C to 400 °C.

Solution



8-8 Write a paragraph to synopsize potential environmental impact issues of a large coal-fired steam power plant that uses sea water for condenser cooling.

Solution

As coal consists largely of carbon, carbon dioxide is one of the combustion products. The discharge of CO_2 to the environment contributes to global warming because of the greenhouse effect. Coal combustion can also result is other emissions that pollute the atmosphere such as smoke particulates and oxides of sulphur. Heat rejection to the sea may alter the average water temperature in a zone near the discharge of condenser cooling water and this in turn may change the marine habitat. Storage of coal and ash from combustion will need careful management to ensure minimal environmental impact.

Chapter 9 The Refrigeration Plant

9-1 At what position in a refrigeration circuit would the highest refrigerant temperature be measured?

Solution

The highest temperature would be measured at the discharge from the compressor. At this state the refrigerant is superheated relative to the condensing temperature and pressure.

9-2 Is condensation the only process that takes place within the condenser of a refrigeration plant? Explain your answer.

Solution

No, de-superheating also takes place. Refrigerant enters the 'condenser' in a superheated state. Therefore, before it can condense, the refrigerant must first be de-superheated. It loses energy by sensible heat transfer within the condenser before it condenses.

9-3 Think about faults that could cause a thermostatic valve to malfunction and provide a brief explanation for two of them.

Solution

Four examples are provided below.

The orifice within the thermostatic valve could become blocked so that flow was impossible or was severely reduced compared to the required flow rate. This could occur if solid matter lodged in the orifice, e.g. scale from metallic surfaces or dirt that had been allowed into the system.

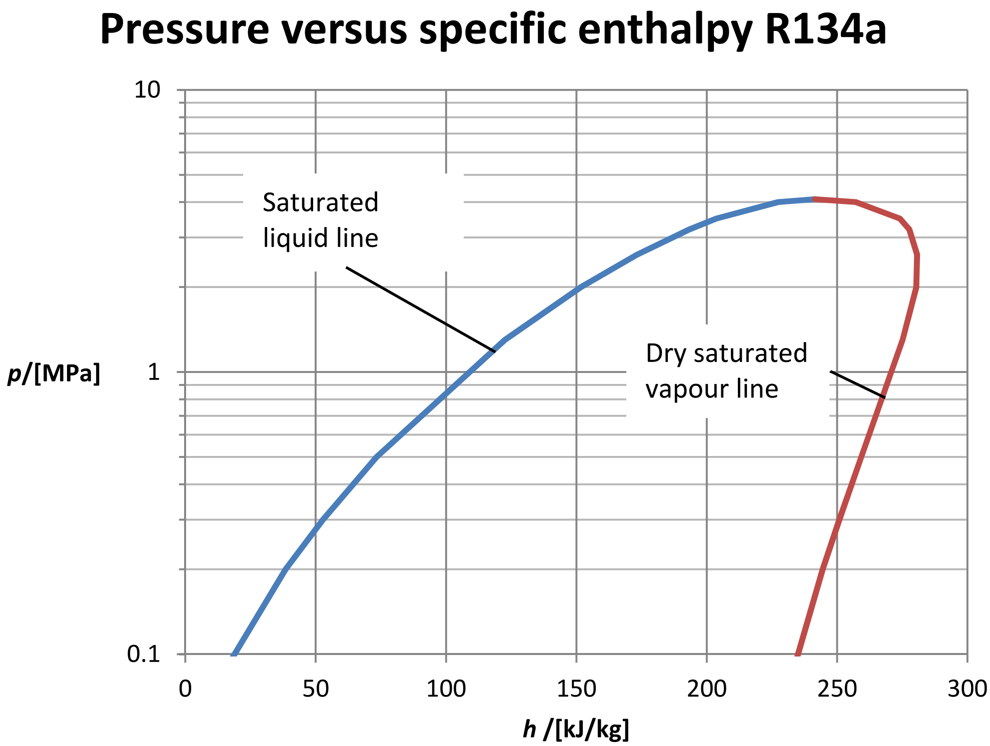
If there was any water moisture within the system, water could freeze within the expansion valve orifice and block it.

The sensor bulb could become detached from the evaporator outlet pipe so that it no longer sensed the amount of superheat correctly. This could happen if the tie strap or clamp holding the sensor bulb against the pipe became detached or loose.

If the sensor bulb was not adequately insulated from the surroundings it would reach an equilibrium temperature that was higher than the temperature in the evaporator outlet pipe. The supply of liquid to the evaporator would reduce, causing poor performance of the plant.

9-4 Using a spreadsheet application prepare a diagram, like Figure 9-4, showing only the saturated liquid line and the dry saturated vapour line on a diagram of pressure versus specific enthalpy. Use data values from Table F-1, Appendix F. Plot only sufficient points to obtain a reasonably smooth outline. Use a logarithmic axis for pressure, with a range from 0.1 MPa to 10 MPa.

Solution


Pressure versus specific enthalpy R134a
10
1
0.1
p/[MPa]
0
50
100
150
200
250
300
h /[kJ/kg]
Saturated
liquid line
Dry saturated
vapour line

Chapter 10 Use of Refrigerant Tables

10-1 Find the specific volume and the specific entropy of dry saturated R134a at a saturation pressure of 1.5 MPa.

Solution

At 1.5 MPa

$$v_g = 0.01306 \text{ m}^3/\text{kg}$$

and

$$s_g = 0.909 \text{ kJ/kgK}$$

10-2 Find h_{fg} for refrigerant 134a at a saturation temperature of −26 °C.

Solution

At −26 °C

$$h_{fg} = h_g - h_f = (234.7 - 17.8)\frac{\text{kJ}}{\text{kg}}$$

$$= 216.9 \text{ kJ/kg}$$

10-3 Find the specific enthalpy of refrigerant 134a at a pressure of 14 bar and a temperature of 50 °C.

Solution

For R134a at 14 bar (1.4 MPa) the saturation temperature is 52.4 °C. Therefore the refrigerant is subcooled. The specific enthalpy at the temperature of the liquid can be used.

$$h = h_{f\ @\ 50\ °C} = 123.5\ \frac{\text{kJ}}{\text{kg}}$$

10-4 Find the specific enthalpy of refrigerant 134a if the saturation temperature is −15 °C and the dryness fraction is 0.313.

Solution

For R134a at −15 °C

$$h_{\text{f}} = 32.0 \text{ kJ/kg}$$

and

$$h_{\text{g}} = 241.5 \frac{\text{kJ}}{\text{kg}}$$

Therefore

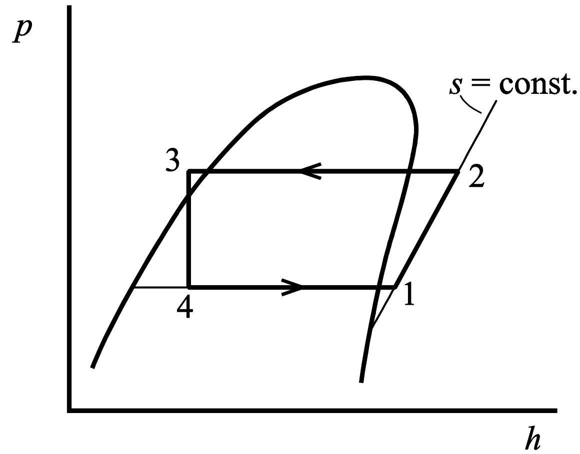
$$h_{\text{fg}} = (241.5 - 32.0) \frac{\text{kJ}}{\text{kg}}$$
$$= 209.5 \text{ kJ/kg}$$

Hence,

$$h = h_{\text{f}} + xh_{\text{fg}}$$
$$= (32.0 + 0.313 \times 209.5) \frac{\text{kJ}}{\text{kg}}$$
$$= 97.6 \text{ kJ/kg}$$

10-5 R134a enters the condenser of a refrigeration plant at a temperature of 65 °C and condenses at a temperature of 35 °C. The mass flow rate is 23.8×10^{-3} kg/s and the refrigerant leaves the condenser with 5 K of subcooling. Calculate the rate of heat rejection in the condenser.

Solution



From the table for R134a at the condensing temperature, 35 °C,

$$p_s = 0.887 \text{ MPa}$$

As the refrigerant enters the condenser (at state 2) at 65 °C and condenses at 35 °C, the amount of superheat at state 2 is (65 − 35) K = 30 K.

$$h_2 = h_{30\text{K s/h}} = 300.5 \text{ kJ/kg}$$

The refrigerant leaving the condenser is subcooled by 5 K, so its temperature is (35−5) °C = 30 °C. For subcooled liquid refrigerant (at state 3), the specific enthalpy of saturated liquid at the same temperature can be used. Therefore

$$h_3 \approx h_{\text{f @ 30 °C}} = 93.6 \text{ kJ/kg}$$

The rate of heat rejection in the condenser is given by

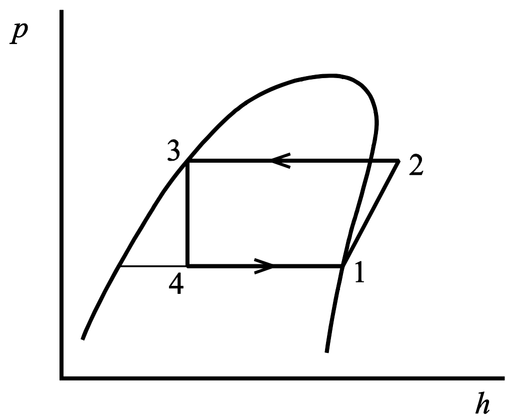
$$\dot{Q}_{\text{ cond, out}} = \dot{m}_{\text{ refr}} \,(h_2 - h_3)$$

$$= 23.8 \times 10^{-3} \left[\frac{\text{kg}}{\text{s}}\right] (300.5 - 93.6) \text{ [kJ/kg]}$$

$$= 4.92 \text{ kW}$$

10-6 R134a leaves the condenser of a refrigeration plant as saturated liquid at a temperature of 37 °C and passes through an expansion valve into the evaporator, in which the saturation temperature is −15 °C. The refrigerant leaves the evaporator as dry saturated vapour. Calculate the rate of heat transfer to the refrigerant in the evaporator if the mass flow rate of the refrigerant is 278.3×10^{-3} kg/s.

Solution



$$h_4 = h_3 = h_{f\ @\ 37\ °C} = 103.8\ \text{kJ/kg}$$

$$h_1 = h_{g\ @\ -15\ °C} = 241.5\ \text{kJ/kg}$$

$$\dot{Q}_{\text{evap, in}} = \dot{m}\,(h_1 - h_4)$$

$$= 278.3 \times 10^{-3} \left[\frac{\text{kg}}{\text{s}}\right] (241.5 - 103.8)\ [\text{kJ/kg}]$$

$$= 38.3\ \text{kW}$$

Chapter 11 Refrigeration and Heat Pump Performance

11-1 A commercial heat pump plant operates with the following parameters:

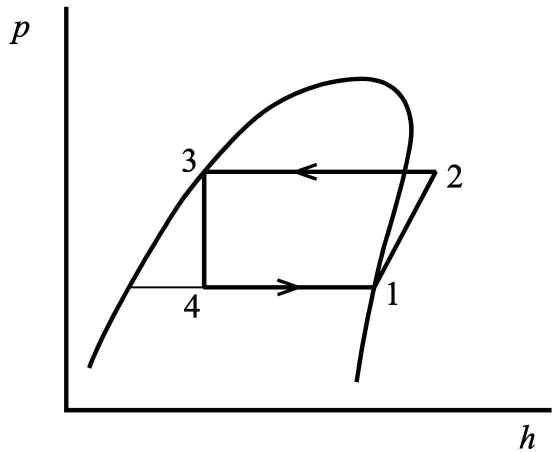
Refrigerant:	R134a
Condensing temperature	65 °C
Amount of subcooling at condenser exit	0 K
Amount of superheat at entry to the condenser (compressor exit)	26 K
Compressor work input (electrical) per unit mass of refrigerant	59.1 kJ/kg

(a) Calculate the amount of heat rejection in the condenser per unit mass of refrigerant.

(b) Determine the heat pump C.O.P. for the plant.

(c) What is the rate of heat output if the mass flow rate of refrigerant is 0.306 kg/s?

Solution



(a)

From the table for R134a find the specific enthalpy of refrigerant with 26 K of superheat relative to a saturation temperature of 65 °C:

The saturation pressure is 1.890 MPa.

With 10 K of superheat

$$h_{10\text{ K}} = 293.4\ \frac{\text{kJ}}{\text{kg}}$$

With 30 K of superheat

$$h_{30\text{ K}} = 318.0\ \frac{\text{kJ}}{\text{kg}}$$

Hence, with 26 K of superheat

$$h_2 = \left[293.4 + \frac{26-10}{30-10}(318.0-293.4)\right]\frac{\text{kJ}}{\text{kg}} = 313.1\ \frac{\text{kJ}}{\text{kg}}$$

For saturated liquid at 65 °C

$$h_3 = h_\text{f} = 147.6\ \frac{\text{kJ}}{\text{kg}}$$

Hence,

$$q_{\text{cond, out}} = h_2 - h_3$$

$$= (313.1 - 147.6)\ \frac{\text{kJ}}{\text{kg}}$$

$$= 165.5\ \frac{\text{kJ}}{\text{kg}}$$

(b)

$$\text{COP}_{\text{heat pump}} = \frac{q_{\text{cond, out}}}{w_{\text{in, elec}}}$$

$$= \frac{165.5\ \left[\frac{\text{kJ}}{\text{kg}}\right]}{59.1\ \left[\frac{\text{kJ}}{\text{kg}}\right]}$$

$$= 2.80$$

(c)

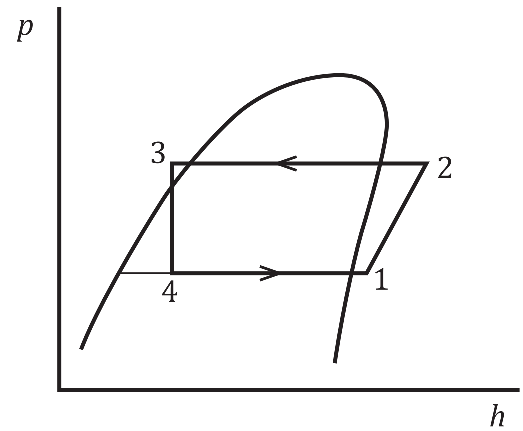
$$\dot{Q}_{\text{cond}} = \dot{Q}_{\text{out}} = \dot{m}\,(h_2 - h_3) = \dot{m}\,q_{\text{cond, out}}$$

$$= 0.306\ \left[\frac{\text{kg}}{\text{s}}\right] \times 165.5\ \left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$= 50.6\ \text{kW}$$

11-2 R134a enters the condenser of a heat pump plant at a pressure of 1.6 MPa and with 30 K of superheat. It leaves the condenser as liquid that is subcooled by 10 K. Determine the saturation temperature in the condenser and calculate the mass flow rate of the refrigerant if the rate of heat rejection in the condenser is 11.6 kW.

Solution



For R134a at 1.6 MPa

$$t_s = 57.9\,℃$$

Use subscript 2 to refer to the condenser inlet state and subscript 3 to refer to the outlet state.

With 30 K of superheat

$$h_2 = 314.1\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

As the liquid leaving the condenser is subcooled by 10 K, its temperature is 57.9 °C – 10 K = 47.9 °C. For subcooled liquid the specific enthalpy of saturated liquid at the same temperature can be used. Therefore,

$$h_3 \approx h_{\mathrm{f\ @\ 47.9\ ℃}} = 120.2\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$\dot{Q}_{\mathrm{cond}} = \dot{m}\,(h_2 - h_3)$$

Hence,

$$\dot{m} = \frac{\dot{Q}_{\mathrm{cond}}}{h_2 - h_3} = \frac{11.6}{314.1 - 120.2}\ \frac{[\mathrm{kW}]}{\left[\frac{\mathrm{kJ}}{\mathrm{kg}}\right]}$$

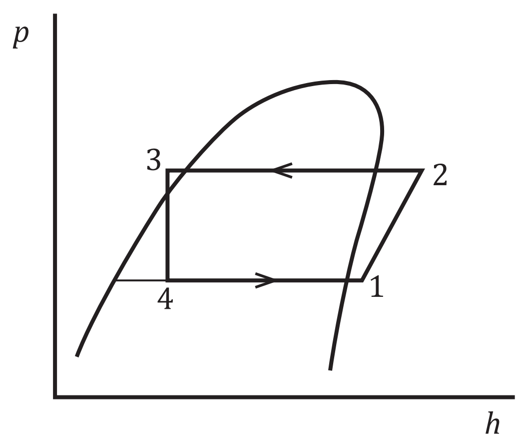
$$= 59.8 \times 10^{-3}\ \frac{\mathrm{kg}}{\mathrm{s}}$$

11-3 A heat pump plant operates with the following parameters:

Refrigerant:	R134a
Evaporating temperature	7 °C
Amount of superheat at evaporator exit	6 K
Condensing temperature	58 °C
Amount of superheat at condenser entry	22 K
Amount of subcooling at condenser exit	4 K
Refrigerant mass flow rate	0.106 kg/s
Compressor power input (electrical)	6.01 kW

Calculate the rate of heat rejection in the condenser, the rate of heat acceptance in the evaporator and the heat pump C.O.P. for the plant.

Solution



For R134a with 6 K of superheat with respect to a 7 °C saturation temperature

$$h_{g\ @\ 7\ °C} = 254.5\ \text{kJ/kg}$$

$$h_{10\ K} = 263.7\ \frac{\text{kJ}}{\text{kg}}.$$

Hence,

$$h_1 = \left[254.5 + \frac{6}{10}(263.7 - 254.5)\right]\left[\frac{\text{kJ}}{\text{kg}}\right] = 260.0\ \frac{\text{kJ}}{\text{kg}}.$$

For 22 K of superheat relative to a saturation temperature of 58 °C

$$h_2 = 290.7 + \left[\frac{12}{20}(314.2 - 290.7)\right]\left[\frac{\text{kJ}}{\text{kg}}\right] = 304.8\ \frac{\text{kJ}}{\text{kg}}.$$

At a temperature of 54 °C (4 K subcooling relative to a saturation temperature of 58 °C)

$$h_3 \approx h_{\text{f @ 54 °C}} = 129.7\ \frac{\text{kJ}}{\text{kg}}.$$

Hence

$$h_4 = h_3 \approx 129.7\ \text{kJ/kg}.$$

$$\dot{Q}_{\text{cond, out}} = \dot{m}\,(h_2 - h_3)$$

$$= 0.106\left[\frac{\text{kg}}{\text{s}}\right] \times (304.8 - 129.7)\left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$= 18.56\ \text{kW}$$

$$\dot{Q}_{\text{evap, in}} = \dot{m}\,(h_1 - h_4)$$

$$= 0.106\left[\frac{\text{kg}}{\text{s}}\right] \times (260.0 - 129.7)\left[\frac{\text{kJ}}{\text{kg}}\right]$$

$$= 13.81\ \text{kW}$$

$$\text{COP}_{\text{heat pump}} = \frac{\dot{Q}_{\text{cond, out}}}{\dot{W}_{\text{in, elec}}}$$

$$= \frac{18.56\left[\frac{\text{kJ}}{\text{kg}}\right]}{6.01\left[\frac{\text{kJ}}{\text{kg}}\right]}$$

$$= 3.09$$

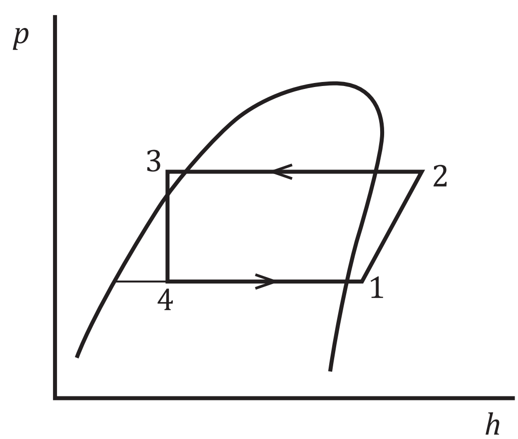
11-4 While running at 1000 r.p.m. an automotive air conditioner provides 3.3 kW of cooling at the operating conditions listed below. Calculate the volume flow rate at the compressor suction condition and calculate the swept volume per revolution of the compressor. Assume that the volumetric efficiency is equal to 90% of the ideal volumetric efficiency given by Equation (4-2), repeated below. The clearance ratio for the compressor is 0.03 and the effective polytropic index for compression is 1.055.

$$E_{\text{vol, ideal}} = 1 - r_{\text{cl}}\left[\left(\frac{p_2}{p_1}\right)^{1/n} - 1\right]$$

$$r_{\text{cl}} = \frac{\mathscr{V}_{\text{cl}}}{\mathscr{V}_{\text{sw}}}$$

Refrigerant:	R134a
Evaporating temperature	5 °C
Amount of superheat at evaporator exit	5 K
Condensing temperature	60 °C
Amount of subcooling at condenser exit	5 K

Solution



Saturation pressure at 5 °C

$$p_1 = 0.3497 \text{ MPa}$$

Saturation pressure at 60 °C

$$p_2 = 1.682 \text{ MPa}$$

h_1 for 5 °C saturation temperature with 5 K of superheat, using interpolation:

$$h_1 = [253.3 + 0.5 \times (262.5 - 253.3)] \text{ [kJ/kg]}$$

$$= 257.9 \frac{\text{kJ}}{\text{kg}}$$

v_1 for 5 °C saturation temperature with 5 K of superheat, using interpolation:

$$v_1 = [0.0584 + 0.5 \times (0.0614 - 0.0584)] \text{ [m}^3\text{/kg]}$$

$$= 0.0599 \text{ m}^3\text{/kg}$$

For h_3 at 60 °C saturation temperature with 5 K of subcooling, use h_f at 55 °C. Also $h_4 = h_3$ for the throttling process. Hence, from the tables

$$h_4 = h_3 = 131.3 \text{ kJ/kg.}$$

Calculate the mass flow rate:

$$\dot{m} = \frac{\dot{Q}_{\text{evap}}}{h_1 - h_4} = \frac{3.3 \text{ [kW]}}{(257.9 - 131.3) \text{ [kJ/kg]}}$$

$$= 26.07 \times 10^{-3} \text{ kg/s}$$

Calculate the volume flow rate at entry to the compressor:

$$\dot{\mathcal{V}}_1 = \dot{m}\, v_1$$

$$= 26.07 \times 10^{-3} \left[\frac{\text{kg}}{\text{s}}\right] \times 0.0599 \left[\frac{\text{m}^3}{\text{kg}}\right]$$

$$= 1.562 \times 10^{-3} \text{ m}^3\text{/s}$$

Calculate the volumetric efficiency of the compressor as 90% of the ideal value.

$$E_{\text{vol, ideal}} = 1 - r_{\text{cl}} \left[\left(\frac{p_2}{p_1} \right)^{\frac{1}{n}} - 1 \right]$$

Hence,

$$E_{\text{vol}} = 0.9 \left\{ 1 - 0.03 \left[\left(\frac{1.682}{0.3497} \right)^{\frac{1}{1.055}} - 1 \right] \right\}$$

$$= 0.8073$$

Now use the definition of volumetric efficiency to evaluate the swept volume rate. The volumetric efficiency is the ratio of the induced volume to the swept volume. Hence

$$E_{\text{vol}} = \frac{\mathscr{V}_{\text{ind}}}{\mathscr{V}_{\text{sw}}} = \frac{\dot{\mathscr{V}}_{\text{ind}}}{\dot{\mathscr{V}}_{\text{sw}}}.$$

Hence, the swept volume rate is given by

$$\dot{\mathscr{V}}_{\text{sw}} = \frac{\dot{\mathscr{V}}_1}{E_{\text{vol}}} = \frac{1.562 \times 10^{-3} \left[\frac{\text{m}^3}{\text{s}} \right]}{0.8073}$$

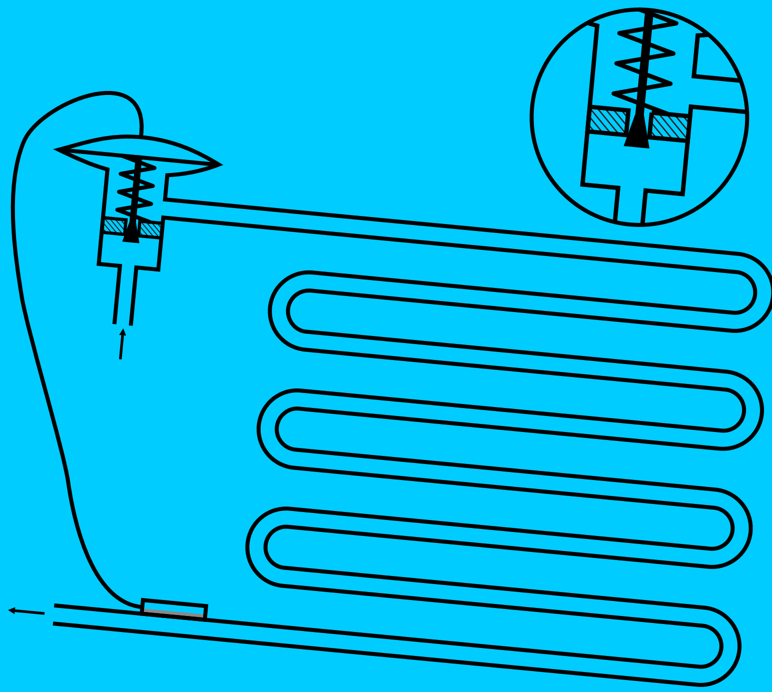
$$= 1.935 \times 10^{-3} \ \frac{\text{m}^3}{\text{s}}.$$

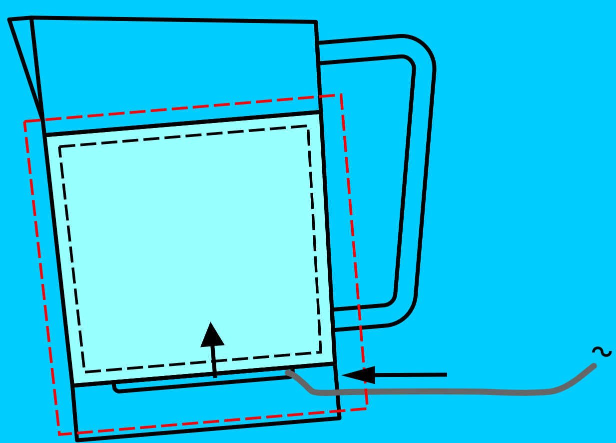
The swept volume per revolution is now calculated by dividing the swept volume rate by the rotational speed of the compressor.

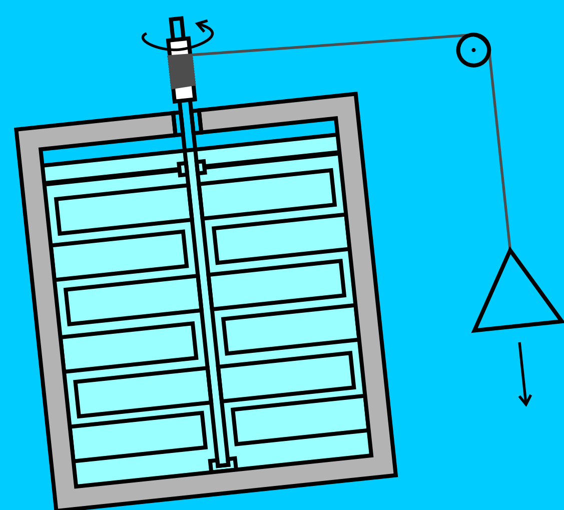
$$\mathscr{V}_{\text{sw}} = \frac{1.935 \times 10^{-3} \left[\frac{\text{m}^3}{\text{s}} \right]}{\left(\frac{1000}{60} \right) \left[\frac{\text{rev}}{\text{s}} \right]}$$

$$= 116.1 \times 10^{-6} \frac{\text{m}^3}{\text{rev}}$$

$$= 116.1 \ \frac{\text{mL}}{\text{rev}}$$







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