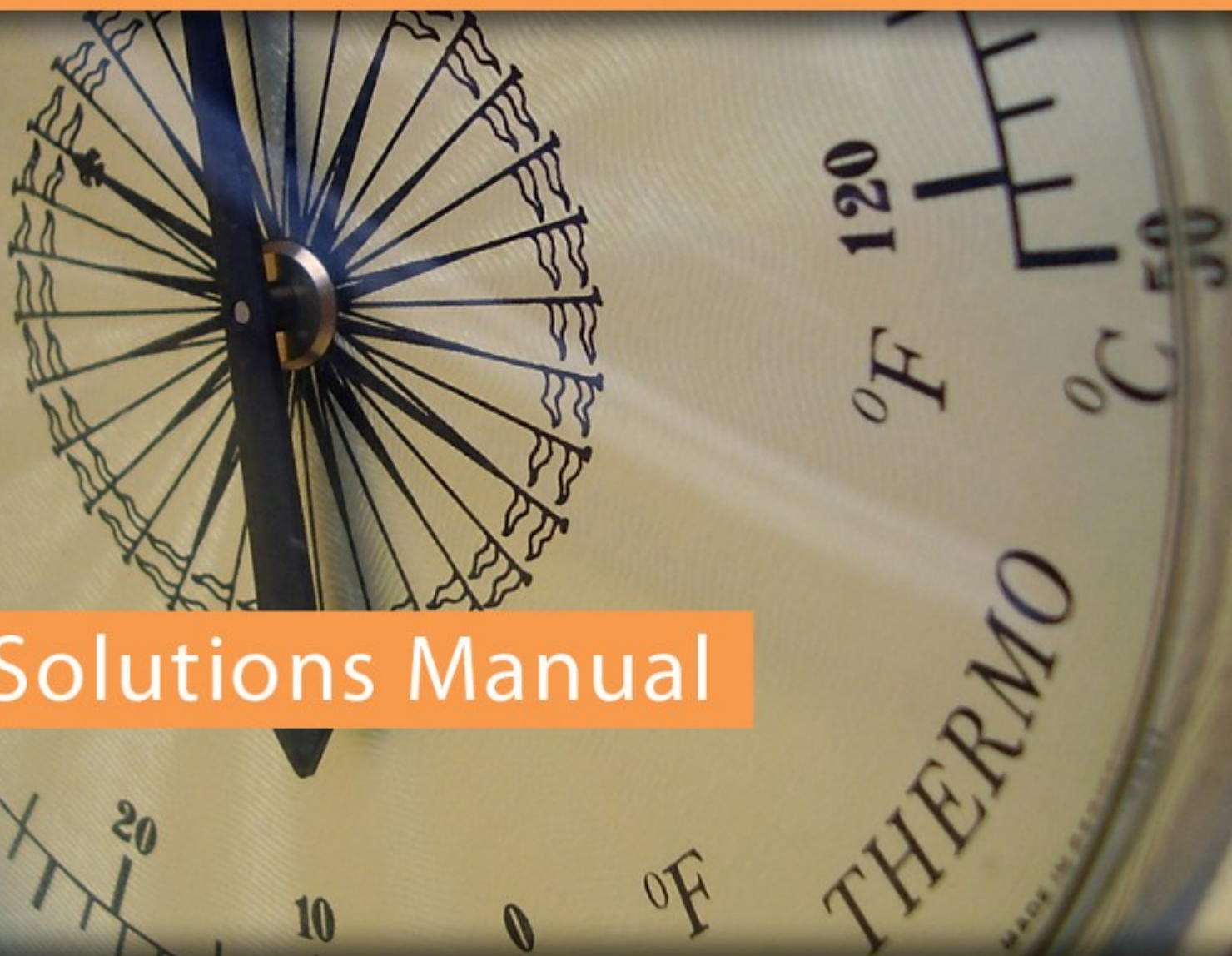


Engineering Thermodynamics Solutions Manual

Prof. T.T. Al-Shemmeri



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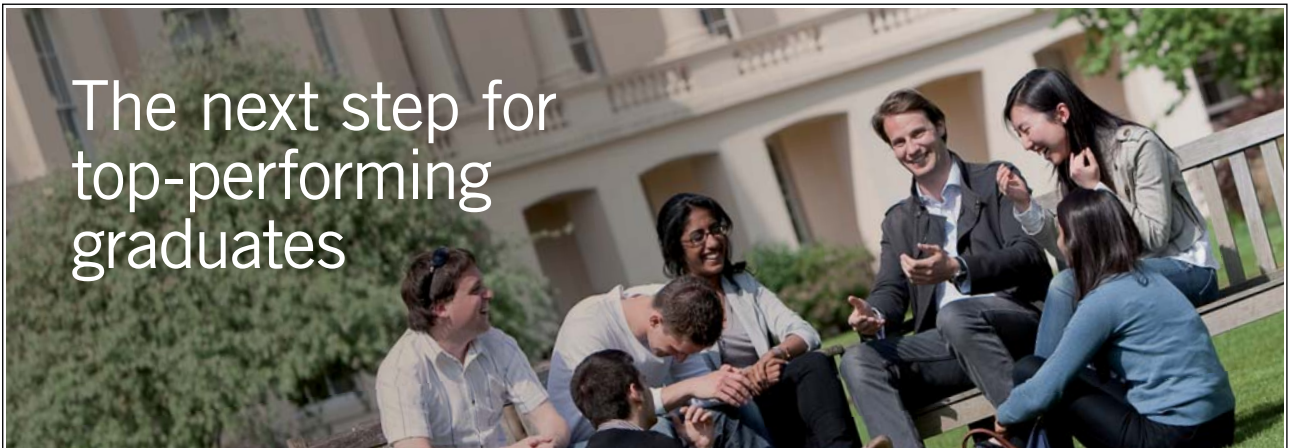
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Foreword

Title - Engineering Thermodynamics - Solutions Manual

Author – Prof. T.T. Al-Shemmerii

Thermodynamics is an essential subject in the study of the behaviour of gases and vapours in real engineering applications.

This book is a complimentary follow up for the book “Engineering Thermodynamics” also published on BOOKBOON, presenting the solutions to tutorial problems, to help students to check if their solutions are correct; and if not, to show how they went wrong, and change it to get the correct answers.

This solutions manual is a small book containing the full solution to all tutorial problems given in the original book which were grouped in chapter four, hence the sections of this addendum book follows the format of the textbook, and it is laid out in three sections as follows:

4.1 First Law of Thermodynamics N.F.E.E Applications

In this section there are 6 tutorial problems

4.2 First Law of Thermodynamics S.F.E.E Applications

In this section there are 5 tutorial problems

4.3 General Thermodynamics Systems

In this section there are 15 tutorial problems

4.1 First Law of Thermodynamics N.F.E.E Applications

1. In a non-flow process there is heat transfer loss of 1055 kJ and an internal energy increase of 210 kJ. Determine the work transfer and state whether the process is an expansion or compression.

[Ans: -1265 kJ, compression]

Solution:

Closed system for which the first law of Thermodynamics applies,

$$Q - W = \Delta U$$

$$1055 - W = 210$$

Hence the work done can be found as:

$$W = -1265 \text{ kJ}$$

Since negative, it must be work input, ie compression.

2. In a non-flow process carried out on 5.4 kg of a substance, there was a specific internal energy decrease of 50 kJ/kg and a work transfer from the substance of 85 kJ/kg. Determine the heat transfer and state whether it is gain or loss.

[Ans: 189 kJ, gain]

Solution:

Closed system for which the first law of Thermodynamics applies,

$$Q - W = \Delta U$$

$$\begin{aligned} Q &= \Delta U + W \\ &= 5.4 \times (-50) + 5.4 \times 85 \\ &= +189 \text{ kJ,} \end{aligned}$$

Since Q is positive, it implies heat is entering the control volume, ie Gain.

3. During the working stroke of an engine the heat transferred out of the system was 150 kJ/kg of the working substance. If the work done by the engine is 250 kJ/kg, determine the change in internal energy and state whether it is decrease or increase.

[Ans: -400 kJ/kg, decrease]

Solution:

Closed system for which the first law of Thermodynamics applies,

$$Q - W = \Delta U$$

Hence

$$\begin{aligned}\Delta U &= Q - W \\ &= (-150) - 250 \\ &= -400 \text{ kJ/kg}\end{aligned}$$

Since the sign is negative, there is a decrease in internal energy.

4. Steam enters a cylinder fitted with a piston at a pressure of 20 MN/m² and a temperature of 500 deg C. The steam expands to a pressure of 200 kN/m² and a temperature of 200 deg C. During the expansion there is a net heat loss from the steam through the walls of the cylinder and piston of 120 kJ/kg. Determine the displacement work done by one kg of steam during this expansion.

[Ans: 168.6 kJ/kg]

Solution:

State 1

at 20 MPa, 500 C: $u = 2942.9 \text{ kJ/kg}$

State 2

at 200 kPa, 200C: $u = 2654.4 \text{ kJ/kg}$

Closed system for which the first law of Thermodynamics applies,

$$Q - W = \Delta U$$

Rearranging to determine the work done:

$$W = Q - \Delta U = (-120) - (2654.4 - 2942.9) = 168.5 \text{ kJ/kg}$$

5. A closed rigid system has a volume of 85 litres contains steam at 2 bar and dryness fraction of 0.9. Calculate the quantity of heat which must be removed from the system in order to reduce the pressure to 1.0 bar. Also determine the change in enthalpy and entropy per unit mass of the system.

[Ans: -38 kJ]

Solution:

Closed system for which the first law of Thermodynamics applies,

| T | $p = 0.2 \text{ MPa (120.23 C)}$ | | | |
|-------------|----------------------------------|--------|--------|---------|
| | v | u | h | s |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00106 | 504.5 | 504.7 | 1.5300 |
| Sat. vapour | 0.8857 | 2529.5 | 2706.7 | 7.1272 |

$$Q - W = \Delta U$$

For a rigid system $W=0$,

$$\text{hence } Q = \Delta U$$

At 2bar, $x=0.9$, the properties are:

Hence:

$$h = h_f + x.(h_g - h_f) = 504.7 + 0.9 (2706.7 - 504.7) = 2486.5 \text{ kJ/kg}$$

$$u = u_f + x.(u_g - u_f) = 504.5 + 0.9 (2529.5 - 504.5) = 2327.0 \text{ kJ/kg}$$

$$v = v_f + x.(v_g - v_f) = 0.00106 + 0.9 (0.8857 - 0.00106) = 0.797 \text{ kJ/kg}$$

$$\text{mass} = \text{volume}/\text{specific volume} = 85 \text{ litres} \times 10^{-3} / 0.797 = 0.1066 \text{ kg}$$

| T | $p = 0.10 \text{ MPa (99.63 C)}$ | | | |
|-------------|----------------------------------|--------|--------|---------|
| | v | u | h | s |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00104 | 417.3 | 417.4 | 1.3030 |
| Sat. vapour | 1.694 | 2506.1 | 2675.5 | 7.3594 |

at 1 bar

$$v = v_f + x.(v_g - v_f)$$

$$x = (v - v_f)/(v_g - v_f) = (0.797 - 0.00104)/(1.694 - 0.00104) = 0.470$$

$$h = 417.4 + 0.470 (2675.5 - 417.4) = 1479.06 \text{ kJ/kg}$$

$$u = 417.3 + 0.470 (2506.1 - 417.3) = 1399.36 \text{ kJ/kg}$$

$Q = m (u_2 - u_1) = 0.1066 \times (2327.0 - 1399.36) = 98.9 \text{ kJ}$ not the answer given in the text, please accept this as the correct answer.

6. 2 kg of air is heated at constant pressure of 2 bar to 500 °C. Determine the initial temperature and the change in its entropy if the initial volume is 0.8 m³.

[Ans: 2.04 kJ/kgK]

Solution:

$$T_1 = \frac{P_1 x V_1}{m x R}$$

$$= \frac{2 \times 10^5 \times 0.8}{2 \times 287}$$

$$= 278.746 \text{ K}$$

$$\Delta S = m.C_p \ln \frac{T_2}{T_1}$$

$$= 2 \times 1005 \times \ln \frac{500 + 273}{278.7}$$

$$= 2.05 \text{ kJ/kgK}$$

4.2 First Law of Thermodynamics S.F.E.E Applications

1. A boiler is designed to work at 14 bar and evaporate 8 kg/s of water. The inlet water to the boiler has a temperature of 40 deg C and at exit the steam is 0.95 dry. The flow velocity at inlet is 10 m/s and at exit 5 m/s and the exit is 5 m above the elevation at entrance. Determine the quantity of heat required. What is the significance of changes in kinetic and potential energy on the result?

[Ans: 20.186 MW]

Solution:

$$1. \text{ SFEE : } \quad Q - W = m[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)]$$

$W = 0$ (since constant pressure process),

ignoring Δke and ΔPe : the SFEE reduces to

$$Q_s = m_s (h_2 - h_1)$$

State 1- h_1 is hf at $T=40^\circ\text{C}$, closest to this is $T_s=45$, $h_1=191.83$ kJ/kg

State 2, $h=h_f+0.95h_{fg}$ at 14 bar.

$$h_2=830.30+0.95 \times 1959.7 = 2692 \text{ kJ/kg}$$

hence

$$Q_s = m_s (h_2 - h_1) = 8 \times (2692 - 191.83) = 2000136 \text{ kW} = 20 \text{ MW}$$

2. Taking into account changes in KE and PE

The KE and PE contribution is calculated

$$X = m \left[\frac{V_2^2 - V_1^2}{2} \right] + g(Z_2 - Z_1)$$

$$= 8 \times \left[\frac{5^2 - 10^2}{2000} + 9.81 \times \left(\frac{5}{1000} \right) \right]$$

$$= -0.3 + 0.049$$

$$= -0.251 \text{ kW}$$

This is tiny (0.001%) in comparison to 20 MW.

2. Steam flows along a horizontal duct. At one point in the duct the pressure of the steam is 1 bar and the temperature is 400°C. At a second point, some distance from the first, the pressure is 1.5 bar and the temperature is 500°C. Assuming the flow to be frictionless and adiabatic, determine whether the flow is accelerating or decelerating.

[Ans: Decelerating]

Solution:

$$1. \text{ SFEE : } \quad Q - W = m[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)]$$

$W = 0$ (since constant pressure process),

$Q = 0$ adiabatic

$PE = 0$ horizontal layout

Hence

$$(h_2 - h_1) = - \frac{V_2^2 - V_1^2}{2}$$

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Find enthalpy values at 1 and 2:

State 1- 1.0 bar and the temperature is 400°C, hence $h_1 = 3263.9$ kJ/kg

State 2- 1.5 bar and the temperature is 500°C, $h_2 = 3473$ kJ/kg

Hence $(h_2 - h_1) = 3473 - 3263.9 = 209.1$ kJ/kg

Since this is positive, then $V_1 > V_2$, ie decelerating

3. Steam is expanded isentropically in a turbine from 30 bar and 400°C to 4 bar. Calculate the work done per unit mass flow of steam. Neglect changes in Kinetic and Potential energies.

[Ans: 476 kJ/kg]

Solution:

$$1. \text{ SFEE : } Q - W = m[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)]$$

$Q = 0$ isentropic expansion

$KE = PE = 0$

Hence $W = m[(h_2 - h_1)]$

State 1- 30 bar and the temperature is 400°C,

| T | $p = 3.00 \text{ MPa (233.90 C)}$ | | | |
|-------------|-----------------------------------|--------|--------|---------|
| | v | u | h | s |
| deg-C | m^3/kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.001216 | 1004.8 | 1008.4 | 2.6457 |
| Sat. vapour | 0.06668 | 2604.1 | 2804.2 | 6.1869 |
| 400 | 0.09936 | 2932.8 | 3230.9 | 6.9212 |

Hence

$h_1 = 3230.9$ kJ/kg,

$s_1 = 6.9212$ kJ/kgK

Expanding at constant entropy, to 4 bar,

Slightly superheated,

$h_2 = 2750$ kJ/kg (approximately)

| T | $p = 0.40$ MPa (143.63 C) | | | |
|-------------|---------------------------|--------|--------|---------|
| | v | u | h | s |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00108 | 604.3 | 604.7 | 1.7766 |
| Sat.Vapour | 0.4625 | 2553.6 | 2738.6 | 6.8959 |
| 150 | 0.4708 | 2564.5 | 2752.8 | 6.9299 |
| 200 | 0.5342 | 2646.8 | 2860.5 | 7.1706 |

Hence

$$\begin{aligned} W &= m (h_2 - h_1) \\ &= 1 \times (3230.9 - 2750) \\ &= 480.9 \text{ kJ/kg} \end{aligned}$$

4. A compressor takes in air at 1 bar and 20°C and discharges into a line. The average air velocity in the line at a point close to the discharge is 7 m/s and the discharge pressure is 3.5 bar. Assuming that the compression occurs isentropically, calculate the work input to the compressor. Assume that the air inlet velocity is very small.

[Ans: -126.6 kW/kg]

Solution:

$$Q - W = m \left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right]$$

Assume adiabatic condition, $Q=0$, and horizontally mounted, ($PE=0$), SFEE reduces to

$$-W = m \left[C_p(T_2 - T_1) + \frac{V_2^2 - V_1^2}{2} \right]$$

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} = 293 \left(\frac{3.5}{1} \right)^{1.4} = 419.1 \text{ K}$$

$$\frac{W}{m} = -[1005(419.1 - 293) + \frac{7^2 - 0}{2}]$$

$$= -[126728 + 24.5]$$

$$= -126.7 \text{ kW/kg}$$

5. Air is expanded isentropically in a nozzle from 13.8 bar and 150°C to a pressure of 6.9 bar. The inlet velocity to the nozzle is very small and the process occurs under steady-flow, steady-state conditions. Calculate the exit velocity from the nozzle knowing that the nozzle is laid in a horizontal plane and that the inlet velocity is 10 m/s.

[Ans: 390.9 m/s]

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Solution:

The situation is an open system for which the SFEE applies:

$$Q - W = m \left[C_p (T_2 - T_1) + \frac{V_2^2 - V_1^2}{2} + g(Z_2 - Z_1) \right]$$

$Q = 0$ adiabatic

$$g(Z_2 - Z_1) = 0 \text{ (Assumed)}$$

And $W=0$ no moving parts

$$\text{Hence SFEE reduces to } 0 = m \left[C_p (T_2 - T_1) + \frac{V_2^2 - V_1^2}{2000} \right]$$

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} = (273 + 150) \times \left(\frac{6.9}{13.8} \right)^{\frac{0.4}{1.4}} = 347 \text{ K}$$

The SFEE can now be used to determine the mass flow rate

$$0 = m \left[1.005(347 - 423) + \frac{V_2^2 - 10^2}{2000} \right]$$

$$m = 1$$

hence

$$V_2 = \sqrt{100 + 2000 \times 1.005 \times 76} = 390 \text{ m/s}$$

4.3 General Thermodynamics Systems

1. A rotary air compressor takes in air (which may be treated as a perfect gas) at a pressure of 1 bar and a temperature of 20°C and compresses it adiabatically to a pressure of 6 bar. The isentropic efficiency of the processes is 0.85 and changes in kinetic and potential energy may be neglected. Calculate the specific entropy change of the air. Take $R = 0.287 \text{ kJ/kg K}$ and $C_p = 1.006 \text{ kJ/kg K}$.

[Ans: 0.07 kJ/kg K]

Solution:

Closed system for which the first law of Thermodynamics applies,

$$dQ - dW = \Delta U$$

$$dQ = T.dS; \quad dW = -pdV; \quad C_v = du/dT,$$

Hence

$$Tds - pdV = C_v.dT$$

$$dS = (P/T)dV + C_v(dT/T)$$

integrating

$$(S_2 - S_1) = R \ln(V_2/V_1) + C_v \ln(T_2/T_1)$$

For isentropic process

$$V_2/V_1 = (P_1/P_2)^{1/n}$$

$$T_2/T_1 = (P_2/P_1)^{(n-1)/n}$$

Hence

$$S_2 - S_1 = R \ln(P_1/P_2)^{1/n} + C_v \ln(T_2/T_1)$$

$$T_2 = T_1 (P_2/P_1)^{(n-1)/n} = 293 (6/1)^{0.4} = 488.5 \text{ K}$$

$$T_2 = T_1 + (T_2s - T_1)/\text{effc} = 293 + (488.5 - 293)/0.85 = 523 \text{ K}$$

$$S_2 - S_1 = R \ln(P_1/P_2)^{1/n} + C_v \ln(T_2/T_1)$$

$$S_2 - S_1 = 0.287 \ln(1/6)^{1/1.4} + (1.006 - 0.287) \ln(523/293)$$

$$= -0.3673 + 0.4166$$

$$= 0.05 \text{ kJ/kgK}$$

Very small quantity, note that if the process is 100% isentropic, the change in entropy would be zero.

2. An air receiver has a capacity of 0.86m^3 and contains air at a temperature of 15°C and a pressure of 275 kN/m^2 . An additional mass of 1.7 kg is pumped into the receiver. It is then left until the temperature becomes 15°C once again. Determine,

- the new pressure of the air in the receiver, and
- the specific enthalpy of the air at 15°C if it is assumed that the specific enthalpy of the air is zero at 0°C .

Take $C_p = 1.005\text{ kJ/kg}$, $C_v = 0.715\text{ kJ/kg K}$

[Ans: 442 kN/m^2 , 15.075 kJ/kg]

Solution:

$$m_1 = \frac{PV}{RT}$$

$$= \frac{275 \times 10^3 \times 0.86}{(2005 - 715) \times 288}$$

$$= 2.8316\text{ kg}$$

added

$$dm = 1.7\text{ kg}$$

hence

$$m_2 = m_1 + dm = 2.8316 + 1.7 = 4.5316\text{ kg}$$

a)

$$P_2 = \frac{mRT_2}{V}$$

$$= \frac{4.5316 \times (2005 - 715) \times 288}{0.86}$$

$$= 440\text{ kPa}$$

b) $h = C_p \cdot dT = 1005 \times (288 - 273) = 15.075\text{ kJ/kg}$.

3. Oxygen has a molecular weight of 32 and a specific heat at constant pressure = 0.91 kJ/kg K.

- Determine the ratio of the specific heats.
- Calculate the change in internal energy and enthalpy if the gas is heated from 300 to 400 K.

[Ans: 1.4, 65 kJ/kg, 91 kJ/kg]

Solution:

$$a) R = \frac{R_o}{M} = \frac{8314.3}{32} = 0.2598 \text{ kJ/kgK}$$

$$C_v = C_p - R = 0.91 - 0.2598 = 0.65 \text{ kJ/kgK}$$

$$n = C_p/C_v = 0.91 / 0.65 = 1.3996$$

$$b) du = C_v (T_2 - T_1) = 0.65 (400 - 300) = 65 \text{ kJ/kg}$$

$$dh = C_p (T_2 - T_1) = 0.91 (400 - 300) = 91 \text{ kJ/kg}$$

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4. A steam turbine inlet state is given by 6 MPa and 500°C. The outlet pressure is 10 kPa. Determine the work output per unit mass if the process:-
- is reversible and adiabatic (ie 100% isentropic),
 - such that the outlet condition is just dry saturated,
 - such that the outlet condition is 90% dry.

[Ans: 1242.7 kJ/kg, 837.5 kJ/kg, 1076.8 kJ/kg]

Solution:

a) when 100% isentropic

$$h_1 = 3422.2 \text{ kJ/kg}, S_1 = 6.8803 \text{ kJ/kgK}$$

$S_2 = s_1$ and x_2 is found using

$$\text{Then } 6.8803 = 0.6493 + x_2 (7.5009), \text{ from which } x_2 = 0.8307$$

$$\text{Thus } h_2 = h_f + x h_{fg} = 191.83 + 0.8307 \times 2392.87 = 2179.6 \text{ kJ/kg}$$

Hence

$$W = h_1 - h_2 = 3422.2 - 2179.6 = 1242.6 \text{ kJ/kg}$$

b) if $x=1$,

$$h_2 = 2584.7 \text{ kJ/kg}$$

$$W = h_1 - h_2 = 3422.2 - 2584.7 = 837.5 \text{ kJ/kg}$$

c) if $x=0.9$

$$h_2 = h_f + x h_{fg} = 191.83 + 0.9 \times 2392.87 = 2345.4 \text{ kJ/kg}$$

Hence

$$W = h_1 - h_2 = 3422.2 - 2345.4 = 1076.8 \text{ kJ/kg}$$

5. Determine the volume for carbon dioxide contained inside a cylinder at 0.2 MPa, 27°C:-
- assuming it behaves as an ideal gas
 - taking into account the pressure and volume associated with its molecules

[Ans: 0.2833m³/kg]

| Substance | Chemical Formula | Molar Mass M (kg/kmol) | Gas constant R (J/kgK) | Critical Temp TC (K) | Critical Pressure PC (MPa) | Van der Waals Constants | |
|----------------|------------------|------------------------|------------------------|----------------------|----------------------------|-------------------------|---------|
| | | | | | | a | b |
| Carbon Dioxide | CO ₂ | 44.01 | 188.918 | 304.20 | 7.386 | 188.643 | 0.00097 |

Solution:

- a) Assuming perfect gas behaviour:

$$R = \frac{R_o}{M} = \frac{8314.3}{44} = 188.96$$

$$V = \frac{mRT}{P}$$

$$= \frac{1 \times 188.96 \times 300}{0.2 \times 10^6}$$

$$= 0.2834 \text{ m}^3 / \text{kg}$$

- b) using Van Der Vaal's equation

$$P = \frac{RT}{v-b} - \frac{a}{v^2}$$

$$0.2 \times 10^6 = \frac{1889.96 \times 300}{v - 0.00097} - \frac{188.643}{v^2}$$

solve

$$V = 0.2833 \text{ m}^3 / \text{kg}$$

6. A cylindrical storage tank having an internal volume of 0.465 m^3 contains methane at 20°C with a pressure of 137 bar. If the tank outlet valve is opened until the pressure in the cylinder is halved, determine the mass of gas which escapes from the tank assuming the tank temperature remains constant.

[Ans: 20.972 kg]

Solution:

$$R = \frac{R_o}{M} = \frac{8314.3}{16} = 519.644 \text{ J/kgK}$$

$$m_1 = \frac{PV}{RT}$$

$$= \frac{137 \times 10^5 \times 0.465}{519.644 \times 293}$$

$$= 41.841 \text{ kg}$$

$$P_2 = 0.5P_1$$

hence

$$m_2 = 0.5m_1 = 20.920 \text{ kg}$$

so

$$dm = 20.920 \text{ kg}$$

7. Find the specific volume for H_2O at 1000 kN/m^2 and 300°C by using:-
- the ideal gas equation assuming $R = 461.5 \text{ J/kg K}$
 - steam tables

[Ans: $0.264 \text{ m}^3/\text{kg}$, $0.258 \text{ m}^3/\text{kg}$]

Solution:

- a) for a perfect gas

$$v = \frac{RT}{P}$$

$$= \frac{461.5 \times 573}{1 \times 10^6}$$

$$= 0.2644 \text{ m}^3 / \text{kg}$$

- b) using the steam Tables

$$V = 0.2579 \text{ m}^3/\text{kg}$$

The difference = 2.4% under-estimation if assumed ideal gas.

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8. Determine the specific volume of steam at 6 MPa using the steam tables for the following conditions:-

- dryness fraction $x = 0$
- dryness fraction $x = 0.5$
- dryness fraction $x = 1$
- its temperature is 600°C

[Ans: 0.001319, 0.01688, 0.03244, 0.06525 m³/kg]

| T | $p = 6.0 \text{ Mpa (257.64 deg-C)}$ | | | |
|-------------|--------------------------------------|--------|--------|---------|
| | v | u | h | s |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00132 | 1205.4 | 1213.3 | 3.0267 |
| Sat. vapour | 0.03244 | 2589.7 | 2784.3 | 5.8892 |
| 300 | 0.03616 | 2667.2 | 2884.2 | 6.0674 |
| 350 | 0.04223 | 2789.6 | 3043.0 | 6.3335 |
| 400 | 0.04739 | 2892.9 | 3177.2 | 6.5408 |
| 450 | 0.05214 | 2988.9 | 3301.8 | 6.7193 |
| 500 | 0.05665 | 3082.2 | 3422.2 | 6.8803 |
| 550 | 0.06101 | 3174.6 | 3540.6 | 7.0288 |
| 600 | 0.06525 | 3266.9 | 3658.4 | 7.1677 |
| 700 | 0.07352 | 3453.1 | 3894.2 | 7.4234 |
| 800 | 0.0816 | 3643.1 | 4132.7 | 7.6566 |
| 900 | 0.08958 | 3837.8 | 4375.3 | 7.8727 |
| 1000 | 0.09749 | 4037.8 | 4622.7 | 8.0751 |
| 1100 | 0.10536 | 4243.3 | 4875.4 | 8.2661 |
| 1200 | 0.11321 | 4454.0 | 5133.3 | 8.4474 |
| 1300 | 0.12106 | 4669.6 | 5396.0 | 8.6199 |

Solution:

- $v = v_f = 0.001319 \text{ m}^3/\text{kg}$
- $v = v_f + X(v_g - v_f) = 0.00132 + 0.5(0.03244 - 0.00132)$
 $= 0.01688 \text{ m}^3/\text{kg}$
- $v = v_g = 0.03244 \text{ m}^3/\text{kg}$
- $v = 0.06525 \text{ m}^3/\text{kg}$

9. Steam at 4 MPa, 400°C expands at constant entropy till its pressure is 0.1 MPa. Determine:

- the energy liberated per kg of steam
- repeat if the process is 80% isentropic

[Ans: 758 kJ/kg, 606 kJ/kg]

| T | $p = 4.0 \text{ MPa (250.4 deg C)}$ | | | |
|-------------|-------------------------------------|----------------|----------------|------------------|
| | v | u | h | s |
| deg-C | m^3/kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00125 | 1082.3 | 1087.3 | 2.7964 |
| Sat. vapour | 0.04978 | 2602.3 | 2801.4 | 6.0701 |
| 275 | 0.05457 | 2667.9 | 2886.2 | 6.2285 |
| 300 | 0.05884 | 2725.3 | 2960.7 | 6.3615 |
| 350 | 0.06645 | 2826.7 | 3092.5 | 6.5821 |
| 400 | 0.07341 | 2919.9 | 3213.6 | 6.7690 |

| T | $p = 0.10 \text{ MPa (99.63 C)}$ | | | |
|-------------|----------------------------------|----------------|----------------|------------------|
| | v | u | h | s |
| deg-C | m^3/kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00104 | 417.3 | 417.4 | 1.3030 |
| Sat. vapour | 1.694 | 2506.1 | 2675.5 | 7.3594 |

Solution:

a) $h_1 = 3213.6 \text{ kJ/kg}$, $S_1 = 6.769 \text{ kJ/kgK}$

$$X_2 = \frac{S_1 - S_f}{S_g - S_f} = \frac{6.7690 - 1.303}{7.3594 - 1.303} = 0.9024$$

$$h_2 = h_f + X_2(h_g - h_f) = 417.4 + 0.9024(2675.5 - 417.4) = 2455.4 \text{ kJ/kg}$$

$$W = h_1 - h_2 = 3213.6 - 2455.4 = 758.2 \text{ kJ/kg}$$

b) if efficiency = 80%

$$\begin{aligned} W &= 0.8(h_1 - h_2) \\ &= 0.8(3213.6 - 2455.39) \\ &= 606.6 \text{ kJ/kg} \end{aligned}$$

10. a) Steam (1 kg) at 1.4 MPa is contained in a rigid vessel of volume 0.16350 m³. Determine its temperature.
 b) If the vessel is cooled, at what temperature will the steam be just dry saturated?
 c) If cooling is continued until the pressure in the vessel is 0.8 MPa; calculate the final dryness fraction of the steam, and the heat rejected between the initial and the final states.

[Ans: 250°C, 188°C, 0.678; 8181 kJ]

Solution:

- a) at 1.4 MPa and $v = 0.16350 \text{ m}^3/\text{kg}$, from steam tables, it can be verified that the condition of the fluid is superheated, at 250 C.

$h_1 = 2927.2 \text{ kJ/kg}$

| <i>T</i> | <i>p = 1.40 MPa (195.07°C)</i> | | | |
|-------------|--------------------------------|----------|----------|----------|
| | <i>v</i> | <i>u</i> | <i>h</i> | <i>s</i> |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00115 | 828.7 | 830.3 | 2.2842 |
| Sat. Vapour | 0.14084 | 2592.8 | 2790.0 | 6.4693 |
| 200 | 0.14302 | 2603.1 | 2803.3 | 6.4975 |
| 250 | 0.16350 | 2698.3 | 2927.2 | 6.7467 |
| 300 | 0.18228 | 2785.2 | 3040.4 | 6.9534 |



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- b) now if the vessel is cooled, at constant volume, till $x=1$, then the temperature is equal to the saturation value at a new pressure of 1.2 MPa, $T=T_s=187.99\text{C}$

| T | $p = 1.20 \text{ MPa (187.99 C)}$ | | | |
|-------------|-----------------------------------|-----------------------|-----------------------|-------------------------|
| | v | u | h | s |
| deg-C | m^3/kg | kJ/kg | kJ/kg | $\text{kJ}/\text{kg K}$ |
| Sat. liquid | 0.00114 | 797.3 | 798.6 | 2.2166 |
| Sat. vapour | 0.16333 | 2588.8 | 2784.4 | 6.5233 |

- c) further cooling, to a reduced pressure of 0.8MPa, the fluid is in the wet region, as v lies between v_f and v_g at this pressure.

| T | $p = 0.80 \text{ MPa (170.43 C)}$ | | | |
|-------------|-----------------------------------|-----------------------|-----------------------|-------------------------|
| | v | u | h | s |
| deg-C | m^3/kg | kJ/kg | kJ/kg | $\text{kJ}/\text{kg K}$ |
| Sat. liquid | 0.00111 | 720.2 | 721.1 | 2.0462 |
| Sat. vapour | 0.2404 | 2576.8 | 2769.1 | 6.6628 |

$$\text{Then } 0.16333 = 0.00111 + x_2(0.2404-0.00111),$$

$$\text{from which } x_2 = 0.678$$

$$\begin{aligned} h_2 &= h_f + x h_{fg} \\ &= 721.1 + 0.678(2769.1 - 721.1) \\ &= 2109.5 \text{ kJ/kg} \end{aligned}$$

$$h_1 = 2927.2 \text{ kJ/kg}$$

$$Q = m(h_1 - h_2) = 1 \times (2927.2 - 2109.5) = \mathbf{818 \text{ kJ}}$$

11. Steam (0.05 kg) initially saturated liquid, is heated at constant pressure of 0.2 MPa until its volume becomes 0.0658 m³. Calculate the heat supplied during the process.

[Ans: 128.355 kJ]

Solution:

| <i>T</i> | <i>p</i> = 0.2 MPa (120.23 C) | | | |
|-------------|-------------------------------|----------|----------|----------|
| | <i>v</i> | <i>u</i> | <i>h</i> | <i>s</i> |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00106 | 504.5 | 504.7 | 1.5300 |
| Sat. vapour | 0.8857 | 2529.5 | 2706.7 | 7.1272 |
| 150 | 0.9596 | 2576.9 | 2768.8 | 7.2795 |
| 200 | 1.0803 | 2654.4 | 2870.5 | 7.5066 |
| 250 | 1.1988 | 2731.2 | 2971.0 | 7.7086 |
| 300 | 1.3162 | 2808.6 | 3071.8 | 7.8926 |
| 400 | 1.5493 | 2966.7 | 3276.6 | 8.2218 |

at 0.2 MPa and $x=0$,

$$h_1 = 504.70 \text{ kJ/kg}$$

$$v_2 = 0.0658 / 0.05 = 1.316 \text{ m}^3/\text{kg},$$

$$P_2 = 0.2 \text{ MPa},$$

$$h_2 = 3071.48 \text{ kJ/kg}$$

hence the heat supplied during the process 1-2 is calculated as follows:

$$\begin{aligned} Q &= m (h_1 - h_2) \\ &= 0.05 \times (3071.80 - 504.70) \\ &= 128.355 \text{ kJ} \end{aligned}$$

12. Steam at 0.6 MPa and dryness fraction of 0.9 expands in a cylinder behind a piston isentropically to a pressure of 0.1 MPa. Calculate the changes in volume, enthalpy and temperature during the process.

[Ans: 1.1075 m³, -276 kJ/kg, -59°C]

Solution:

| <i>T</i> | <i>p</i> = 0.60 MPa (158.85 C) | | | |
|-------------|--------------------------------|----------|----------|----------|
| | <i>v</i> | <i>u</i> | <i>h</i> | <i>s</i> |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00110 | 669.4 | 670.6 | 1.9312 |
| Sat. vapour | 0.3175 | 2567.4 | 2756.8 | 6.7600 |

at 0.6 MPa and $x=0.9$,

$T=158.85\text{ C}$

$$h_1 = h_f + x h_{fg}$$

$$= 670.6 + 0.9(2756.8 - 670.6)$$

$$= 2548.18\text{ kJ/kg}$$

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$$\begin{aligned}
 V_1 &= V_f + x V_{fg} \\
 &= 0.0011 + 0.9x(0.3715 - 0.0011) \\
 &= 0.28424 \text{ m}^3/\text{kg}
 \end{aligned}$$

$$\begin{aligned}
 S_1 &= S_f + x S_{fg} \\
 &= 1.9312 + 0.9x(6.7600 - 1.9312) \\
 &= 6.2771 \text{ kJ/kgK}
 \end{aligned}$$

| T | $p = 0.10 \text{ MPa (99.63 C)}$ | | | |
|-------------|----------------------------------|--------|--------|---------|
| | v | u | h | s |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00104 | 417.3 | 417.4 | 1.3030 |
| Sat. vapour | 1.694 | 2506.1 | 2675.5 | 7.3594 |

at 0.1 MPa, constant entropy,

$$S_2 = S_1 = 6.2771 \text{ kJ/kgK}$$

$$T = 99.63 \text{ C}$$

$$X_2 = \frac{S_1 - S_f}{S_g - S_f} = \frac{6.2771 - 1.303}{7.3594 - 1.303} = 0.821$$

$$h_2 = h_f + X_2(h_g - h_f) = 417.4 + 0.821(2675.5 - 417.4) = 2272.2 \text{ kJ/kg}$$

$$v_2 = v_f + X_2(v_g - v_f) = 0.00104 + 0.821(1.694 - 0.00104) = 1.3909 \text{ m}^3/\text{kg}$$

hence

$$dT = 158.85 - 99.63 = 59.22 \text{ C}$$

$$dv = 1.3909 - 0.28424 = 1.107 \text{ m}^3/\text{kg}$$

$$dh = 2548.18 - 2272.2 = 276.0 \text{ kJ/kg}$$

13. The pressure in a steam main pipe is 1.2 MPa; a sample is drawn off and throttled where its pressure and temperature become 0.1 MPa, 140°C respectively. Determine the dryness fraction of the steam in the main stating reasonable assumptions made!

[Ans: 0.986, assuming constant enthalpy]

Solution:

state 2, at 0.1 MPa and T=140C

$$h_2 = 2756.36 \text{ kJ/kg}$$

$$S_2 = 7.5630 \text{ kJ/kgK}$$

| T | $p = 0.10 \text{ MPa (99.63 C)}$ | | | |
|-------------|----------------------------------|--------|--------|---------|
| | v | u | h | s |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00104 | 417.3 | 417.4 | 1.3030 |
| Sat. vapour | 1.694 | 2506.1 | 2675.5 | 7.3594 |
| 100 | 1.6958 | 2506.7 | 2676.2 | 7.3614 |
| 150 | 1.9364 | 2582.8 | 2776.4 | 7.6143 |

at 1.2 MPa, constant enthalpy, $h_1 = h_2 = 2756.36 \text{ kJ/kg}$

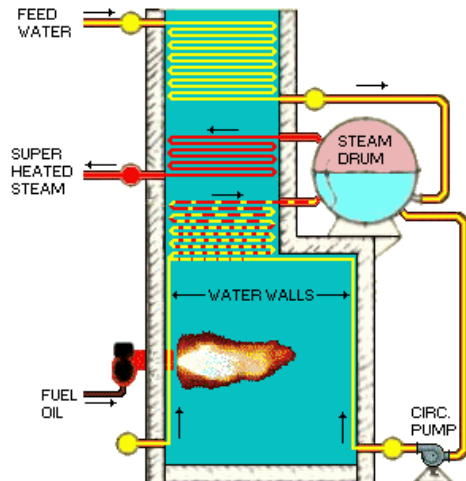
| T | $p = 1.20 \text{ MPa (187.99 C)}$ | | | |
|-------------|-----------------------------------|--------|--------|---------|
| | v | u | h | s |
| deg-C | m ³ /kg | kJ/kg | kJ/kg | kJ/kg K |
| Sat. liquid | 0.00114 | 797.3 | 798.6 | 2.2166 |
| Sat. vapour | 0.16333 | 2588.8 | 2784.4 | 6.5233 |

$$X_1 = \frac{h_1 - h_f}{h_g - h_f} = \frac{2756.36 - 798.6}{2784.4 - 798.6} = 0.9858$$

14. A boiler receives feed water at 20 kPa as saturated liquid and delivers steam at 2 MPa and 500°C. If the furnace of this boiler is oil fired, the calorific value of oil being 42000 kJ/kg; determine the efficiency of the combustion when 4.2 tonnes of oil was required to process 42000 kg of steam.

[Ans: 76%]

Solution:



- a) Constant pressure process.

$$h_1 = h_{f@20 \text{ kPa}} = 251.40 \text{ kJ/kg}$$

$$h_2 = 3467.6 \text{ kJ/kg}$$

SFEE ignoring W , Δke and ΔPe :

$$Q_s = m_s (h_2 - h_1) = 42000 (3467.6 - 251.4) = 135 \times 10^6 \text{ kJ}$$

- b) The heat generated by burning oil in the furnace is

$$= \text{mass of oil burned} \times \text{calorific value}$$

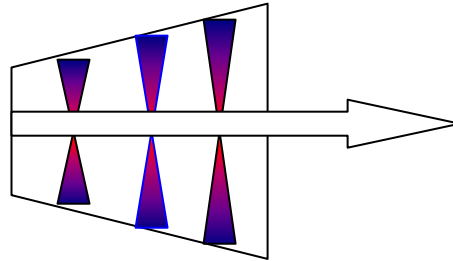
$$= 4200 \times 42000 = 176 \times 10^6 \text{ kJ}$$

$$\therefore \text{Efficiency} = \frac{\text{Energy Output}}{\text{Energy Input}} = \frac{135}{176} = 76.7\%$$

15. 10 kg/s steam at 6 MPa and 500°C expands isentropically in a turbine to a pressure of 100 kPa. If the heat transfer from the casing to surroundings represents 1 per cent of the overall change of enthalpy of the steam, calculate the power output of the turbine. Assume exit is 5 m above entry and that initial velocity of steam is 100 m/s whereas exit velocity is 10 m/s.

[Ans: 9 MW]

Solution:



At 6 MPa, 500 °C

$$h_1 = 3422.2 \text{ kJ/kg}$$

$$s_1 = 6.8803 \text{ kJ/kgK}$$

at 100 kPa,

$$s_f = 1.303, s_{fg} = 6.056 \text{ kJ/kgK}$$

$$h_f = 417, h_{fg} = 2258 \text{ kJ/kg}$$

$$x_2 = x_2 = \frac{6.8803 - 1.303}{6.056} = 0.921$$

$$h_2 = 417 + 0.921 \times 2258 = 2496.5 \text{ kJ/kg}$$

The Steady Flow Energy Equation applies to this situation:

$$Q - W = m \left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right]$$

$$\text{but } Q = - \frac{m}{100} (h_2 - h_1) \text{ Heat loss (negative sign)}$$

$$W = -m \left[1.01 (h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right]$$

$$W = 10 \times \left[1.01(3422.2 - 2496.5) + \frac{10^2 - 100^2}{2 \times 1000} + \frac{9.8 \times 5}{1000} \right] = 9 \text{ MW}$$