Thermodynamics (ME2121)
Tutorial 1

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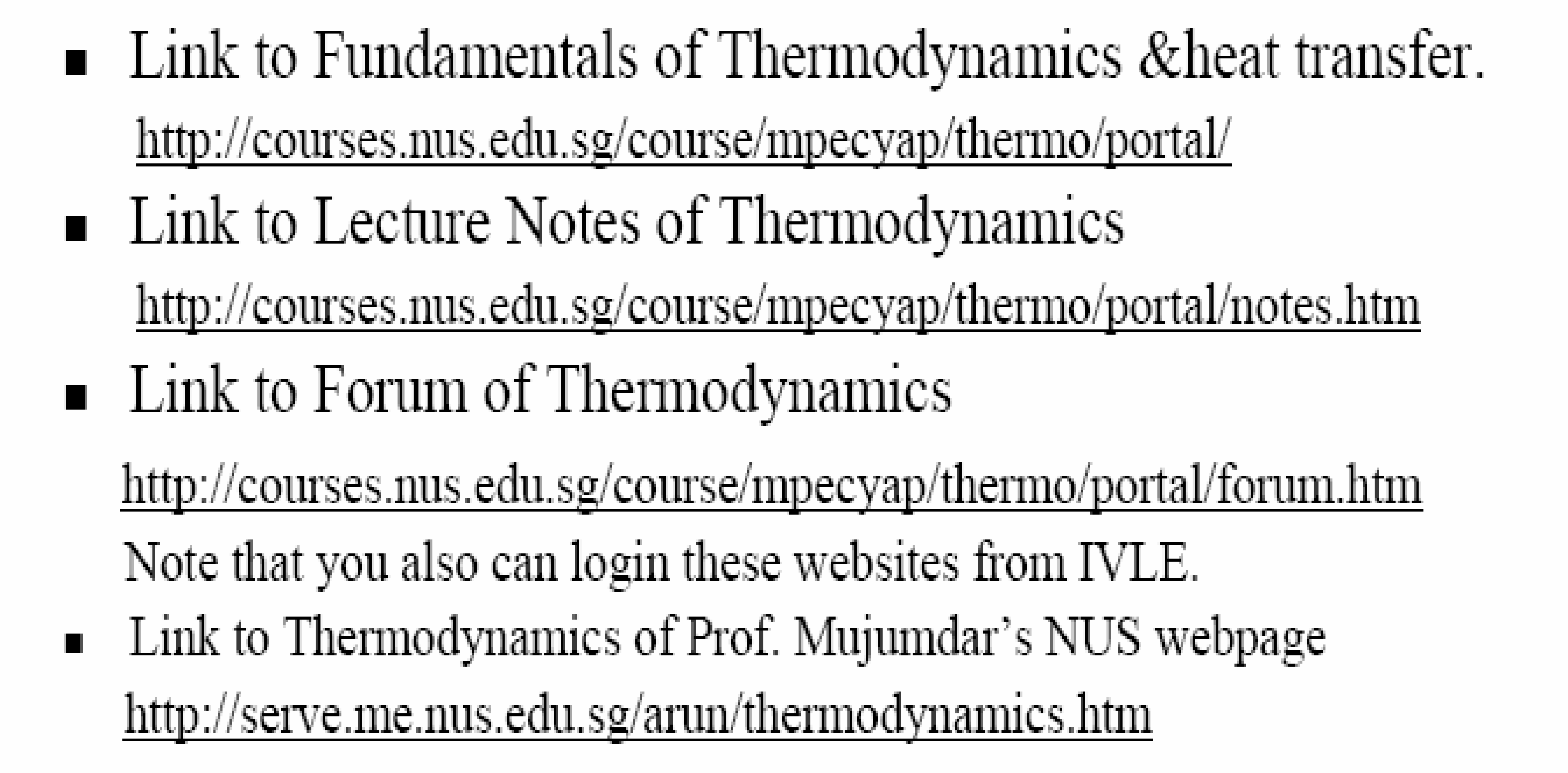
Some useful links



- Link to Fundamentals of Thermodynamics &heat transfer.
  http://courses.nus.edu.sg/course/mpecyap/thermo/portal/
- Link to Lecture Notes of Thermodynamics
  http://courses.nus.edu.sg/course/mpecyap/thermo/portal/notes.htm
- Link to Forum of Thermodynamics

  http://courses.nus.edu.sg/course/mpecyap/thermo/portal/forum.htm

  Note that you also can login these websites from IVLE.
- Link to Thermodynamics of Prof. Mujumdar’s NUS webpage
  http://serve.me.nus.edu.sg/arun/thermodynamics.htm

Outline and objectives of Tutorial 1

Outline

1. A brief summary of chapter 2
2. A few demos for the use of water and steam data tables
3. Six tutorial problems related to Chapter 2

Objectives

1. Intensifying the understanding of basic concepts
2. Knowing the use of water and steam data tables
3. Applications of basic concepts and property data tables to solve practical problems

You are strongly encouraged to obtain raw solution before attendance of each tutorial!

A survey

1. How many do read questions before coming to class?
2. How many try to work out solutions -even partially?
3. How many simply want to get full solutions?
4. How many keep up with class material i.e. study at home after class?

Summary of Chapter 2

* Basic concepts used frequently in Thermodynamics

Pure substance and its Phase-change process (Compressed and saturated liquid, mixture, saturated and superheated vapor), Property diagrams for Phase-change process (T-v, P-v, P-h, etc.), Enthalpy ($h= u + Pv$), Quality, etc.

* The use of various property tables

Ideal-gas specific heats of various common gas (Table A-2 P825), Saturated water and steam table (Table A-4, P830), Superheated water (Table A-6, P834), Compressed liquid water (Table A-7, P838), etc.

* The ideal-gas equation of state

$Pv = RT \qquad PV = mRT \qquad PV = nR_uT$

R is called the gas constant, R_u is the universal gas constant

* Specific heats

$du = CvdT$

$dh = CpdT$

$Cp = Cv + R$

Specific heat ratio, $k = Cp/Cv$

The use of water and steam table
Table A-4

Temp T °C	Press Psat kPa	Specific volume m^3/kg		Internal energy kJ/kg			Enthalpy kJ/kg			Entropy kJ/kg K		
		Sat liquid v_f	Sat vapor v_g	Sat liquid u_f	Evap. u_{fg}	Sat vapor u_g	Sat liquid hu_f	Evap. h_{fg}.	Sat vapor h_g	Sat liquid s_f	Evap. s_{fg}	Sat vapor s_g
0.01	0.6113	0.001	206.14	0	2375.3	2375.3	0.01	2501.3	2501.4	0.0	9.1562	9.1562
5	**0.8721**	**0.001**	**147.12**	**20.97**	**2361.3**	**2382.3**	**20.98**	**2489.6**	**2510.6**	**0.0761**	**8.9496**	**9.0257**
10	1.2276	0.001	106.38	**42**	2347.2	2389.2	42.01	2477.7	2519.8	0.151	8.7498	8.9008
15	1.7051	0.001	77.93	**62.99**	2333.1	2396.1	62.99	2465.9	2528.9	0.2245	8.5569	8.7814
….	….	….	….	…	…	….	…	….	…..	….	….	…..

Examples

1. T =5 °C

2. T =13.2 °C

The use of water and steam table Table A-4

Examples

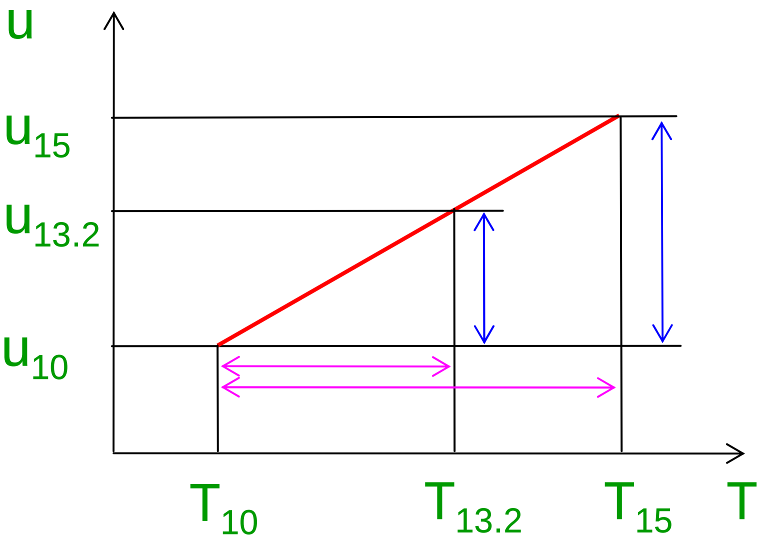
2. T =13.2 °C Not available directly in the table, so we need to do a linear interpolation as follows

$$\frac{u_{T=13.2\,^{o}C} - u_{T10}}{u_{T15} - u_{T10}} = \frac{T_{13.2} - T_{10}}{T_{15} - T_{10}} \Rightarrow$$

$$u_{T=13.2\,^{o}C} = u_{T10} + (u_{T15} - u_{T10}) \times \frac{T_{13.2} - T_{10}}{T_{15} - T_{10}}$$

$$= 42 + (62.99 - 42) \times \frac{13.2 - 10}{15 - 10}$$

$$= 55.43 kJ / kg$$



The use of water and steam table
Table A-5

Press Psat kPa	Temp T °C	Specific volume m^3/kg		Internal energy kJ/kg			Enthalpy kJ/kg			Entropy kJ/kg K		
		Sat liquid v_f	Sat vapor v_g	Sat liquid u_f	Evap. u_{fg}	Sat vapor u_g	Sat liquid hu_f	Evap. h_{fg}.	Sat vapor h_g	Sat liquid s_f	Evap. s_{fg}	Sat vapor s_g
0.6113	0.01	0.001	206.14	0.0	2375.3	2375.3	0.01	2501.3	2501.4	0	9.1562	9.1562
1	6.98	0.001	129.21	29.3	2355.7	2385	29.3	2484.9	2514.2	0.1059	8.8697	8.9756
1.5	13.03	0.001	87.98	54.71	2338.6	2393.3	54.71	2470.6	2525.3	0.1957	8.6322	8.8279
2	17.5	0.001	67	73.48	2326.0	2399.5	73.48	2460	2533.5	0.2607	8.4629	8.7237
….	….	….	….	…	…	….	…	….	…..	….	….	…..

Examples

1. P = 1 kPa

2. P = 1.2 kPa. Not available directly in the table, so we need to do a linear interpolation as follows

$$u_{p=1.2kPa} = u_{p1.5} + (u_{p1.5} - u_{p1.0}) \times \frac{P_{1.2} - P_{1.0}}{P_{1.5} - P_{1.0}}$$

$$= ?$$

The use of superheated water table Table A-6

T ºC	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg K
	P = 0.20 MPa (120.23 ºC)				P = 0.30 MPa (133.55 ºC)			
Sat	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761	7.0778
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115
250	1.1988	2731.2	2971	7.7086	0.7964	2728.7	2967.6	7.5166
…	…	…	…	…	…	…	…	…

Examples

1. P = 0.2 MPa and T=150 ºC
2. P = 0.2 MPa and T=180 ºC. Not available directly in the table, so we need to do a linear interpolation as follows

$$\mathrm{u}_{\mathrm{T}=180\,^{\circ}\mathrm{C}} = \mathrm{u}_{\mathrm{T150}} + (\mathrm{u}_{\mathrm{T200}} - \mathrm{u}_{\mathrm{T150}}) \times \frac{T_{180} - T_{150}}{T_{200} - T_{150}}$$

$$= 2576.9 + (2654.4 - 2576.9) \times \frac{180 - 150}{200 - 150}$$

$$= 2623.4 kJ / kg$$

The use of superheated water table
Table A-6

T °C	**v m³/kg**	**u kJ/kg**	**h kJ/kg**	**s kJ/kg K**	**v m³/kg**	**u kJ/kg**	**h kJ/kg**	**s kJ/kg K**
	P = 0.20 MPa (120.23 °C)				**P = 0.30 MPa (133.55 °C)**			
Sat	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761	7.0778
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115
…	…	…	…	…	…	…	…	…

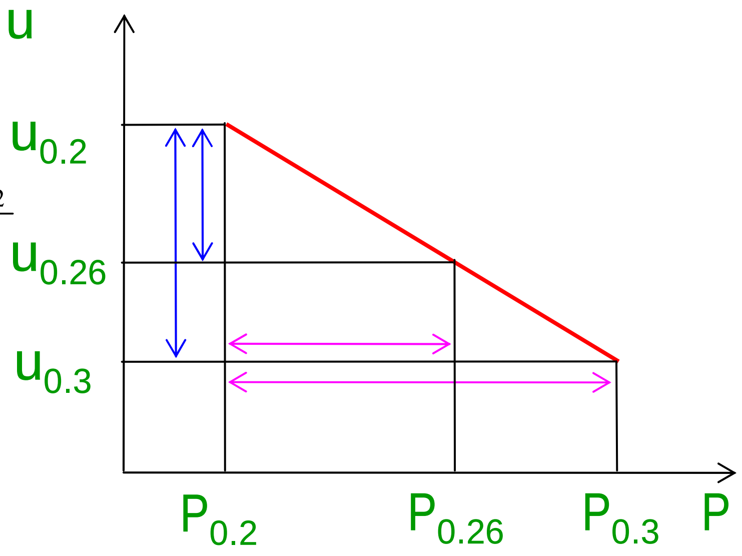
3. P = 0.26 MPa and T=150 °C. Not available directly in the table, so we need to do a linear interpolation as follows

$$\frac{u_{P\,0.2,\,T150} - u_{P=0.26\text{MPa},T=150\,^{o}C}}{u_{P\,0.2,T150} - u_{P\,0.3,T150}} = \frac{P_{0.26} - P_{0.2}}{P_{0.3} - P_{0.2}}$$

$$u_{P=0.26\text{MPa},T=150\,^{o}C} = u_{P\,0.2,\,T150} - (u_{P\,0.2,T150} - u_{P\,0.3,T150}) \times \frac{P_{0.26} - P_{0.2}}{P_{0.3} - P_{0.2}}$$

$$= 2576.9 - (2576.9 - 2570.8) \times \frac{0.26 - 0.2}{0.3 - 0.2}$$

$$= 2573.24 kJ/kg$$



The use of superheated water table
Table A-6

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg K
	P = 0.20 MPa (120.23 °C)				**P = 0.30 MPa (133.55 °C)**			
Sat	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761	7.0778
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115
…	…	…	…	…	…	…	…	…

4. P = 0.26 MPa and T=180 °C. Not available directly in the table, so we need to do a linear interpolation as follows

First, do a linear interpolation to get the value of u at P = 0.26 MPa and T=200 °C
Note: we have known the value of u at P = 0.26 MPa and T = 150 °C from example 3

$$\frac{\mathrm{u}_{\mathrm{P\,0.2,\,T200}} - \mathrm{u}_{\mathrm{P=0.26MPa,T=200\,^oC}}}{\mathrm{u}_{\mathrm{P\,0.2,T200}} - \mathrm{u}_{\mathrm{P\,0.3,T200}}} = \frac{P_{0.26} - P_{0.2}}{P_{0.3} - P_{0.2}}$$

$$\mathrm{u}_{\mathrm{P=0.26MPa,T=200\,^oC}} = \mathrm{u}_{\mathrm{P\,0.2,\,T200}} - (\mathrm{u}_{\mathrm{P\,0.2,T200}} - \mathrm{u}_{\mathrm{P\,0.3,T200}}) \times \frac{P_{0.26} - P_{0.2}}{P_{0.3} - P_{0.2}}$$

$$= 2654.4 - (2654.4 - 2650.7) \times \frac{0.26 - 0.2}{0.3 - 0.2}$$

$$= 2652.18 kJ/kg$$

The use of superheated water table Table A-6

Then, as example 2, do a linear interpolation at P = 0.26 MPa to obtain the value of u at T = 180 ^{o}C

$$u_{P=0.26\text{MPa},T=180\,^{o}C} = u_{P\,0.26\text{MPa},\,T\,150} + (u_{P\,0.26\text{MPa},T200} - u_{P0.26\text{MPa},T150}) \times \frac{T_{180} - T_{150}}{T_{200} - T_{150}}$$

$$= 2573.24 + (2652.18 - 2573.24) \times \frac{180 - 150}{200 - 150}$$

$$= 2620.6 kJ / kg$$

The use of compressed liquid water table Table A-7

This table shares the similar form as the superheated water table. Therefore, please refer to the demo calculation of Table A-6 for the use of Table A-7

Note: in all the examples above, we take the calculation of internal energy as an demo. Following the same line of calculation, we can obtain all other properties shown on Tables A-4 through A-7, i.e. entropy, specific volume, etc..

Problem 1

<u>Problem A1</u>(Problem 2-45)

Water in a 5-cm-deep pan is observed to boil at 98°C. At what temperature will the water in a 40-cm-deep pan boil? Assume both pans are full of water.

<u>Solution</u>

Properties: The density of liquid water is approximately $\rho = 1000 kg/m^3$

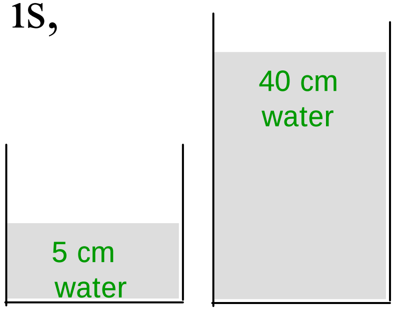
The pressure at the bottom of the 5cm deep pan is the saturation pressure corresponding to the boiling point of 98°C **(Table A-4):** $P_1 = 94.63$ kPa

The pressure difference between the bottoms of the two pans is,

$$\Delta P = \rho g \Delta h = 1000*9.81*0.35 = 3.43 \text{ kPa}$$

Thus, the pressure at the bottom of 40 cm deep pan is,

$$P_2 = P_1 + \Delta P = 94.63 + \Delta P = 98.06 \text{kPa}$$



Find $T_{boiling}$ corresponding to this pressure, P_2, from **Table A-5.**

$$T_{boiling} = T_{sat@98.06kPa} = 99.0^o C$$

Problem 2

Problem A2 (Problem 2-52)

A 0.5 m^3 vessel contains 10 kg of refrigerant 134a at – 20^oC. Determine (a) the pressure, (b) the total internal energy, and (c) the volume occupied by the liquid phase.

R-134a
10 kg
- 20^0C

Solutions:

(a) The specific volume of the refrigerant is

$$v = \frac{V}{m} = \frac{0.5\ m^3}{10\,kg} = 0.05\,m^3 / kg$$

At -20^0C, $v_f = 0.0007361\ m^3/\ kg$ and $v_g.=0.1464 m^3/kg$ **(Table A-11).**

Thus, the tank contains a liquid-vapor mixture since $v_f < v < v_g$, and the pressure must be the saturation pressure at the specified temperature, **(Table A-11)**

$$P = P_{sat@\,-20^0c} = 132.99\ kPa$$

Problem 2

Problem A2 (Problem 2-52)

A 0.5-m^3 vessel contains 10 kg of refrigerant – 134a at – 20^{o}C. Determine (a) the pressure, (b) the total internal energy, and (c) the volume occupied by the liquid phase.

Solutions:

R-134a
10 kg
- 20^{0}C

(b) The quality of the refrigerant-134a and its total internal energy are determined from

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.05 - 0.0007361}{0.1464 - 0.0007361} = 0.338$$

Thus, the specific internal energy

$$u = u_f + x u_{fg} = 24.17 + 0.338 \times (215.84 - 24.17) = 88.95\, kJ/kg$$

and the total internal energy

$$U = mu = (10\, kg)(88.95\ kJ/kg) = 889.5\ kJ$$

Problem 2

Problem A2 (Problem 2-52)

A 0.5-m^3 vessel contains 10 kg of refrigerant – 134a at – 20^{o}C. Determine (a) the pressure, (b) the total internal energy, and (c) the volume occupied by the liquid phase.

Solutions:

R-134a
10 kg
- 20^{0}C

(c) The mass of the liquid phase and its volume are determined from

$x = m_g/m = (m - m_f)/m$

Rearranging

$m_f = (1\text{-}x)m = (1\text{-}\ 0.338) \times 10 = 6.62$ kg

$V_f = m_f\, v_f = (6.62 \text{ kg})\ (0.0007361 \text{ m}^3/\text{kg}) = 0.00487 \text{ m}^3$

Problem 3

Problem A3 (Problem 2-57)

A piston-cylinder device initially contains 50 L of liquid water at 25°C and 300 kPa. Heat is added to the water at constant pressure until the entire liquid is vaporized.

(a) What is the mass of the water?

(b) What is the final temperature?

(c) Determine the total enthalpy change.

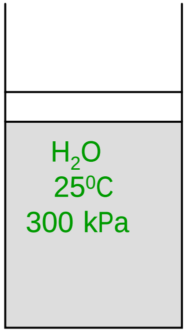
(d) Show the process on a T-v diagram with respect to saturation lines.

Solutions:

Initially the cylinder contains compressed liquid (since $P>P_{atm\,@\,25}{}^{0}c = 3.169\ kPa$) that can be approximated as a saturated liquid at the specified temperature, from **Table A-4**

Specific volume: $v_1 \cong v_{f\,@\,25^0 c} = 0.001003\ m^3/kg$

Enthalpy: $h_1 \cong h_{f\,@\,25^0 C} = 104.89\, kJ/kg$



(a) The mass is determined from

$$m = \frac{V_1}{v_1} = \frac{0.50\, m^3}{0.001003\, m^3/kg} = 49.85\, kg$$

Problem 3

Problem A3 (Problem 2-57)

A piston-cylinder device initially contains 50 L of liquid water at 25°C and 300 kPa. Heat is added to the water at constant pressure until the entire liquid is vaporized.

(a) What is the mass of the water?

(b) What is the final temperature?

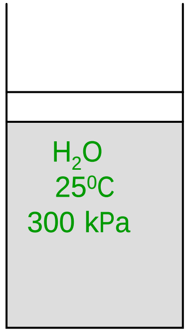
(c) Determine the total enthalpy change.

(d) Show the process on a T-v diagram with respect to saturation lines.

Solutions:

(b) At the final state, the cylinder contains saturated vapor and thus the final temperature must be the saturation temperature at the final pressure, **(Table A-5)**

$$T = T_{sat@300\,kPa} = 133.55^{0}C$$



(c) The final enthalpy is $h_2 = h_{g\,@\,300\,kPa} = 2725.3$ kJ/kg. **(Table A-5)**
Thus,

$$\Delta H = m(h_2 - h_1) = (49.85\,kg)(2725.3 - 104.89)\,kJ/kg = 130{,}627\,kJ$$

Problem 3

Problem A3 (Problem 2-57)

A piston-cylinder device initially contains 50 L of liquid water at 25^{o}C and 300 kPa. Heat is added to the water at constant pressure until the entire liquid is vaporized.

(a) What is the mass of the water?

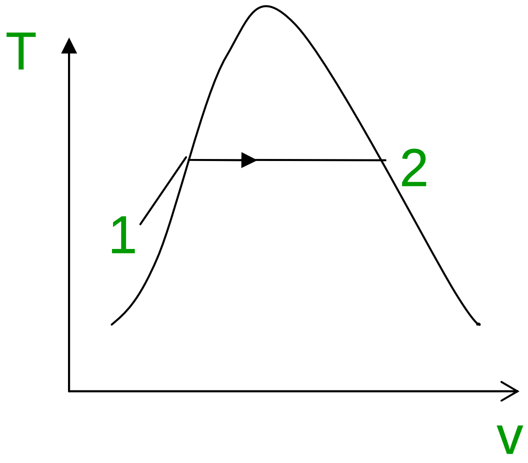
(b) What is the final temperature?

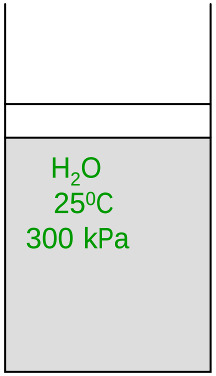
(c) Determine the total enthalpy change.

(d) Show the process on a T-v diagram with respect to saturation lines.

Solutions:

(d)





Problem 4

Problem A4(Problem 2-62)

Piston-cylinder device contains 0.8 kg of steam at 300^oC and 1 MPa. Steam is cooled at constant pressure until one-half of the mass condenses.

(a) Find the final temperature.

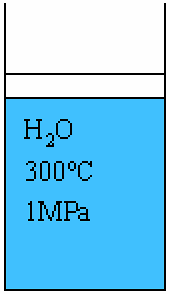
(b) Determine the volume change.

(c) Show the process on a T-v diagram.

Solution:

(a) At the final state the cylinder contains saturated liquid-vapor mixture, and thus the final temperature must be the saturation temperature at the final pressure, **(Table A-5)**

$$T = T_{sat@1\ MPa} = 179.91^0C$$



(b) The quality at the final state is specified to be $x_2 = 0.5$.

The specific volumes at the initial state of $P_1 = 1.0$ MPa, $T_1 = 300^0C$

$v_1 = 0.2579\ m^3/kg$ **(Table A-6)**

at the final state of $P_2 = 1.0$ MPa, $T_2 = T_{sat@1\ MPa} = 179.91^0C$

$v_g = 0.19444\ m^3/kg$ **(Table A-5)**

$v_f = 0.001127\ m^3/kg$ **(Table A-5)**

Problem 4

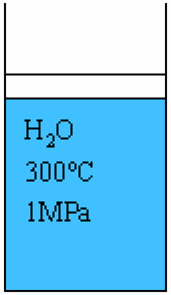
Problem A4(Problem 2-62)

Piston-cylinder device contains 0.8 kg of steam at 300°C and 1 MPa. Steam is cooled at constant pressure until one-half of the mass condenses.

(a) Find the final temperature.

(b) Determine the volume change.

(c) Show the process on a T-v diagram.



Solution:

(b) The quality at the final state is specified to be $x_2 = 0.5$.

The specific volumes at the final state of $P_2 = 1.0$ MPa, $x_2 = 0.5$

$$\begin{aligned} v_2 = v_f + x_2\, v_{fg} &= 0.001127 + 0.5 \times (\, 0.19444 - 0.0001127) \\ &= 0.0978 \text{ m}^3/\text{ kg} \end{aligned}$$

Thus,

$$\Delta V = m\,(\, v_2 - v_1) = (0.8 \text{ kg})\, (0.0978 - 0.2579\,) \text{ m}^3/\text{ kg} = -\, 0.128 \text{ m}^3$$

Problem 4

Problem A4(Problem 2-62)

Piston-cylinder device contains 0.8 kg of steam at 300°C and 1 MPa. Steam is cooled at constant pressure until one-half of the mass condenses.

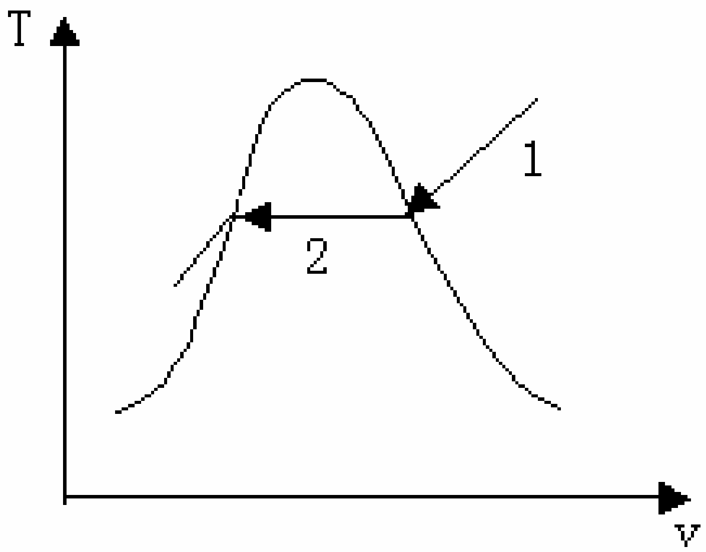
(a) Find the final temperature.

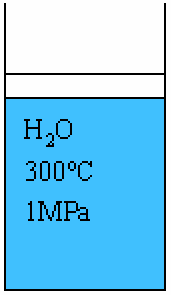
(b) Determine the volume change.

(c) Show the process on a T-v diagram.

Solution:

(c)





Problem 5

Problem A5(Problem 2-104)

Determine the enthalpy change Δh of nitrogen, in kJ/kg, as it is heated from 600 to 1000K, using:

(a) the empirical specific heat equation as a function of temperature (Table A-2c)

(b) the Cp value at the average temperature (Table A-2b)

(c) the Cp value at room temperature (Table A-2a)

<u>Solution:</u>

(a) Using the empirical equation from Table A-2c (P827, textbook)

$$\overline{C}_p(T) = a + bT + cT^2 + dT^3$$

where a=28.9,b=-0.1571x10-2,c=0.8081x10-5, and d=-2.873x10-9. Then

$$\begin{aligned}\overline{\Delta h} &= \int_1^2 \overline{C}_p(T)dT = \int_1^2 (a + bT + cT^2 + dT^3)dT \\ &= a(T_2 - T_1) + \frac{1}{2}b(T_2^2 - T_1^2) + \frac{1}{3}c(T_2^3 - T_1^3) + \frac{1}{4}d(T_2^4 - T_1^4) \\ &= 12544 kJ/kmol\end{aligned}$$

Problem 5

$$\Delta h = \frac{\overline{\Delta h}}{M_{O_2}} = \frac{12544}{28.013} = 447.8(kJ/kg)$$

(b) Using the constant Cp value from Table A-2b at the average temperature (800K)

$$C_{p,ave} = C_{p@800K} = 1.121 kJ/kg.K$$

$$\Delta h = C_{p,ave}(T_2 - T_1) = 448.4 kJ/kg$$

$$error = \frac{448.4 - 447.8}{447.8} \times 100\% = 0.134\%$$

(c) Using the constant C_p value from **Table A-2a** at room temperature (300K)

$$C_{p,ave} = C_{p@300K} = 1.039 kJ/kg.K$$

$$\Delta h = C_{p,ave}(T_2 - T_1) = 415.6 kJ/kg$$

$$error = \frac{415.6 - 447.8}{447.8} \times 100\% = -7.19\%$$

Problem 6

Problem A6 (Problem 2-106)
Determine the internal energy change Δu of hydrogen, in kJ/kg, as it is heated from 400 to 1000K, using:
(a) the empirical specific heat equation as a function of temperature (Table A-2c)
(b) the Cv value at the average temperature (Table A-2b)
(c) the Cv value at room temperature (Table A-2c)

Solution:

(a) Using the empirical relation for $\overline{C}_p(T)$ from Table A-2c and relating it to $\overline{C}_v(T)$

$$\overline{C}_v(T)=\overline{C}_p(T)-R_u=(a-R_u)+bT+cT^2+dT^3$$

where a=29.11,b=-0.1916x10^{-2},c=0.4003x10^{-5}, and d=-0.8704x10^{-9}. Then

Problem 6

$$\overline{\Delta u} = \int_1^2 \overline{C}_v(T)dT = \int_1^2 [(a - R_u) + bT + cT^2 + dT^3]dT$$

$$= (a - R_u)(T_2 - T_1) + \frac{1}{2}b(T_2^2 - T_1^2) + \frac{1}{3}c(T_2^3 - T_1^3) + \frac{1}{4}d(T_2^4 - T_1^4)$$

$$= 12691 kJ / kmol$$

$$\Delta u = \frac{\overline{\Delta u}}{M_{H_2}} = \frac{12691}{2.016} = 6295.3(kJ / kg)$$

Problem 6

Solution:

(b) Using the constant C_v value from **Table A-2b** at the average temperature (700K)

$$C_{v,ave} = C_{v@700K} = 10.48 kJ/kg.K$$

$$\Delta u = C_{v,ave}(T_2 - T_1) = 6288 kJ/kg$$

$$error = \frac{6288 - 6295.3}{6295.3} \times 100\% = -0.116\%$$

(c) Using the constant Cv value from **Table A-2a** at the room temperature (300K)

$$C_{v,ave} = C_{v@300K} = 10.183 kJ/kg.K$$

$$\Delta u = C_{v,ave}(T_2 - T_1) = 6110 kJ/kg$$

$$error = \frac{6110 - 6295.3}{6295.3} \times 100\% = -2.94\%$$

Thank you for your attendance!