Homework #1

MEMS 0051 - Introduction to Thermodynamics

Assigned January 18^{th}, 2020
Due: January 24^{th}, 2020

Problem #1

Given the following properties, determine the remaining properties (i.e. pressure, temperature, specific volume and quality, if applicable), for water. Indicate if the water is existing as a compressed/subcooled liquid, saturated liquid water, saturated vapor or superheated steam. Additionally, using the Matlab Script titled "`Pv_and_Tv_curves`.m", plot and label each item on both a $P-\nu$ and $T-\nu$ diagram. Note: interpolation may be required multiple times.

(a) $T = 145$ [°C], ν =0.2 [m^3/kg]

Looking at Table B.1.1 on page 776, the given specific volume is between the saturated liquid and saturated vapor specific volume. Thus, the pressure is the saturation pressure, 415.4 [kPa], and the quality is found as:

$$x = \frac{\nu - \nu_f}{\nu_g - \nu_f} = \frac{(0.2 - 0.001085)\,[\text{m}^3/\text{kg}]}{(0.44632 - 0.001085)\,[\text{m}^3/\text{kg}]} = 0.4468$$

(b) $T = 255$ [°C], $P = 3{,}000$ [kPa]

Looking at Table B.1.1 on page 778, the given pressure is higher than the saturation pressure for the given temperature. Thus, the substance is a superheated vapor, and the quality is undefined. The specific volume is found by looking at Table B.1.3 on page 787 and interpolating between the 250 and 300 °C entries:

$$\frac{(255-250)\,[°\text{C}]}{(300-250)\,[°\text{C}]} = \frac{(\nu - 0.07058)\,[\text{m}^3/\text{kg}]}{(0.08114 - 0.07058)\,[\text{m}^3/\text{kg}]} \implies \nu = 0.02306\,[\text{m}^3/\text{kg}]$$

(c) $T = 370$ [°C], $P = 15{,}000$ [kPa]

Looking at Table B.1.1 on page 778, the given pressure is less than the saturation pressure for the given temperature. Thus, the substance is a superheated vapor, and the quality is undefined. The specific volume is found by looking at Table B.1.3 on page 789 and interpolating between the 350 and 400 °C entries:

$$\frac{(370-350)\,[°\text{C}]}{(400-350)\,[°\text{C}]} = \frac{(\nu - 0.01147)\,[\text{m}^3/\text{kg}]}{(0.01565 - 0.01147)\,[\text{m}^3/\text{kg}]} \implies \nu = 0.01314\,[\text{m}^3/\text{kg}]$$

(d) $T = 100$ [°C], $\nu = 16.8$ [m^3/kg]

Looking at Table B.1.1 on page 776, the given specific volume is greater than the saturated vapor specific volume. Thus, the fluid exists as a superheated vapor, and the quality is undefined. Looking at Table B.1.3 on page 784, the specific volume exists between the 10 and 50 [kPa] pressure entry tables. Interpolating between pressure at a temperature of 100 °C:

$$\frac{(P-10)\,[\text{kPa}]}{(50-10)\,[\text{kPa}]} = \frac{(16.8 - 17.19561)\,[\text{m}^3/\text{kg}]}{(3.41833 - 17.19561)\,[\text{m}^3/\text{kg}]} \implies P = 11.15\,[\text{kPa}]$$

(e) $T = 200$ [°C], $P = 5{,}000$ [kPa]

Looking at Table B.1.1 on page 778, the pressure is greater than the saturation pressure. Thus, the fluid exists as a compressed/subcooled liquid, and the quality is undefined. Looking at Table B.1.4 on page 790, the specific volume is found to be 0.001153 [m^3/kg].

(f) $P = 760$ [kPa], x=0.72

Since quality is given, the fluid is existing as saturated water. Looking at Table B.1.2 on page 780, we interpolate between 750 and 800 [kPa] to determine the saturation temperature:

$$\frac{(760 - 750)\,[\text{kPa}]}{(800 - 750)\,[\text{kPa}]} = \frac{(T - 167.77)\,[^\circ\text{C}]}{(170.43 - 167.77)\,[^\circ\text{C}]} \implies T = 168.30\,[^\circ\text{C}]$$

We interpolate between 750 and 800 [kPa] to determine the saturated liquid specific volume:

$$\frac{(760 - 750)\,[\text{kPa}]}{(800 - 750)\,[\text{kPa}]} = \frac{(\nu_f - 0.001111)\,[\text{m}^3/\text{kg}]}{(0.001115 - 0.001111)\,[\text{m}^3/\text{kg}]} \implies \nu_f = 0.001112\,[\text{m}^3/\text{kg}]$$

We interpolate between 750 and 800 [kPa] to determine the saturated vapor specific volume:

$$\frac{(760 - 750)\,[\text{kPa}]}{(800 - 750)\,[\text{kPa}]} = \frac{(\nu_f - 0.25560)\,[\text{m}^3/\text{kg}]}{(0.24043 - 0.25560)\,[\text{m}^3/\text{kg}]} \implies \nu_g = 0.25257\,[\text{m}^3/\text{kg}]$$

The specific volume is determined from the definition of quality:

$$\nu = (1 - x)\nu_f + x\nu_g = (0.8)(0.001112\,[\text{m}^3/\text{kg}]) + (0.2)(0.25257\,[\text{m}^3/\text{kg}]) = 0.051403\,[\text{m}^3/\text{kg}]$$

(g) $P = 125$ [kPa], T=20 [°C]

Looking at Table B.1.2 on page 780, the temperature is less than the saturated temperature for the given pressure, thus the fluid exists as a compressed/subcooled liquid. The quality is undefined. Since the lowest pressure entry on Table B.1.4 on page 790 is 500 [kPa], we use Table B.1.1 on page 776 and take the saturated liquid specific volume at 20 °C. Thus, the specific volume is 0.001002 [m^3/kg].

(h) $P = 1{,}300$ [kPa], $\nu = 0.254$ [m^3/kg

Looking at Table B.1.2 on page 782, the specific volume is greater than the saturated vapor specific volume, thus the fluid exists as a superheated vapor, and the quality is undefined. Looking at Table B.1.3 on page 786, we see the specific volume exists between 400 and 500 °C. Constructing an intermediate pressure table for 1,300 [kPa], the specific volume at 400 °C is:

$$\frac{(1,300 - 1,200)\,[\text{kPa}]}{(1,400 - 1,200)\,[\text{kPa}]} = \frac{(\nu_{400\,[^\circ\text{C}]} - 0.25480)\,[\text{m}^3/\text{kg}]}{(0.21780 - 0.25480)\,[\text{m}^3/\text{kg}]} \implies \nu_{400\,[^\circ\text{C}]} = 0.23630\,[\text{m}^3/\text{kg}]$$

Constructing an intermediate pressure table for 1,300 [kPa], the specific volume at 500 °C is:

$$\frac{(1,300 - 1,200)\,[\text{kPa}]}{(1,400 - 1,200)\,[\text{kPa}]} = \frac{(\nu_{500\,[^\circ\text{C}]} - 0.29463)\,[\text{m}^3/\text{kg}]}{(0.25215 - 0.29463)\,[\text{m}^3/\text{kg}]} \implies \nu_{500\,[^\circ\text{C}]} = 0.27339\,[\text{m}^3/\text{kg}]$$

Interpolating between 400 and 500 °C at 1,300 [kPa]:

$$\frac{(T_{1,300\,[\text{kPa}]} - 400)\,[^\circ\text{C}]}{(500 - 400)\,[^\circ\text{C}]} = \frac{(0.254 - 0.23630)\,[\text{m}^3/\text{kg}]}{(0.27339 - 0.23630)\,[\text{m}^3/\text{kg}]} \implies T_{1,300\,[\text{kPa}]} = 447.72\,[^\circ\text{C}]$$

(i) $P = 1{,}250$ [kPa], T =63 [°C]

Looking at Table B.1.2 on page 782, the given temperature is less than the saturation temperature for the given pressure. Thus, the fluid exists as a compressed/subcooled liquid and the quality is undefined. The specific volume can be found via double-interpolation between pressure and temperature using Table B.1.4 on page 790, or through single-interpolation between temperature using Table B.1.2 on page 776. Using the latter:

$$\frac{(63 - 60)\,[^\circ\text{C}]}{(65 - 60)\,[^\circ\text{C}]} = \frac{(\nu - 0.001017)\,[\text{m}^3/\text{kg}]}{(0.001020 - 0.001017)\,[\text{m}^3/\text{kg}]} \implies \nu = 0.001019\,[\text{m}^3/\text{kg}]$$

(j) $T = 100$ °C, $P = 101.3$ [kPa]

Looking at Table B.1.1 on page 776 of the steam tables, water at 100 °C has a saturation pressure of 101.3 [kPa]. Therefore, it is existing as a saturated water. Without any other identifying property (i.e. quality), the specific volumes can range between that of the saturated liquid and saturated vapor specific volumes: $0.001044 \leq \nu\,[\text{m}^3/\text{kg}] \leq 1.67290$.

(k) $T = 180$ °C, $P = 2{,}000$ [kPa]

Looking at Table B.1.1 on page 776 of the steam tables, water at 180 °C has a saturation pressure of 1,002.2 [kPa]. The given pressure is greater than the saturation pressure ($P > P_{\text{sat}}$), which indicates it is existing as a compressed/subcooled liquid. Alternatively, we could look at Table B.1.2 on page 782 and see for an entry of 2,000 [kPa] that the saturation temperature is 212.42 °C. The given temperature is less than the saturation temperature ($T < T_{\text{sat}}$), which indicates again it is existing as a compressed/subcooled liquid. Quality is therefore undefined

Using Table B.1.4 on page 790, the specific volume correspond to 180 °C and 2,000 [kPa]is found as 0.001127 [m^3/kg]. Alternatively, we recognize that water is an incompressible substance and can use the saturate water temperature table (B.1.1) on page 776 and take the specific volume corresponding to the given temperature. We note the saturated liquid specific volume taken at 180 °C is the same as the specific volume taken from the compressed/subcooled liquid table.

(l) $T = 160$ °C, $P = 400$ [kPa]

Looking at Table B.1.1 on page 776 of the steam tables, water at 160 °C has a saturation pressure of 617.8 [kPa]. The given pressure is less than the saturation pressure ($P < P_{\text{sat}}$), which indicates it is existing as a superheated vapor. Alternatively, we could look at Table B.1.2 on page 780 and see for an entry of 400 [kPa] that the saturation temperature is 143.63 °C. The given temperature is greater than the saturation temperature ($T > T_{\text{sat}}$), which indicates again it is existing as a superheated vapor. Quality is therefore undefined.

Using Table B.1.3 on page 784, the specific volume would exist between the temperature entries of 150 and 200 °C. Using interpolation, we can set up the following equation to determine the specific volume:

$$\frac{(160 - 150)\,[^\circ\text{C}]}{(200 - 150)\,[^\circ\text{C}]} = \frac{(\nu - 0.47084)\,[\text{m}^3/\text{kg}]}{(0.53422 - 0.47084)\,[\text{m}^3/\text{kg}]} \implies \nu = 0.483516\,[\text{m}^3/\text{kg}]$$

(m) $T = 400$ °C, $P = 200$ [kPa]

We immediately recognize 400 °C is greater than the critical temperature of water. This does not mean water is existing as a supercritical fluid, rather, it most likely will exist in the superheated vapor phase. Looking at Table B.1.2 on page 780, the given temperature is greater than the saturation temperature corresponding to 200 [kPa] which is 120.23 °C, i.e. $T > T_{\text{sat}}$, which indicates it is existing as a superheated vapor. Quality is therefore undefined. Using Table B.1.3 on page 784, the specific volume is directly found as 1.54930 [m^3/kg].

(n) $T = 133.5$ °C, $P = 300$ [kPa]

The given temperature exists in between published temperature values in Table B.1.1 on page 776, so using Table B.1.2 on page 780, it is evident that the given temperature is less than the saturation temperature corresponding to 300 [kPa], i.e. $T < T_{\text{sat}}$. Thus, it is existing as a compressed/subcooled liquid. Quality is therefore undefined. Consulting Table B.1.4 on page 790, there exists no 300 [kPa] pressure entry and the given temperature is between temperature entries. Using this table would require the use of interpolation three times. Thus, using Table B.1.1, the specific volume is taken as the saturated liquid specific volume evaluated at 133.5 °C, which is found via interpolation:

$$\frac{(133.5 - 130)\,[^\circ\text{C}]}{(135 - 130)\,[^\circ\text{C}]} = \frac{(\nu - 0.001070)\,[\text{m}^3/\text{kg}]}{(0.001075 - 0.001070)\,[\text{m}^3/\text{kg}]} \implies \nu = 0.001074\,[\text{m}^3/\text{kg}]$$

(o) $T = 100$ °C, $P = 800$ [kPa]

Looking at Table B.1.1 on page 776, the given pressure is greater than the saturation pressure of water at 100 °C, which indicates it is existing as a compressed/subcooled liquid. Quality is therefore undefined. The specific volume is equal to the saturated liquid specific volume evaluated at 100 °C, which is taken as 0.001044 [m^3/kg] from Table B.1.1 on page 776, or can be determined via interpolation from Table B.1.4 on page 790 via the following equation:

$$\frac{(800-500)\,[\text{kPa}]}{(2,000-500)\,[\text{kPa}]} = \frac{(\nu-0.001043)\,[\text{m}^3/\text{kg}]}{(0.001043-0.001043)\,[\text{m}^3/\text{kg}]} \implies \nu = 0.001043\,[\text{m}^3/\text{kg}]$$

(p) $P = 100$ [kPa], $\nu = 1.500$ [m^3/kg]

Looking at Table B.1.1 on page 776, the given specific volume is bounded between the saturated liquid and saturated vapor specific volume, i.e. $\nu_f(100\ [\text{kPa}])<\nu<\nu_g(100\ [\text{kPa}])$, $0.001043<\nu\ [\text{m}^3/\text{kg}]<1.69400$. Therefore, it is existing as a saturated liquid with a saturation temperature of 99.62 °C. The quality is found as:

$$x = \frac{(1.5-0.001043)\,[\text{m}^3/\text{kg}]}{(1.69400-0.001043)\,[\text{m}^3/\text{kg}]} = 0.8854$$

(q) $P = 100$ [kPa], $\nu = 2.500$ [m^3/kg]

Looking at Table B.1.2 on page 780, it is evident the specific volume is greater than the saturated vapor specific volume, i.e. $\nu>\nu_g(100\ [\text{kPa}])$, 2.50 [m^3/kg]>1.694 [m^3/kg]. Thus, it exists as a superheated vapor. Quality is therefore undefined. The temperature is found by interpolating between 250 and 300 °C under the 100 [kPa] pressure entry on Table B.1.3 on page 784:

$$\frac{(T-250)\,[°\text{C}]}{(300-250)\,[°\text{C}]} = \frac{(2.500-2.40604)\,[\text{m}^3/\text{kg}]}{(2.63876-2.40604)\,[\text{m}^3/\text{kg}]} = 270.18\,[°\text{C}]$$

(r) $P = 500$ [kPa], $\nu = 0.001070$ [m^3/kg]

Looking at Table B.1.2 on page 780, it is evident the specific volume is less than the saturated liquid specific volume, i.e. $\nu<\nu_f([500\ [\text{kPa}])$, 0.001070 [m^3/kg]<0.001093 [m^3/kg]. Thus, it exists as a compressed/subcooled liquid. Quality is therefore undefined. Using Table B.1.4 on page 790, we interpolated for temperature using specific volume:

$$\frac{(T-120)\,[°\text{C}]}{(140-120)\,[°\text{C}]} = \frac{(0.001070-0.001060)\,[\text{m}^3/\text{kg}]}{(0.001080-0.001060)\,[\text{m}^3/\text{kg}]} \implies T = 130\,[°\text{C}$$

(s) $T = 50$ °C, $\nu = 5.0$ [m^3/kg]

Looking at Table B.1.1 on page 776, the given specific volume is bounded between the saturated liquid and saturated vapor specific volume, i.e. $\nu_f(50\ °\text{C})<\nu<\nu_g(50\ °\text{C})$, $0.001012<\nu\ [\text{m}^3/\text{kg}]<12.0318$. Therefore, it is existing as a saturated liquid. The pressure is that of saturation at 50 °C, 12.350 [kPa], and the quality is:

$$x = \frac{(5.0-0.001012)\,[\text{m}^3/\text{kg}]}{(12.0318-0.001012)\,[\text{m}^3/\text{kg}]} = 0.416$$

(t) $T = 150$ °C, $\nu = 1.5$ [m^3/kg]

Looking at Table B.1.1 on page 776, it is evident the specific volume is greater than the saturated vapor specific volume, i.e. $\nu>\nu_g(150\ °\text{C})$, 1.5 [m^3/kg]>0.39278 [m^3/kg]. Thus, it exists as a superheated vapor. Quality is therefore undefined. The pressure is found via double-interpolation on Table B.1.3 on page 784:

$$\frac{(P-100)\,[\text{kPa}]}{(200-100)\,[\text{kPa}]} = \frac{(1.5-1.93639)\,[\text{m}^3/\text{kg}]}{(0.95964-1.93639)\,[\text{m}^3/\text{kg}]} \implies P = 144.68\,[\text{kPa}]$$

(u) $T = 100$ °C, $\nu = 0.001043$ [m^3/kg]

Looking at Table B.1.1 on page 776, it is evident the specific volume is less than the saturated liquid specific volume, i.e. $\nu < \nu_f(100$ °C$)$, 0.001043 [m^3/kg]<0.001044 [m^3/kg]. Thus, it exists as a compressed/subcooled liquid. Quality is therefore undefined. The pressure is found to be in the range of 500 and 2,000 [kPa] from Table B.1.4 on page 790.

(v) $T = 320$ °C, $P = 200$ [kPa]

Looking at Table B.1.1 on page 778, the saturation pressure corresponding to the given temperature is 11,274 [kPa], indicating it is existing as a superheated vapor. Alternatively, looking at Table B.1.2 on page 780, the saturation temperature corresponding to the given pressure is 120.23 °C which is less than the given temperature, further indicating it is a superheated vapor. Quality is therefore undefined. Consulting the superheated steam table, Table B.1.3 on page 784, the specific volume can be determined by interpolating between 300 and 400 °C:

$$\frac{(320-300)\,[^\circ\mathrm{C}]}{(400-300)\,[^\circ\mathrm{C}]} = \frac{(\nu - 1.31616)\,[\mathrm{m}^3/\mathrm{kg}]}{(1.54930 - 1.31616)\,[\mathrm{m}^3/\mathrm{kg}]} \implies \nu = 1.362728\,[\mathrm{m}^3/\mathrm{kg}]$$

(w) $T = 105$ °C, $P = 2{,}000$ [kPa]

Looking at Table B.1.1 on page 776, the given pressure is greater than the saturation pressure for the given temperature, indicating it is a compressed/subcooled liquid. Quality is therefore undefined. Using the saturated liquid specific volume value for 105 °C, ν=0.001047 [m^3/kg].

Alternatively, you could interpolate between 100 and 120 °C on the compressed/subcooled liquid water table, Table B.1.4 on page 790, using the following:

$$\frac{(105-100)\,[^\circ\mathrm{C}]}{(120-100)\,[^\circ\mathrm{C}]} = \frac{(\nu - 0.001043)\,[\mathrm{m}^3/\mathrm{kg}]}{(0.001059 - 0.001043)\,[\mathrm{m}^3/\mathrm{kg}]} \implies \nu = 0.001047\,[\mathrm{m}^3/\mathrm{kg}]$$

(x) $T = 60$ °C, $P = 200$ [kPa]

Looking at Table B.1.1 on page 776, the given pressure is greater than the saturation pressure for the given temperature, indicating it is a compressed/subcooled liquid. Quality is therefore undefined. Using the saturated liquid specific volume value for the given temperature, ν=0.001017 [m^3/kg]. It is noted that the lowest entry for the compressed/subcooled liquid water table, Table B.1.4 on page 790, is 500 [kPa].

(y) Saturated liquid at 400 [kPa]

Using Table B.1.2 on page 780, ν=0.001084 [m^3/kg] and the temperature is 143.63 °C.

(z) Saturated vapor at 125 °C

Using Table B.1.1 on page 776, ν=0.77059 [m^3/kg] and the pressure is 232.1 [kPa].