ECE 309 M.M. Yovanovich

Week 11

Lecture 1

• Hand out Tables of Properties of Compressed water.
• Hand out $P - v$-diagram for water. Show the critical point, the saturated liquid line and the saturated vapor line.
• Show locations of the constant temperature, constant pressure and constant quality lines under the dome.
• Show location of constant temperature and pressure curves outside the dome.

• Discuss Tables $B \cdot 1a$ and $B \cdot 1b$ for saturated water.
• The columns are $T, P, v_f, v_g, u_f, u_g, h_f, h_{fg}, h_g, s_f, s_{fg}, s_g$
• The subscripts: f and g denote properties at saturated liquid and saturated vapor states. The subscript fg denotes the change from liquid to vapor states.

$$v_{fg} = v_g - v_f, \quad u_{fg} = u_g - u_f, \quad h_{fg} = h_g - h_f, \quad s_{fg} = s_g - s_f$$

• At critical point where $T = 374.136°C, P = 22.08\,MPa,\ v_{fg} = 0, u_{fg} = 0, h_{fg} = 0, s_{fg} = 0$. See Tables $B \cdot 1a$ and $B \cdot 1b$

• Quality denoted as x is a dimensionless property of a liquid-vapor mixture.
• Definition of quality:

$$x = \frac{\text{Mass of Vapor}}{\text{Total Mass of Mixture}} = \frac{M_g}{M_g + M_f}$$

• At points on the saturated liquid line $x = 0, M_f = M, M_v = 0$, and at points on the saturated vapor line $x = 1, M_f = 0, M_v = M$
• Under the dome where $0 < x < 1$ the components of the mixture are:

$$M_g = xM, \quad M_f = (1 - x)M$$

Lecture 2

• Makeup lecture from 10:00-11:30 AM

- Hand out a $T - v$ Diagram for H_2O and Methodology for Energy Analysis.

- Some Thermodynamic Properties. Consider specific heat capacities: c_v, c_p
- Specific heat capacity under constant volume process, c_v

$$u = u(T, v), \quad \text{therefore} \quad du = \left(\frac{\partial u}{\partial T}\right)_v dT + \left(\frac{\partial u}{\partial v}\right)_T dv$$

For constant volume process $dv = 0$, and

$$du = \left(\frac{\partial u}{\partial T}\right)_v dT = c_v(T)\, dT, \quad \text{therefore} \quad c_v(T) = \left(\frac{\partial u}{\partial T}\right)_v dT, \quad \left[\frac{kJ}{kg \cdot K}\right]$$

- Mean value of $c_v(T)$ over temperature range: $T_1 \leq T \leq T_2$

$$\bar{c}_v = \frac{1}{(T_2 - T_1)} \int_{T_1}^{T_2} c_v(T)\, dT$$

- Specific heat capacity under constant pressure process, c_p

$$h = h(T, P), \quad \text{therefore} \quad dh = \left(\frac{\partial h}{\partial T}\right)_p dT + \left(\frac{\partial h}{\partial P}\right)_T dP$$

For constant pressure process $dP = 0$, and

$$dh = \left(\frac{\partial h}{\partial T}\right)_P dT = c_p(T)\, dT, \quad \text{therefore} \quad c_p(T) = \left(\frac{\partial h}{\partial T}\right)_P dT, \quad \left[\frac{kJ}{kg \cdot K}\right]$$

- Mean value of $c_p(T)$ over temperature range: $T_1 \leq T \leq T_2$

$$\bar{c}_p = \frac{1}{(T_2 - T_1)} \int_{T_1}^{T_2} c_p(T)\, dT$$

- Both $c_v(T)$ and $c_p(T)$ are weak functions of T.
- Changes in u and h between States 1 and 2:

$$u_2 - u_1 = \bar{c}_v(T_2 - T_1) \quad \text{and} \quad h_2 - h_1 = \bar{c}_p(T_2 - T_1)$$

- Ideal (Perfect) Gas

$$PV = MRT \quad \text{or} \quad Pv = RT \quad \text{or} \quad \rho = \frac{P}{RT}$$

• See Table $B.6b$, p. 642, for nominal values of properties at low pressures (SI Units): $c_v, c_v, R, k = c_p/c_v$
• Real gases behave like an ideal gas if they are dilute or when ρ is small. The density is small when $P/P_{\text{critical}} << 1$ and $T/T_{\text{critical}} >> 1$

• Compressibility Factor $Z\,[-]$
• Definition

$$Z = \frac{Pv}{RT} = 1, \quad \text{For Ideal Gas}$$

• Real Gases

$$Z = Z(T^\star, P^\star)$$

where $P^\star = P/P_{\text{critical}}$ and $T^\star = T/T_{\text{critical}}$. When the value of Z is close to one, then the real gas can be modeled as an ideal gas.

• Can water vapor be modeled as an ideal gas given the following data:
$T_1 = 200°F, \quad P_1 = 2\,psia, \quad v_1 = 196\,ft^3/lbm$
• From Table B.2, p. 634-637, $T_{sat} = 126°F$.
• From Table B.6, $R = 85.78 ft \cdot lbf/(lbm \cdot R)$.
• Calculation of Z_1

$$Z_1 = \frac{P_1 v_1}{RT_1} = \frac{(2 \times 144) \cdot (196)}{(85.78) \cdot (200 + 460)} = 0.997$$

Yes, this water vapor is slightly superheated and it can be modeled as an ideal gas.

• Relation between specific heat capacities for ideal gas.

$$h = u + Pv = u + RT, \quad \text{therefore} \quad dh = du + RdT, \quad \text{and} \quad c_p = c_v + R$$

Also

$$k = \frac{c_p}{c_v} = 1 + \frac{R}{c_v} > 1$$

• Under the dome we have the relations:

$$V = v_f M_f + v_g M_g = (1 - x) M v_f + x M v_g$$

$$U = u_f M_f + u_g M_g = (1 - x) M u_f + x M u_g$$

and the intensive properties are obtained from

$$v = (1 - x) v_f + x v_g$$

$$u = (1 - x)u_f + xu_g$$

• Chapter 5: Energy Analysis
• Principal Tools for Analysis are:
• 1) Conservation of Mass
• 2) Conservation of Energy
• 3) Equation of State

• Methodology:

• Control Mass Analysis:
– Fixed Mass
– Closed System

• Control Volume Analysis:
– Specified Volume which may be moving and changing shape
– Open System

• Control Volume Analysis
Powerful technique for energy analysis of many important engineering devices such as:
– turbines and pumps
– compressors
– boilers and condensers
– pressure vessels
– nozzles
– thermoelectric devices
– etc.

• Text gives several examples of the Control Mass Analysis:
– Evaporation at constant pressure:

$$Q_{12} = M\left[P(v_2 - v_1) + (u_2 - u_1\right] = M(h_2 - h_1)$$

– Dry-Ice Cooler (A Sublimation Process), Solid $\rightarrow$ Gas

$$Q_{12} = M\left[P(v_2 - v_1) + (u_2 - u_1\right] = M(h_2 - h_1) = M(h_g - h_s) = Mh_{sg}$$

where $h_{sg} = h_g - h_s$ is the Enthalpy of Sublimation. See Fig. 4.2 and 5.2
• Illustrate the analysis procedure for the Dry-Ice cooler.

Lecture 3

- Hand out Project 2. Due Date is Friday, July 23.

- Steady State, Steady Flow Systems (Devices) (SSSF)
- Assumptions for SSSF Devices

1) Control Volume (CV) is fixed with respect to a coordinate frame
2) Mass flux and state of mass on control volume surface are time independent, and $\dot{M}_{in} = \dot{M}_{out}$
3) Mass and its state at every point within the control volume are time independent, and

$$\frac{dE_{cv}}{dt} = \frac{d}{dt}\int_{CV} e\rho dV = 0$$

4) Rates at which heat and work cross the control surface remain constant, and

$$\frac{\dot{Q}}{dt} = 0, \quad \frac{\dot{W}_{shaft}}{dt} = 0$$

- Conservation of Mass for Control Volume

$$\frac{dM_{CV}}{dt} = \dot{M}_{in} - \dot{M}_{out}, \quad \text{when} \quad \frac{dM_{CV}}{dt} = 0, \quad \dot{M}_{in} = \dot{M}_{out} = \dot{M}$$

- Mass Flow Rate

$$\dot{M} = \rho A\bar{V} \quad \left[\frac{kg}{s}\right]$$

where ρ = mass density, A = flow area, and $\bar{V}$ = average velocity over flow area.

- First Law of Thermodynamics for Control Volume (FLOT/CV)

$$\left[\dot{M}(e + Pv)\right]_1 + \dot{W}_{shaft} + \dot{Q} = \left[\dot{M}(e + Pv)\right]_2$$

where the total specific energy is e, and the other terms represent rates of energy transfer as heat and work.

$$e = u + ke + pe, \quad \dot{Q} = \frac{dQ}{dt}, \quad \dot{W}_{shaft} = \frac{dW}{dt}$$

and the product Pv is called flow work. The subscripts 1 and 2 denote inlet and outlet respectively. Also note that u and Pv can be combined as the specific enthalpy: $h = u + Pv$.

• Specific Kinetic and Potential Energies

$$ke = \frac{\bar{V}^2}{2}, \quad pe = gz$$

• Uniform State, Uniform Flow Processes USUF
• Assumptions for USUF Processes
1) Control Volume (CV) is fixed with respect to a coordinate frame
2) State of the mass crossing the control surface is independent of time and it is uniform over the various areas of the control surface where flow occurs.
3) State of the mass within the control volume may change with time, but at any instant in time, the state is uniform over the entire control volume.

• USUF is useful in the analysis of unsteady processes which involve rapid mixing within the control volume, e.g.,
– filling of tanks
– discharging pressure vessels

• FLOT/CV

$$\frac{dE_{CV}}{dt} = \frac{d}{dt}\left(M_{CV}e_{CV}\right) = \dot{Q} + \dot{W}_{shaft} + \left[(\dot{M}(e+Pv)\right]_{in} - \left[(\dot{M}(e+Pv)\right]_{out}$$

• Alternative Form of FLOT/CV

$$(M_{CV})_2 - (M_{CV})_1 = Q + W_{shaft} + \{[M(e+Pv)]_{in}\}_{1\to 2} - \{[M(e+Pv)]_{out}\}_{1\to 2}$$

during the time interval: $(t_1 \leq t \leq t_2)$.
• See the example in text on pages 137-8: Charging of a high-pressure tank. The tutorial will also pertain to this topic.

Lecture 4

• Hand out Mollier diagram (h-s diagram) for water.

• Simple Power Plant
– Pump
– Boiler
– Turbine
– Condenser

- Show processes on $T - v$ diagram

- Example of Steam Turbine

Example of a SSSF process: a steam turbine. The mass flow rate through a steam turbine is 1.5 kg/s, and the heat transfer rate from the boundaries of the turbine is 8.5 kW. Determine the power output of the turbine.

The following data are given for the steam entering and leaving the turbine.

	Inlet Conditions	Outlet Conditions
Pressure	2.0 MPa	0.1 MPa
Temperature	350 ^{0}C	
Quality		100 %
Velocity	50 m/s	200 m/s
Elevation above reference	6 m	3 m

Solution

- Sketch the turbine and define the control volume with control surface.
- The general continuity equation for a control volume becomes:

$$\dot{M}_{\text{in}} - \dot{M}_{\text{out}} = 0 \qquad \text{therefore} \qquad \dot{M}_{\text{in}} = \dot{M}_{\text{out}} = \dot{M}$$

- The general energy equation for a control volume becomes

$$\dot{Q} + \dot{W}_{\text{shaft}} + \left[\dot{M}\left(h + ke + pe\right)\right]_{\text{in}} - \left[\dot{M}\left(h + ke + pe\right)\right]_{\text{out}} = 0$$

- Inlet conditions

$P_{\text{i}} = 2\,MPa, T_{\text{i}} = 350\,^0C$; From Table B-2, p. 628: $h_{\text{i}} = 3137.0\,kJ/kg$, $v_{\text{i}} = 0.1386\,m^3/kg$; $\bar{V}_{\text{i}} = 50\,m/s, z_{\text{i}} = 6\,m$.

Therefore $ke_{\text{i}} = \bar{V}/2 = (50)^2/2 = 1.25\,kJ/kg; pe_{\text{i}} = gz_{\text{i}} = (9.81) \times (6) = 0.059\,kJ/kg$.

- Outlet conditions

Saturated steam: $x = 1$, $P_{\text{o}} = 0.1\,MPa$. From Table B1b, p. 624: $h_{\text{o}} = 2675.5\,kJ/kg, v_{\text{o}} = v_{\text{g}} = 1.694\,m^3/kg, T_{\text{o}} = 99.6\,^0C, \bar{V}_{\text{o}} = 200\,m/s, z_{\text{o}} = 3\,m$.

Therefore $ke_{\text{o}} = \bar{V}_{\text{o}}^2/2 = (200)^2/2 = 20.0\,kJ/kg, pe_{\text{o}} = gz_{\text{o}} = (9.81) \times (3) = 0.029\,kJ/kg$.

• <u>Energy Equation: SSSF Process</u>

$$\dot{Q} + \dot{W}_{\text{shaft}} + \dot{M}\left[(h_{\text{i}} - h_{\text{o}}) + (ke_{\text{i}} - ke_{\text{o}}) + (pe_{\text{i}} - pe_{\text{o}})\right] = 0$$

Substitution gives:

$$-8.5 + \dot{W}_{\text{shaft}} + 1.5\left[(3137.0 - 2675.5) + (1.25 - 20.0) + (0.059 - 0.029)\right] = 0$$

and

$$-8.5 + \dot{W}_{\text{shaft}} + 1.5\left[461.5 - 18.75 + 0.030\right] = 0$$

and

$$-8.5 + \dot{W}_{\text{shaft}} + 1.5\left[442.78\right] = 0$$

Therefore

$$\dot{W}_{\text{shaft}} = 8.5 - (1.5) \times (442.78) = -655.67 \qquad \left[\frac{kJ}{s}\right]$$

The power **out of** the turbine (CV) is

$$\dot{W}_{\text{shaft}} = -0.656\, MW$$

Observe that the contribution of the potential energy is negligible. Also note that the kinetic energy of the steam exiting the turbine decreases the available work from the turbine.

Show the process on a $T - v$ diagram and an $h - s$ diagram which is called a Mollier diagram (see Fig. B.2, p. 603).
