### **Thermodynamics I**

Spring 1432/1433H (2011/2012H) Saturday, Wednesday 8:00am - 10:00am & Monday 8:00am - 9:00am MEP 261 Class ZA

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> Chapter #3 Sebtember XX, 2011

<u>Announcements:</u> Dr. Walid's e-mail and Office Hours walid\_aniss@yahoo.com

Office hours for Thermo 01 will be every Sunday and Tuesday from **9:00 – 12:00 am** in *Dr. Walid's* office (Room 5-213). <u>Text book:</u>

*Thermodynamics An Engineering Approach* Yunus A. Cengel & Michael A. Boles 7<sup>th</sup> Edition, McGraw-Hill Companies, ISBN-978-0-07-352932-5, 2008

### Chapter 3 PROPERTIES OF PURE SUBSTANCES

## **Objectives of CH3: To**

- Introduce the concept of a pure substance.
- Discuss the physics of phase-change processes.
- Illustrate the *P-v*, *T-v*, and *P-T property* diagrams and *P-v-T* surfaces of pure substances.
- Demonstrate the procedures for determining thermodynamic properties of pure substances from tables of property data.
- Describe the hypothetical substance "ideal gas" and the ideal-gas equation of state.

\* Apply the ideal-gas equation of state in the solution of typical problems.

### Chapter 3 PROPERTIES OF PURE SUBSTANCES

### 3–1 ■ PURE SUBSTANCE

<u>A substance that has a fixed chemical composition</u> <u>throughout</u> is <u>called</u> a **pure substance. Water**, **nitrogen**, **helium**, **and carbon dioxide**, **for example**, are all pure substances



Nitrogen and gaseous air are pure substances.

A mixture of two or more phases of a pure substance is still a pure substance as long as the chemical composition of all phases is the same.



# A mixture of liquid and gaseous water is a pure substance

#### 3–2 PHASES OF A PURE SUBSTANCE



### 3–3 PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

- Compressed Liquid and Saturated Liquid

Consider a piston–cylinder device containing liquid <u>water at 20 °C and</u> <u>1 atm pressure</u> (state 1). <u>Under</u> <u>these conditions</u>, <u>water exists in</u> the liquid phase, and it is <u>called</u> a **compressed liquid**, or a subcooled liquid.



At 1 atm and 20 °C, water exists in the liquid phase (*compressed liquid*).



*T-v diagram for the heating process of water at constant pressure.* 

As more heat is transferred, the temperature keeps rising until it reaches 100°C (state 2). At this point water is still a liquid, but any heat addition will cause some of the liquid to vaporize. That is, a phase-change process from liquid to vapor is about to take place. A liquid that is about to vaporize is called a saturated liquid.



At 1 atm pressure and 100 ℃, <u>water exists as</u> a liquid that is ready to vaporize (*saturated liquid*).

### **Saturated Vapor and Superheated Vapor**

Once boiling starts, the temperature stops rising until the L is completely vaporized. i.e., the temperature will remain constant during the entire phase-change process if the pressure is held constant. Midway about the vaporization line (state 3), the cylinder contains equal amounts of L and V Water vapor called steam

 $\omega$ 



As we continue transferring heat, the vaporization process continues until the last drop of liquid is vaporized (state4). At this point, the entire cylinder is filled with vapor



At 1 atm pressure, the temperature remains constant at 100°C until the last drop of liquid is vaporized (saturated vapor). Further transfer of heat results in an increase in both the temperature and the specific volume . At state 5, the temperature of the vapor is, let us say, 300 °C. Water at state 5 is a superheated vapor.

As more heat is transferred, the temperature of the vapor starts to rise (*superheated vapor*).



If the entire process described here is reversed by cooling the water while maintaining the pressure at the same value, the water will go back to state 1, retracing the same path, and in so doing, the <u>amount of heat released</u> will exactly match the <u>amount of heat added during</u> the <u>heating process</u>.

## Saturation Temperature and Saturation Pressure

"The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature".

# Water starts boiling at 100°C if the pressure is held constant at 1 atm (101.325 kPa).

# Water starts boiling at 151.8 °C if the pressure is held constant at 500 kPa.

### 3–4 PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

Variations of properties during phasechange processes are best studied and understood with the help of property diagrams(*T-v*, *P-v*, and *P-T diagrams for* pure substances



As the pressure is increased, saturation line continues to shrink, and it becomes a point when the pressure reaches 22.06 MPa for the case of water.

This point is called the **critical point**, and it is **defined as** *the point at which the saturated liquid and saturated vapor states are identical*.

The temperature, pressure, and specific **volume** of a substance **at** the **critical point** are called, respectively, the *critical* temperature; T<sub>cr</sub>, critical pressure  $p_{cr}$ , and critical specific volume  $v_{cr}$ . The critical-point properties of water are  $p_{cr} = 22.06 MPa$ ,  $T_{cr} = 373.95^{\circ}C$ , and  $v_{cr} = 0.003106 \text{ m}^3/\text{kg}$ .

The critical properties for various substances are given in Table A–1 in the appendix

At pressures above the **critical pressure**, there is not a distinct phase change process. Instead, the specific volume of the substance *continually increases*, and at all times there is only one phase present



At supercritical pressures  $(p > p_{cr})$ , there is no distinct phase-change (boiling) process. The saturated liquid states can be <u>connected</u> by a <u>line called</u> the saturated liquid line, and saturated vapor states in the same figure can be <u>connected</u> by another line, called the saturated vapor line.

These two lines meet at the critical point, forming a dome as shown in the next Figure. All the compressed liquid states are located in the region to the left of the saturated liquid line, called the **compressed liquid region. All the superheated** vapor states are located to the right of the saturated vapor line, called the **superheated vapor region.** 



T-v diagram of a pure substance.

In these two regions, the substance exists in a single phase, a liquid or a vapor. All the states that involve both phases in equilibrium are located under the dome, called the saturated liquid–vapor mixture region, or the wet region.



*p-v diagram of a pure substance.* 

## **Enthalpy—A Combination Property**

# Specific enthalpy, given the symbol h; is defined as:



#### Hence, total enthalpy, *H*, is defined as:

## $H = U + PV \qquad (kJ) \qquad (3-2)$

### 3–5 PROPERTY TABLES 1a Saturated Liquid and Saturated Vapor States

Properties of saturated liquid and saturated vapor for water are listed in Tables A-4 and A-5. Both tables give the same information. The only difference is that in Table A-4 properties are listed under temperature and in Table A–5 **under pressure**. Therefore, it is more convenient to use Table A-4 when temperature is given and Table A–5 when pressure is given. The use of Table A–4 is illustrated in next Figure.

The subscript *f* is used to denote properties of a saturated liquid, and the subscript *g* to denote the properties of saturated vapor. Another subscript commonly used is *fg*, which denotes the difference between the saturated vapor and saturated liquid values of the same property. e.g.

$$v_f = specific volume of saturated liquid$$

$$v_g = specific volume of saturated vapor$$
  
 $v_{fg} = difference between v_g and v_f$ 

$$= v_g - v_f$$

	Sat.	Specific volume m <sup>3</sup> /kg	
Temp.	press.	Sat.	Sat.
°C	kPa	liquid	vapor
T	P <sub>sat</sub>	V <sub>f</sub>	v <sub>g</sub>
85 90 95 Specific temperat	57.868 70.183 84.609	0.001032 0.001036 0.001040 Specific volume of saturated	2.8261 2.3593 1.9808
liquid			Specific
Corresponding			volume of
saturation			saturated
pressure			vapor

From

Table A-4

### **EXAMPLE 3–1 Pressure of Saturated Liquid** *in a Tank*

A rigid tank contains 50 kg of saturated liquid water at 90 ℃. Determine the pressure in the tank and the volume of the tank.



### From Table A-4 (As shown in Slide 30)

 $p_{sat}$  at 90°C = 70.183 kPa.

 $v_{sat \text{ Liquid}}$  at 90°C =  $v_f$  at 90°C = 0.001036 m<sup>3</sup>/kg.

But, v = V/m. Hence,  $V = v * m = 0.001036 \text{ m}^3/\text{kg} * 50 \text{ kg} = 0.0518 \text{ m}^3$ 

# **EXAMPLE 3–3 Volume and Energy Change during Evaporation**

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (*a*) the volume change and (*b*) the amount of energy transferred to the water.

### Solution



#### From Table A–5

a) 
$$v_f$$
 at 100 kPa = 0.001043 m<sup>3</sup>/kg.  
 $v_g$  at 100 kPa = 1.6941 m<sup>3</sup>/kg.  
 $v_{fg} = v_g \cdot v_f = 1.6941$  m<sup>3</sup>/kg - 0.001043 m<sup>3</sup>/kg  
 $v_{fg} = v_g \cdot v_f = 1.6931$  m<sup>3</sup>/kg

 $\Delta v = m * v_{fg} = (200/1000) \text{ kg} * 1.6931 \text{m}^3/\text{kg} = 0.3386 \text{ m}^3$ 

(*b*) The amount of energy needed to vaporize a unit mass of a substance at a given pressure is the enthalpy of vaporization at that pressure (100 kPa), which is

From Table A–5 *h<sub>fg</sub> (at p=100 kPa)=* 2257.5 kJ/kg

Thus, the amount of energy transferred is

**E = m \* h**<sub>fg</sub> =(200/1000) kg\* 2257.5 kJ/kg=451.5 kJ
# **1b Saturated Liquid–Vapor Mixture**

**During** a vaporization process, a substance exists as part liquid and part vapor i.e, a mixture of saturated liquid and saturated vapor; next Figure. To analyze this mixture properly, we need to know the proportions of the liquid and vapor phases in the mixture. This is done by defining a new property called the **quality** x as the ratio of the mass of vapor to the total mass of the mixture:



Value of quality; *x* is **between 0 and 1**. The **quality of** a system that consists **of** *saturated liquid is 0 (or 0* percent), and the **quality of** a system consisting of *saturated vapor is 1 (or* 100 percent).



 $v = v_f + x v_{fg} = v_f + x (v_g - v_f) m^3/kg$ 

## Similarly,

$$u = u_f + x u_{fg} = u_f + x (u_g - u_f) \text{ kJ/kg}$$

$$h = h_f + x h_{fg} = h_f + x (h_g - h_f) \text{ kJ/kg}$$

All the saturated-mixture states are located under the saturation curve, and **to analyze saturated mixtures**, all **we need** are **saturated liquid and saturated vapor data** (Tables A–4 and A–5 in the case of water).

# **EXAMPLE 3–4 Pressure and Volume of a** Saturated Mixture

A rigid tank contains 10 kg of water at 90 °C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine (*a*) the pressure in the tank and (*b*) the volume of the tank. Solution

From Eq. (3-3)  $x = m_{Vapor} / m_{total} = (m_{total} - m_{liquid}) / m_{total}$ i.e. x = (10 kg - 8 kg) / 10 kg = 0.2

# It is clear that the tank contains mixture of Liquid an vapor

# From Table A-4

$$p = p_{sat}$$
 at 90°C = 70.183 kPa.

$$v_f$$
 at 90°C = 0.001036 m<sup>3</sup>/kg.  
 $v_g$  at 90°C = 2.3593 m<sup>3</sup>/kg.

# But

$$v = v_f + x v_{fg} = v_f + x (v_g - v_f) m^3/kg$$

# Hence,

# v = 0.001036 + 0.2 (2.3593 - 0.001036)m<sup>3</sup>/kg = 0.473 m<sup>3</sup>/kg

 $V = m \times v = 10 kg \times 0.473 m^3/kg = 4.73 m^3$ 

#### **EXAMPLE 3–5 Properties of Saturated** Liquid–Vapor Mixture

- An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa.
- Determine (a) the temperature, (b) the quality, (c) the enthalpy of the refrigerant, and (d) the volume occupied by the vapor phase.

# **Solution**

 $V = 80 L = 80 / 1000 \text{ m}^3 = 0.08$ 

 $v = V/m = 0.08 \text{ m}^3/4 \text{ kg} = 0.02 \text{ m}^3/\text{kg}$ 



## From Table A-12

 $v_f$  (at  $p_{sat} = 160$  kPa) = 0.0007437 m<sup>3</sup>/kg.

 $v_g$  (at  $p_{sat} = 160$  kPa) = 0.12348 m<sup>3</sup>/kg.

It is clear that  $v_f$  (= 0.0007437 m<sup>3</sup>/kg) < v (= 0.02 m<sup>3</sup>/kg) <  $v_g$  (= 0.12348 m<sup>3</sup>/kg).

*Hence,* 134a refrigerant is in the **Saturated Liquid–Vapor Mixture** 

(a) The temperature: *Hence*,  $T = T_{sat}$  (at  $p_{sat} = 160$  kPa) = -15.60°C. (b) Quality:  $x = (v - v_f) / v_{fg} = (0.02 - 0.0007437)/$ (0.12348 - 0.0007437) = 0.157(c) The enthalpy of the refrigerant, From Table A–12 :  $h_f$  (At 160 kPa) = 31.21 kJ/kg and  $h_{fg}$  (@ p=160 kPa) = 209.90 kJ/kg.

$$h = h_f + (x * h_{fg}) = 31.21 \text{ kJ/kg} + (0.157 * 209.90 \text{ kJ/kg}) = 64.2 \text{ kJ/kg}$$

(d) Volume occupied by the vapor phase,

$$x = m_g / m_t$$
, Hence  
 $m_g = x * m_t = 0.157 * 4 \text{ kg} = 0.628 \text{ kg}$   
 $V_g = m_g * v_g = 0.628 \text{ kg} * 0.12348 \text{ m}^3/\text{kg}$   
 $= 0.0775 \text{ m}^3$  (or 77.5 *l* )

2 Superheated Vapor (singlephase region (vapor phase only))

Exists in the region to the right of the saturated vapor line and at temperatures above the critical point temperature.

T and p are no longer dependent properties and they can conveniently be used as the two independent properties in the tables.



v



The format of the superheated vapor tables is illustrated in the following figure.

# See the previous two figures



Compared to saturated vapor, superheated vapor is characterized by

- -Lower pressures ( $p < p_{sat}$  at a given T)
- -Higher temperatures  $(T > T_{sat} at a given p)$
- -Higher specific volumes ( $v > v_g$  at a given p or T)
- -Higher internal energies ( $u > u_g$  at a given p or T)
- -Higher enthalpies ( $h > h_g$  at a given p or T)

## **EXAMPLE 3–7 Temperature of Superheated Vapor**

Determine the temperature of water at a state of p = 0.5 MPa and h = 2890 kJ/kg.

#### **Solution**

# From Table A-5

$$T_{sat} (@ p = 0.5 Mpa) = 151.83$$
 °C

$$h_f (@p = 0.5 Mpa) = 640.09 kJ/kg$$

$$h_g (@p = 0.5 Mpa) = 2748.1 kJ/kg$$

It is clear that 
$$h (= 2890 \text{ kJ/kg}) > h_g (= 2748.1 \text{ kJ/kg})$$

#### Hence, water is superheated steam.

# From Table A-6, at p = 0.5 Mpa

T ( °C)	h, kJ/kg
200	2855.8
Τ	2890
250	2961.0



# Hence, by interpolation

=

# [(T-200)/(250-200)] = [(2890-2855.8)/(2961.0-2855.8)] $T = 216.255 \ ^{\circ}C$

# **3 Compressed Liquid**

Compressed liquid *data* are *available in Table A–7.* 

Variation of properties of compressed liquid with pressure is very mild. Increasing the pressure 100 times often causes properties to change less than 1 %. In the absence of compressed liquid data, a general approximation is to treat compressed liquid as saturated liquid at the given temperature



V

# In general Compressed liquid *is* characterized by:

Higher pressures ( $P > P_{sat}$  at a given T) Lower tempreatures ( $T < T_{sat}$  at a given P) Lower specific volumes ( $v < v_f$  at a given P or T) Lower internal energies ( $u < u_f$  at a given P or T) Lower enthalpies ( $h < h_f$  at a given P or T)



# **EXAMPLE 3–8 Approximating Compressed** Liquid as Saturated Liquid

Determine the internal energy of compressed liquid water at 80 °C and 5 MPa, using (*a*) data from the compressed liquid table and (*b*) saturated liquid data. What is the error involved in the second case?.

#### **Solution**

From Table A-5  $T_{sat}$  ( @p = 5MPa) = 263.94°C

It is clear that  $T (= 80^{\circ}C) < T_{sat} (p = 5MPa) = 263.94^{\circ}C$ 

Hence, water is compressed liquid

# (a) Exact solution using the data from the compressed liquid table

From Table A-7 [for compressed liquid water] at p = 5MPa & T = 80 °C, u = 333.82 kJ/kg

(b) Approximate solution

From Table A-4 [for saturated vapor-Temperature table] at  $T_{sat} = 80 \,^{\circ}\text{C}$ ,  $u_f = 334.97 \,\text{kJ/kg}$ , i.e.  $u \approx u_f = 334.97 \,\text{kJ/kg}$ 

% error in u =  $[(u_{approx} - u_{exact})/u_{exact}]^* 100\%$ 

= [(334.97 - 333.82)/333.82]\*100% = 0.3445%

# **Reference State and Reference Values**

#### EXAMPLE 3–9

#### EXAMPLE 3-9 The Use of Steam Tables to Determine Properties

Determine the missing properties and the phase descriptions in the following table for water:

	<i>T</i> , °C	<i>P</i> , kPa	u, kJ/kg	x	Phase description
(a)		200		0.6	
( <i>b</i> )	125		1600		
( <i>c</i> )		1000	2950		
(d)	75	500			
( <i>e</i> )		850		0.0	

#### **Solution**

# (a) Saturated Liquid–Vapor Mixture

[p = 200 kPa & x = 0.6]

From Table A-5 [for saturated water-Pressure table] at  $p_{sat} = 200$  kPa, T = 120.21 °C,  $u_f = 504.5$  kJ/kg &  $u_{fg} = 2024.6$  kJ/kg

 $U = (u_f + x * u_{fg}) = [504.5 \text{ kJ/kg} + (0.6 * 2024.6 \text{ kJ/kg})] = 1719.26 \text{ kJ/kg}$ 

(b) 
$$T = 125 \$$
°C,  $u = 1600 \$ kJ/kg

From Table A-4 [for saturated vapor-Temperature table] at  $T_{sat} = 125 \,^{\circ}\text{C}$ ,  $p = 232.23 \,\text{kPa}$ ,  $u_f = 524.83 \,\text{kJ/kg}$ ,  $u_{fg} = 2009.5 \,\text{kJ/kg} \& u_g = 2534.3 \,\text{kJ/kg}$ 

It is clear that for  $T = T_{sat}$  (= 125 °C),  $u_f$  (= 524.83 kJ/kg) < u (= 1600 kJ/kg) <  $u_g$  (= 2534.3 kJ/kg)

Hence, water is *saturated liquid–vapor mixture* 

$$p = p (T_{sat} = 125 \text{°C}) = 232.23 \text{ kPa}$$
  
 $x = (u - u_f) / u_{fg} = (1600 - 524.83) / 2009.5$ 

*i.e.* 
$$x = (u - u_f) / u_{fg} = (1600 - 524.83) / 2009.5$$
  
*i.e.*  $x = 0.535$ 

# (c) $p = 1000 \, kPa$ , $u = 2950 \, kJ/kg$ From Table A-5 $T_{sat}$ (at p = 1000 kPa) = 179.88 °C $u_f(at p = 1000 kPa) = 761.39 kJ/kg$ $u_g$ (at p = 1000 kPa) = 2582.8 kJ/kg It is clear that u = 2950 kJ/kg $> u_{g}$ (= 2582.8 kJ/kg)

# Hence, water is superheated steam. **From Table A-6**, *at* p = 1000 kPa

T ( °C)	u, kJ/kg	
350	2875.7	Hence, by
Τ	2950	<i>interpolation</i>
400	<i>2957.9</i>	

# [(T-350)/(400-350)] = [(2950-2875.7)/(2957.9-2875.7)] $T = 395.2 \ ^{o}C$



v

We would **leave** the **quality column blank** in this case **since quality has no meaning for a superheated vapor**


#### From Table A-5

 $T_{sat}$  (at  $p = 500 \ kPa$ ) = 151.83 °C

It is clear that  $T (= 75 \ ^{\circ}C) < T_{sat} = 151.83 \ ^{\circ}C$ Hence, water is compressed liquid

From Table A-7 [for compressed liquid water] at p = 500kPa & T = 75 °C {No data in Table A-7 corresponding to p = 500 kPa}

*Hence,*  $u \approx u_f (T_{sat} = T = 75 \text{ °C}) = 313.99$  kJ/kg

(e) x = 0, p = 850 kPaHence, water is saturated liquid

From Table A-5 [for saturated water-Pressure table] at  $p_{sat} = 850$  kPa,  $T = T_{sat} = 172.94$  °C,  $u_f = 731.0$  kJ/kg

	<i>T</i> , °C	<i>P</i> ,	u,	x	Phase
		kPa	kJ/kg		description
<b>(a)</b>	120.21	200	1719.26	0.6	Saturated L–V Mixture
<b>(b)</b>	125	232.2	1600	0.535	Saturated L–V Mixture
(c)	395.2	1000	2950	-	Superheated steam
<b>(d)</b>	75	500	313.99	-	compressed L
<b>(e)</b>	172.94	850	731.0	0.0	Saturated L

# **3-6 THE IDEAL-GAS Equation OF STATE**

Any equation that relates p, T, and v of a substance is called an equation of state

$$p v = R T$$
 or  $p / \rho = R T$  (3-10)

or p V = m R T

### $R = R_u / M \quad R_u = 8.31447 \text{ kJ/kmol.K}$

#### Universal gas constant

Gas constants for different gases; Table A-1

Substance	Formula	Molar mass,	R (kJ/kg K)
		M (kg/kmol)	
Air	-	28.97	0.287
Helium	He	4.003	2.0769
Argon	Ar	39.948	0.2081
Nitrogen	N <sub>2</sub>	28.013	0.2968

#### EXAMPLE 3–10 Mass of Air in a Room

Determine the mass of the air in a room whose dimensions are  $4 \text{ m} \times 5 \text{ m} \times 6 \text{ m}$  at 100 kPa and  $25 \,^{\circ}\text{C}$ .



#### **Solution**

- p V = m R T
- *p* = 100 kPa
- $T = 25^{\circ}C = 25 + 273 = 298K$
- $V = 4 \text{ m} \times 5 \text{ m} \times 6 \text{ m} = 120 \text{ m}^3$

 $(100 \times 10^{3} \text{ Pa}) \times 120 \text{ m}^{3} = m \times [0.287 \times 10^{3} \text{ (J/kg K)}] \times 298 \text{K}$ 

*Hence*, m = 140.3 kg

## **Homework**

3–26, 3–27, 3–30, 3–31,3-32, 3-34, 3-35, 3-36, 3-37,3-77,3-80.