



**Lecture 11 : Phase-Change Processes of pure substance**

by: Asst. Lect. Karrar Al-Mansoori

## 11-1 Saturation Temperature and Saturation Pressure

- ✚ It probably came as no surprise to you that water started to boil at 100°C. Strictly speaking, the statement “water boils at 100°C” is incorrect. The correct statement is “water boils at 100°C at 1 atm pressure.”
- ✚ The only reason water started boiling at 100°C was because we held the pressure constant at 1 atm (101.325 kPa). If the pressure inside the cylinder were raised to 500 kPa by adding weights on top of the piston, water would start boiling at 151.8°C.
- ✚ **The temperature at which water starts boiling depends on the pressure;** therefore, if the pressure is fixed, so is the boiling temperature. **At a given pressure, the temperature at which a pure substance changes phase is called the saturation temperature  $T_{sat}$ .** Likewise, **at a given temperature, the pressure at which a pure substance changes phase is called the saturation pressure  $P_{sat}$ .** At a pressure of 101.325 kPa,  $T_{sat}$  is 99.97°C.

❖ جميعنا يعلم بأن الماء يغلي عند درجة حرارة ١٠٠ درجة مئوية. بالمعنى الدقيق للكلمة ، فإن عبارة

"الماء يغلي عند درجة حرارة ١٠٠ درجة مئوية" هي عبارة غير صحيحة . العبارة الصحيحة هي ان:

"الماء يغلي عند درجة حرارة ١٠٠ درجة مئوية و ضغط مقداره ١ ضغط جوي".

❖ السبب الوحيد الذي جعل الماء يغلي عند ١٠٠ درجة مئوية هو اننا حافظنا على ضغط ثابت مقداره

( ١ atm أي ١٠١,٣٢٥ كيلوباسكال ) ، إذا تم رفع الضغط داخل الأسطوانة إلى ٥٠٠ كيلو باسكال

بإضافة أوزان أعلى المكبس سيبدأ الماء في الغليان عند ١٥١,٨ درجة مئوية.

❖ درجة حرارة الغليان تعتمد على قيمة الضغط لذلك تسمى درجة الحرارة التي تتغير فيها طور المادة النقية

بـ "درجة حرارة التشيع  $T_{sat}$  . وبالمثل ، عند درجة حرارة معينة ، يسمى الضغط الذي تتغير فيه طور المادة

النقية بضغط التشيع  $P_{sat}$  .

❖ عند ضغط ١٠١,٣٢٥ كيلو باسكال ،  $T_{sat}$  هي ٩٩,٩٧ درجة مئوية.



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Temperature $T, ^\circ\text{C}$	Saturation Pressure $P_{\text{sat}}, \text{kPa}$
-10	0.260
-5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581

Saturation tables that list the saturation pressure against the temperature (or the saturation temperature against the pressure) are available for practically all substances. A partial listing of such a table is given in (Table 11–1) for water. *This table indicates that the pressure of water changing phase (boiling or condensing) at 25°C must be 3.17 kPa, and the pressure of water must be maintained at 3976 kPa (about 40 atm) to have it boil at 250 °C.*

❖ هناك جداول خاصة تسمى بجداول التشبع التي تدرج ضغط التشبع مقابل درجة الحرارة (أو درجة حرارة التشبع مقابل الضغط) لجميع المواد تقريباً. (الجدول ١١-١) يوضح قائمة جزئية لضغط التشبع للماء مقابل درجة الحرارة.

**Table (11-1):** Saturation (or vapor)

pressure of water at various temperatures

✚ Also, water can be frozen by dropping its pressure below 0.61 kPa. It takes a large amount of energy to melt a solid or vaporize a liquid. *The amount of energy absorbed or released during a phase-change process is called the latent heat.* More specifically, the amount of energy **absorbed during melting** is called **the latent heat of fusion** and is equivalent to the amount of energy released during **freezing**. Similarly, the amount of energy **absorbed during vaporization** is called **the latent heat of vaporization** and is equivalent to the energy released during **condensation**.

✚ يلزم ذوبان مادة صلبة أو تبخير سائل معين كمية كبيرة من الطاقة.

✚ تسمى كمية الطاقة الممتصة أو المنبعثة من المادة أثناء عملية تغيير الطور "بالحرارة الكامنة". وبشكل

أكثر تحديداً ، تُطلق على كمية الطاقة الممتصة أثناء الصهر "بالحرارة الكامنة للانصهار" وتعاذل

كمية الطاقة المنبعثة أثناء التجميد. وبالمثل ، تسمى كمية الطاقة الممتصة أثناء التبخير

"بالحرارة الكامنة للتبخير" وتعاذل الطاقة المنبعثة أثناء التكثيف.

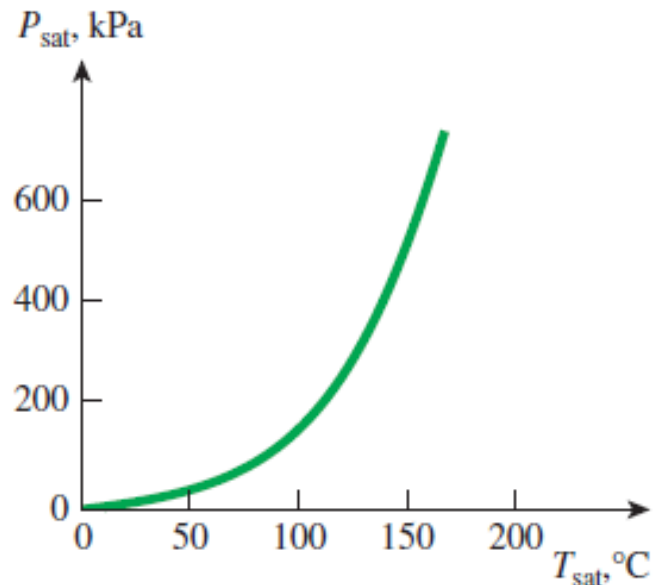


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- The magnitudes of the latent heats **depend** on the **temperature** or **pressure** at which the phase change occurs. At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg. A plot of  $T_{\text{sat}}$  versus  $P_{\text{sat}}$ , such as the one given for water in (Fig. 11-1), is called a liquid–vapor saturation curve.

**Figure (11-1) :** The liquid–vapor saturation curve of a pur substance (numerical values are for water).



It is clear from (Fig. 11-1 ) that  $T_{\text{sat}}$  **increases with  $P_{\text{sat}}$** . Thus, **a substance at higher pressures boils at higher temperatures**. In the kitchen, higher boiling temperatures mean shorter cooking times and energy savings. A beef stew, for example, may take 1 to 2 h to cook in a regular pan that operates at 1 atm pressure, but only 20 min in a pressure cooker operating at 3 atm absolute pressure (corresponding boiling temperature: 134°C).



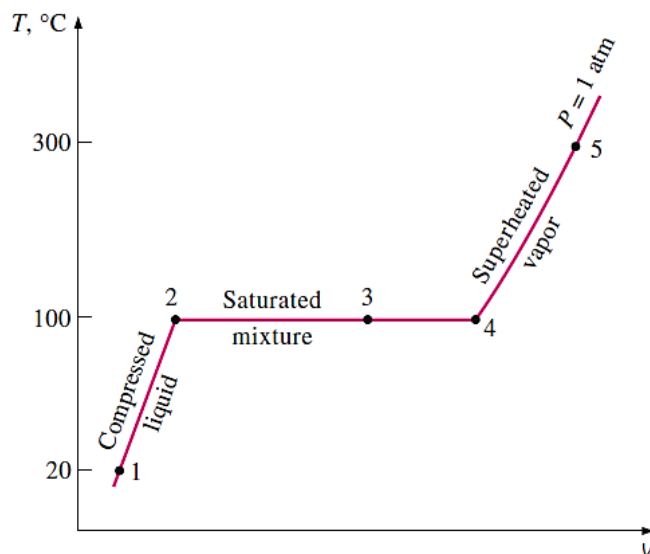
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## 11-2 Property Diagrams for Phase-Change Processes

The variations of properties during phase-change processes are best studied and understood with the help of property diagrams. We develop and discuss the T-v, P-v, and P-T diagrams for pure substances.

- **11.2.1 The T-v Diagram :** The phase-change process of water at 1 atm pressure was described in detail in the last section and plotted on a T-v diagram in (Fig.11-2). Now we repeat this process at different pressures to develop the T-v diagram.



**Figure (11-2):** T-v diagram for the heating process at constant pressure

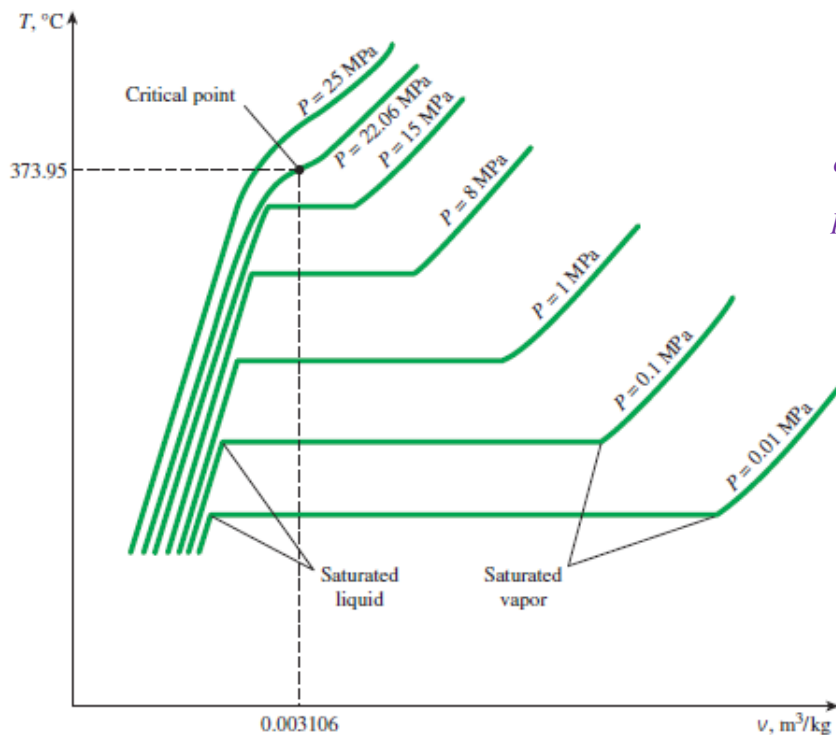
Let us **add weights on top of the piston** until the pressure inside the cylinder reaches **1 MPa**. As heat is transferred to the water at this new pressure, the process follows a path that looks very much like the process path at 1 atm pressure, as shown in (Fig. 11-3), but there are some noticeable differences.



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*First*, water starts boiling at a much higher temperature (179.9 °C) at this pressure. *Second*, the specific volume of the saturated liquid is larger and the specific volume of the saturated vapor is smaller than the corresponding values at 1 atm pressure. That is, the horizontal line that connects the saturated liquid and saturated vapor states is much shorter.



**Figure (11-3):** *T-v diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).*

As the pressure is increased further, this saturation line continues to shrink, as shown in (Fig. 11–3 ), 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  $T_{cr}$ , critical pressure  $P_{cr}$ , and critical specific volume  $V_{cr}$ . The critical-point properties of water are  $P_{cr} = 22.06$  MPa,  $T_{cr} = 373.95$  °C, and  $V_{cr} = 0.003106$  m<sup>3</sup>/kg. *For helium*, they are 0.23 MPa, -267.85 °C, and 0.01444 m<sup>3</sup>/kg.



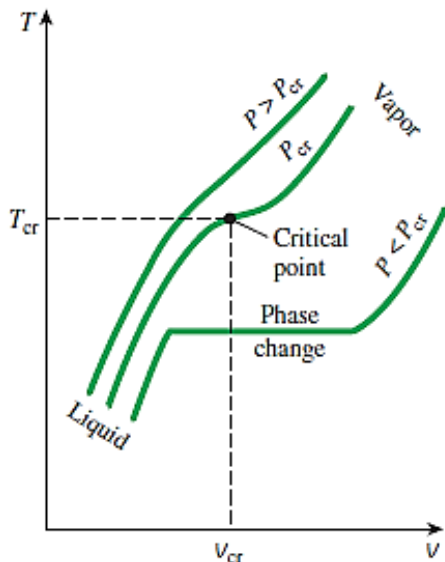
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الرسم المبين أعلاه يمثل العلاقة بين درجات الحرارة والحجم النوعي عند ضغوط مختلفة تبدأ ب 0.01 MPa و تصل الى 22.06 MPa والذي يمثل الضغط الحرج Critical Pressure للماء الذي يتحول عنده الماء من الحالة السائلة الى الغازية في لحظة واحدة وتكون نقطة الـ Saturation Liquid هي نفسها Saturation Vapour.

نلاحظ أيضا انه كلما ارتفع الضغط فإن عملية التبخر تكون اسرع لان الخط الواصل بين نقطتي الـ Saturation Liquid و Saturation Vapour يقل طوله والذي يمثل مرحلة التبخر. النقطة الحرجة : هي النقطة التي لا يوجد فيها فواصل واضحة بين حالات المادة، (مثل فواصل بين الحالة السائلة، والحالة الصلبة، أو الحالة الغازية). فعلى سبيل المثال تُعرف درجة الحرارة الحرجة بأنها درجة الحرارة التي فوقها لا يمكن التمييز بين الحالة الغازية والسائلة لمادة ما.

At pressures above the critical pressure, there is not a distinct phase change process (Fig. 11-4). Eventually, it resembles a vapor, but we can never tell when the change has occurred. Above the critical state, there is no line that separates the compressed liquid region and the superheated vapor region. However, it is customary to refer to the substance as superheated vapor at temperatures above the critical temperature and as compressed liquid at temperatures below the critical temperature.



- لا توجد عملية تغيير طور واضحة في المنطقة الواقعة فوق الحالة الحرجة -  
لانه لا يوجد خط يفصل بين المنطقة السائلة المضغوطة ومنطقة البخار  
شديدة الحرارة . ومع ذلك ، من المؤلف الإشارة إلى المادة على أنها  
Super heated في درجات حرارة أعلى من درجة الحرارة الحرجة وكسائل  
مضغوط Comp. liquid في درجات حرارة أقل من درجة الحرارة الحرجة.

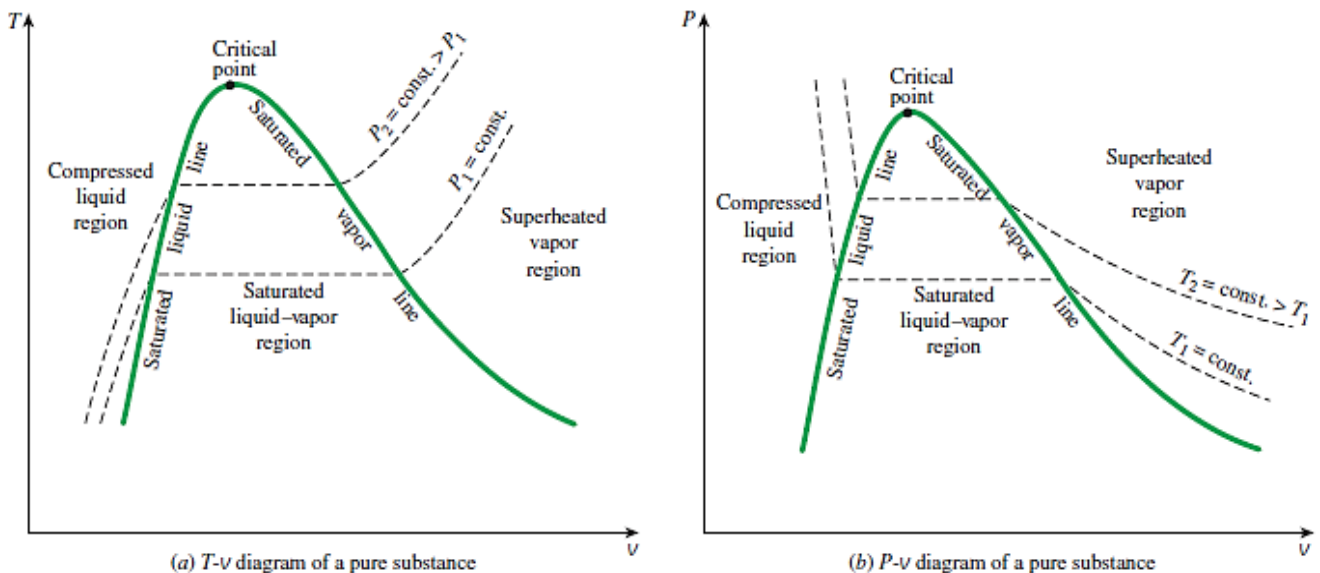
**Figure (11-4):** At supercritical pressures ( $P > P_{cr}$ ), there is no distinct phase-change (boiling) process. (numerical values are for water).



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The saturated liquid states in (Fig. 11–3) can be connected by a line called the **saturated liquid line**, and saturated vapor states in the same figure can be connected by another line, called **the saturated vapor line**. These two lines meet at **the critical point**, forming a dome as shown in (Fig. 11–5 a). 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**. 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**.



**Figure (11-5):** Property diagrams of a pure substance.



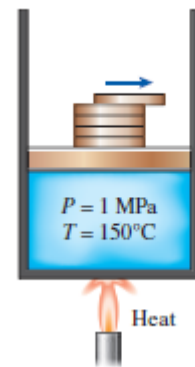


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➤ **11.2.2 The P-v Diagram:** The general shape of the P-v diagram of a pure substance is very much like the T-v diagram, but the T= constant lines on this diagram have a downward trend, as shown in (Fig. 11-5 b). Consider again a piston–cylinder device that contains liquid water at 1 MPa and 150°C. Water at this state exists as a compressed liquid. Now the weights on top of the piston are removed one by one so that the pressure inside the cylinder decreases gradually (Fig. 11-6). The water is allowed to exchange heat with the surroundings so its temperature remains constant.

**Figure (11-6)** The pressure in a piston–cylinder device can be reduced by reducing the weight of the piston.



As the pressure decreases, the volume of the water increases slightly. When the pressure reaches the saturation-pressure value at the specified temperature (0.4762 MPa), the water starts to boil. During this vaporization process, both the temperature and the pressure remain constant, but the specific volume increases. Once the last drop of liquid is vaporized, further reduction in pressure results in a further increase in specific volume. Notice that during the phase-change process, we did not remove any weights. Doing so would cause the pressure and therefore the temperature to drop [since  $T_{sat} = f(P_{sat})$ ], and the process would no longer be isothermal. When the process is repeated for other temperatures, similar paths are obtained for the phase-change processes. Connecting the saturated liquid and the saturated vapor states by a curve, we obtain the P-v diagram of a pure substance, as shown in (Fig. 11–5b).





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### 11-3 Property Tables

For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations. Therefore, properties are frequently presented in the form of tables. Some thermodynamic properties can be measured easily, but others cannot and are calculated by using the relations between them and measurable properties. The results of these measurements and calculations are presented in tables in a convenient format. In the following discussion, the steam tables are used to demonstrate the use of thermodynamic property tables. Property tables of other substances are used in the same manner.

For each substance, the thermodynamic properties are listed in more than one table. In fact, a separate table is prepared for each region of interest such as the superheated vapor, compressed liquid, and saturated (mixture) regions. Property tables are given in the appendix in both SI and English units.

تكون العلاقات بين الخواص الديناميكية الحرارية معقدة للغاية بحيث لا يمكن التعبير عنها بالمعادلات البسيطة. لذلك ، يتم عرض الخصائص بشكل أبسط في جداول خاصة ، يتم سرد الخصائص الحرارية في أكثر من جدول. في الواقع ، يتم إعداد جدول منفصل لكل منطقة ذات أهمية من مناطق تغيير حالة المادة مثل منطقة البخار المحمص Super heated region ومنطقة السائل المضغوط Compressed liquid region والمنطقة المشبعة Saturated region .

#### ➤ 11.3.1 Saturated Liquid and Saturated Vapor States :

The subscript " f " is used to denote properties of a saturated liquid, and the subscript "g" to denote the properties of saturated vapor. These symbols are commonly used in thermodynamics and originated from German. Another subscript commonly used is "fg", which denotes the difference between the saturated vapor and saturated liquid values of the same property. For example,



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$v_f$  = specific volume of saturated liquid.

$v_g$  = specific volume of saturated vapor.

$v_{fg}$  = difference between  $v_g$  and  $v_f$  (that is,  $v_{fg} = v_g - v_f$ )

Temp. °C $T$	Sat. press. kPa $P_{sat}$	Specific volume m <sup>3</sup> /kg	
		Sat. liquid $v_f$	Sat. vapor $v_g$
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Specific volume of saturated liquid

Specific volume of saturated vapor

Corresponding saturation pressure

**Figure (11-7)** A partial list of table.

The quantiti "  $h_{fg}$  " is called the **enthalpy of vaporization** (or latent heat of vaporization). It represents the amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure. It decreases as the temperature or pressure increases and becomes zero at the critical point.

المحتوى الحراري للتبخير (أو الحرارة الكامنة للتبخير): تُعرف على أنها كمية الطاقة اللازمة لتبخير كتلة

معينة من السائل المشبع عند درجة حرارة أو ضغط معين. يقل مقدارها مع زيادة درجة الحرارة أو الضغط

وتصبح قيمتها صفراً عند النقطة الحرجة.



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#### ➤ 11.3.2 Saturated Liquid–Vapor Mixture

During a vaporization process, a substance exists as part liquid and part vapor. That is, it is a mixture of saturated liquid and saturated vapor (Fig. 11-8). 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  $x$  (Dryness Fraction) defined as the ratio of the mass of vapor to the total mass of the mixture.

أثناء عملية تغيير الطور توجد المادة في صورة مزيج جزء سائل وجزء بخار و لتحليل هذا الخليط بشكل صحيح ، نحتاج إلى معرفة نسبة الكمية السائلة ونسبة كمية البخار في الخليط. يتم ذلك عن طريق تحديد خاصية جديدة تسمى "x dryness fraction" كنسبة كتلة البخار إلى الكتلة الكلية للخليط.

$$x = \frac{\text{mass of saturated vapor}}{\text{Total mass}} = \frac{m_g}{m_f + m_g}$$

$m_f$  = mass of liquid

$m_g$  = mass of gass

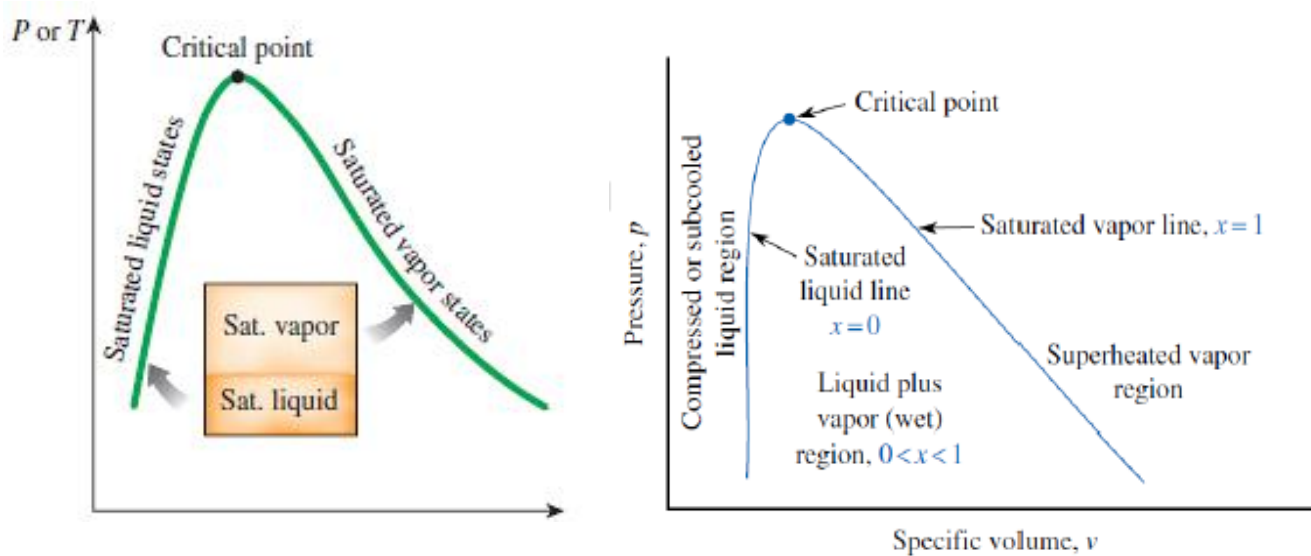
There are two important limits to remember:

- $x = 0$ : corresponds to  $m_{\text{vap}} = 0$ . This is the all liquid limit.
- $x = 1$ : corresponds to  $m_{\text{vap}} = m_{\text{total}}$ . This is the all gas limit. ( $0 \leq x \leq 1$ )



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**Figure (11-8)** The relative amounts of liquid and vapor phases in a saturated mixture are specified by the quality  $x$ .

We note :

$$V = V_f + V_g$$

$$m = m_f + m_g$$

$$V = mv, \quad V_f = m_f v_f, \quad V_g = m_g v_g$$

$$mv = m_f v_f + m_g v_g$$

$$v = \frac{m_f v_f}{m} + \frac{m_g v_g}{m}$$

**Lecture 11 : Phase-Change Processes of pure substance***by: Asst. Lect. Karrar Al-Mansoori***➤ 11.3.3 Superheated Vapor**

In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor. Since the superheated region is a single-phase region (vapor phase only), temperature and pressure are no longer dependent properties and they can conveniently be used as the two independent properties in the tables. In these tables, the properties are listed against temperature for selected pressures starting with the saturated vapor data. The saturation temperature is given in parentheses following the pressure value:

Compared to saturated vapor, superheated vapor is characterized by:

Lower pressures ( $P < P_{\text{sat}}$  at a given  $T$ )

Higher temperatures ( $T > T_{\text{sat}}$  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  $T$ ).