# Chemical Engineering (Thermodynamics I) (UCH305)

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# Lecture 7

# <u>Outline</u>

- Saturated Liquid–Vapor Mixture

- Quality of steam

- Property evaluation for liquid–Vapor Mixture

- Saturation temperature & saturation pressure

# 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.).

- 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 ($m_g$) to the total mass of the mixture ($m_t$):
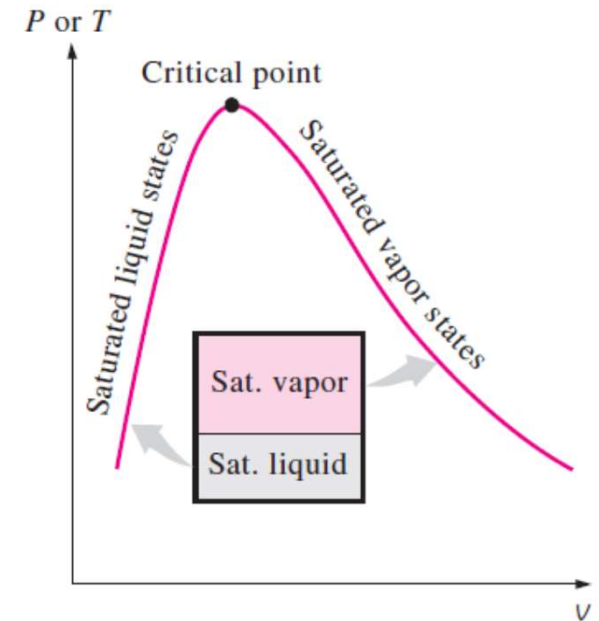


The relative amounts of liquid and vapor phases in a saturated mixture are specified by the *quality x*.

# Quality of steam, *x*

- Mass of the pure substance, $m_{total} = m_{liquid} + m_{vapor} = m_f + m_g$

$$x = \frac{m_{vapor}}{m_{total}} = \frac{m_g}{m_{total}}$$

- Quality has significance for ***saturated mixtures*** only.

- It has no meaning in the compressed liquid or superheated vapor regions.

- Its value 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**).

▪ Consider a tank that contains a saturated liquid–vapor mixture.

▪ The volume occupied by saturated liquid is $V_f$, and

▪ the volume occupied by saturated vapor is $V_g$.

| Saturated vapor, $v_g$ | $=$ | Saturated vapor-liquid mixture, $v_{avg}$ |
| Saturated liquid, $v_f$ | | |
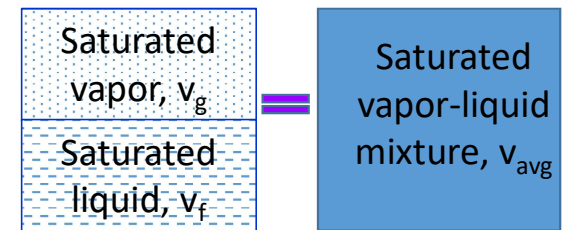
▪ The total volume $V$ is the sum of the above two: $V_t = V_f + V_g$

▪ *But,*

• $V = m \times v$

• $V_t = m_t \times v_{avg}$

*Specific volume of steam varies with operating conditions.*
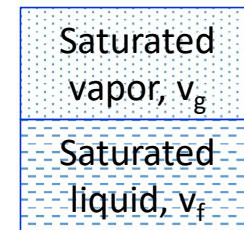$v_1 \neq v_2$

- *Then*
  - $V_t = V_f + V_g$
    - $m_t v_{avg} = m_f v_f + m_g v_g$
      - *But, $m_t = m_f + m_g$    or    $m_f = (m_t - m_g)$*
    - $m_t v_{avg} = (m_t - m_g)v_f + m_g v_g$

  - Dividing by $m_t$ yields:
    - $v_{avg} = (1 - x)v_f + x \, v_g$
      - Since, $x = m_g / m_t$.

Saturated
vapor, $v_g$

Saturated
liquid, $v_f$

- This relation can also be expressed as:
  - $v_{avg} = (1-x)v_f + x\, v_g$

  - $v_{avg} = v_f - x\, v_f + x\, v_g$

  - $v_{avg} = v_f + x\, v_g - x\, v_f$

  - $v_{avg} = v_f + x\, (v_g - v_f)$

  - $\boldsymbol{v_{avg} = v_f + x\, v_{fg}}$     **(m³/kg)**

    \* Where, $v_{fg} = (v_g - v_f)$.

- Solving for quality, we obtain: $$x = \frac{v_{avg} - v_f}{v_{fg}} = \frac{v_{avg} - v_f}{v_g - v_f}$$

# Different relations for quality, $x$

- $v_{avg} = v = v_f + x\, v_{fg}$       m$^3$/kg

- $u_{avg} = u = u_f + x\, u_{fg}$       kJ/kg

- $h_{avg} = h = h_f + x\, h_{fg}$       kJ/kg

- $s_{avg} = s = s_f + x\, s_{fg}$       kJ/(kg.K)

# Compressed Liquid (Subcooled Liquid)

- Consider a piston–cylinder device containing liquid water at 20°C and 1 atm pressure (state 1, Fig. 1).

- Under these conditions, water exists in the liquid phase, and it is called a **compressed liquid, or a subcooled liquid,** meaning that it is *not about to vaporize*.
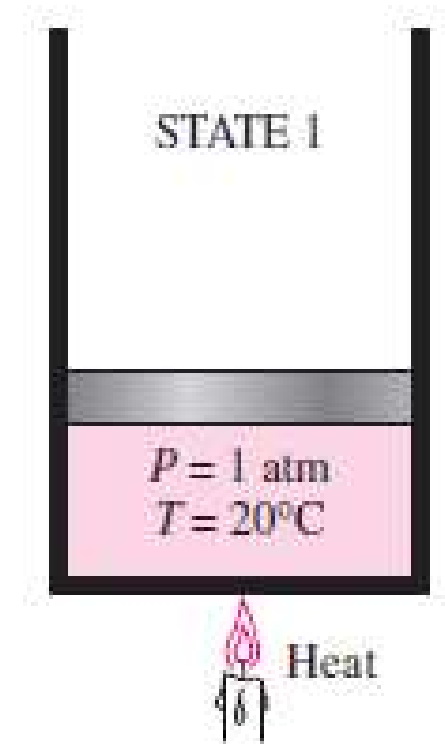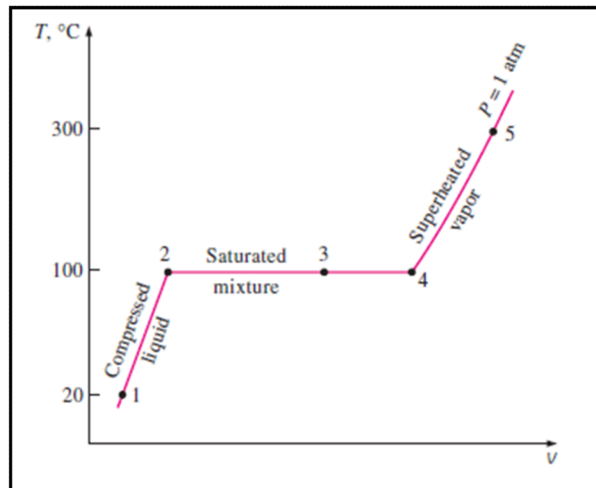
*FIGURE-1: At 1 atm and 20°C, water exists in the liquid phase (compressed liquid).*

- *Heat is now transferred to the water* until its temperature rises to, say, 40°C.

- As the temperature rises, the liquid water expands slightly, and so its specific volume increases.

- To accommodate this expansion, the piston moves up slightly.

- The pressure in the cylinder remains constant at 1 atm during this process since it depends on the outside barometric pressure and the weight of the piston, both of which are constant.

- Water is still a compressed liquid at this state since it has not started to vaporize.

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# Saturated Liquid

- As more heat is transferred, the temperature keeps rising until it reaches 100°C (state 2, Fig. 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.**

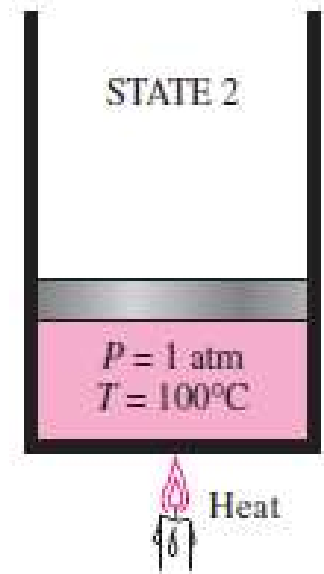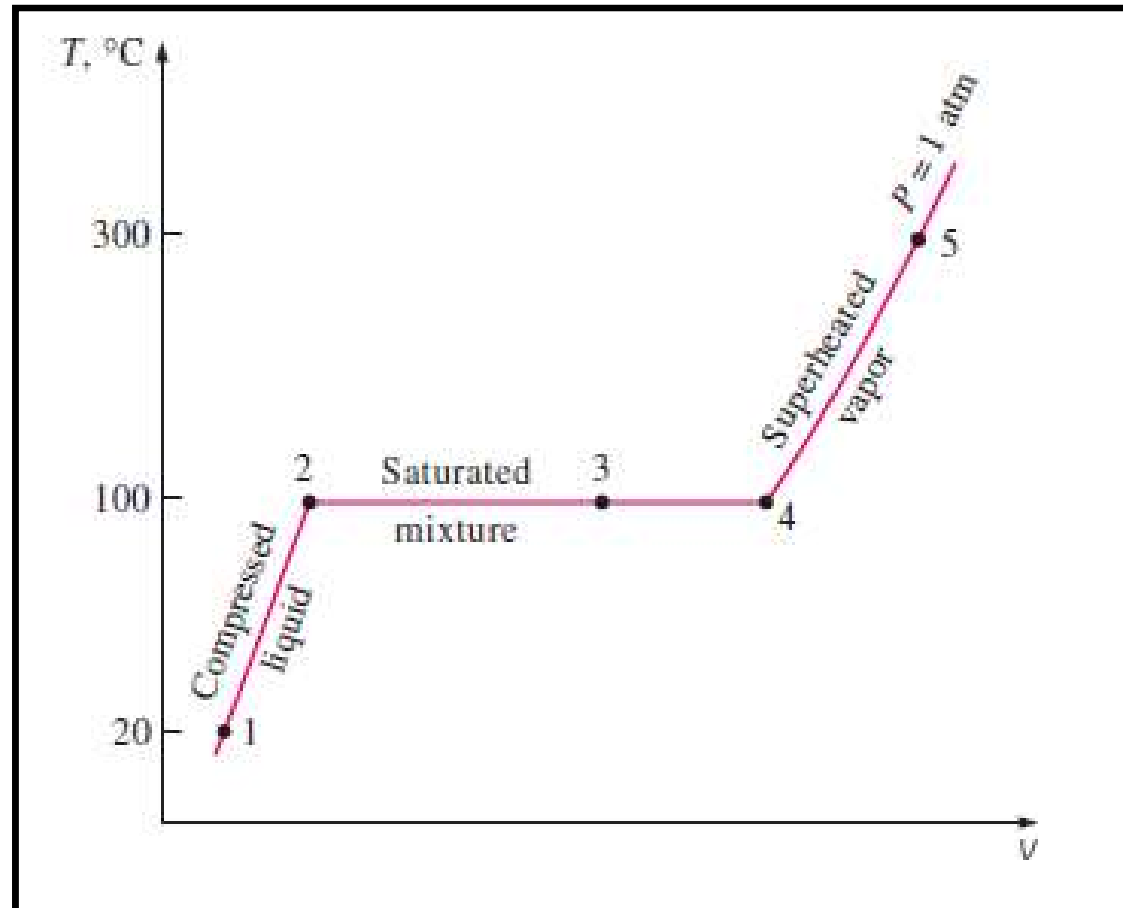- *Therefore, state 2 is a* **saturated liquid** *state.*



**FIGURE-2:** At 1 atm pressure and 100°C, water exists as a liquid that is ready to vaporize (*saturated liquid*).

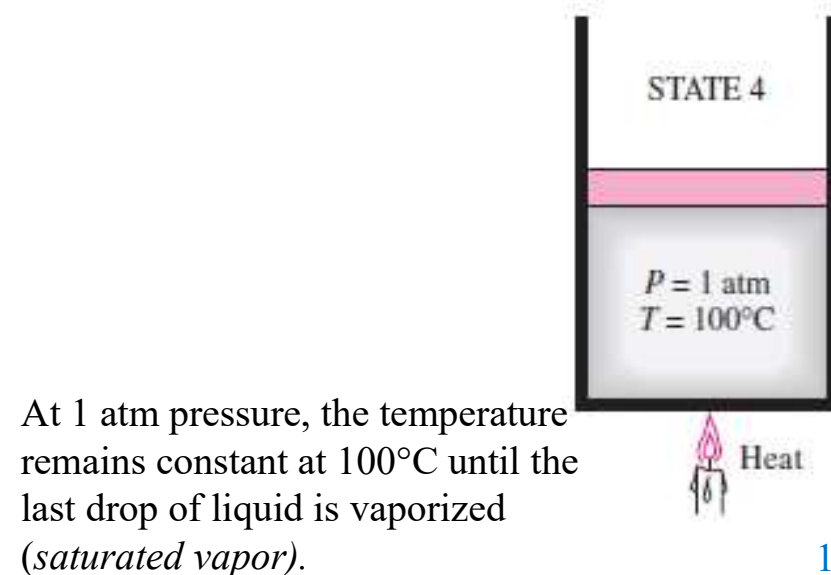# T-V diagram for the heating process of water at constant pressure

# Saturated Vapor

- Once boiling starts, the temperature stops rising until the liquid is completely vaporized.

- That is, the temperature will remain constant during the entire phase-change process if the pressure is held constant.

- This can easily be verified by placing a thermometer into boiling pure water on top of a stove.

- At sea level (*P = 1 atm*), the thermometer will always read 100°C if the pan is uncovered or covered with a light lid.

- During a boiling process, the only change we will observe is a large increase in the volume and a steady decline in the liquid level as a result of more liquid turning to vapor.

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- Midway about the vaporization line (state 3, Fig. 3), the cylinder contains equal amounts of liquid and vapor.

- As we continue transferring heat, the vaporization process continues until the last drop of liquid is vaporized (state 4, Fig. 4).

- At this point, the entire cylinder is filled with vapor that is on the borderline of the liquid phase.

STATE 3

Saturated vapor

$P = 1$ atm
$T = 100°C$

Saturated liquid
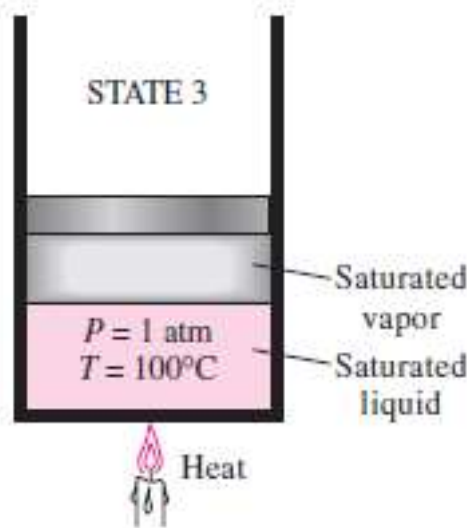
Heat

As more heat is transferred, part of the saturated liquid vaporizes (*saturated liquid–vapor mixture*).

STATE 4

$P = 1$ atm
$T = 100°C$

At 1 atm pressure, the temperature remains constant at 100°C until the last drop of liquid is vaporized (*saturated vapor*).

Heat

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# T-V diagram for the heating process of water at constant pressure
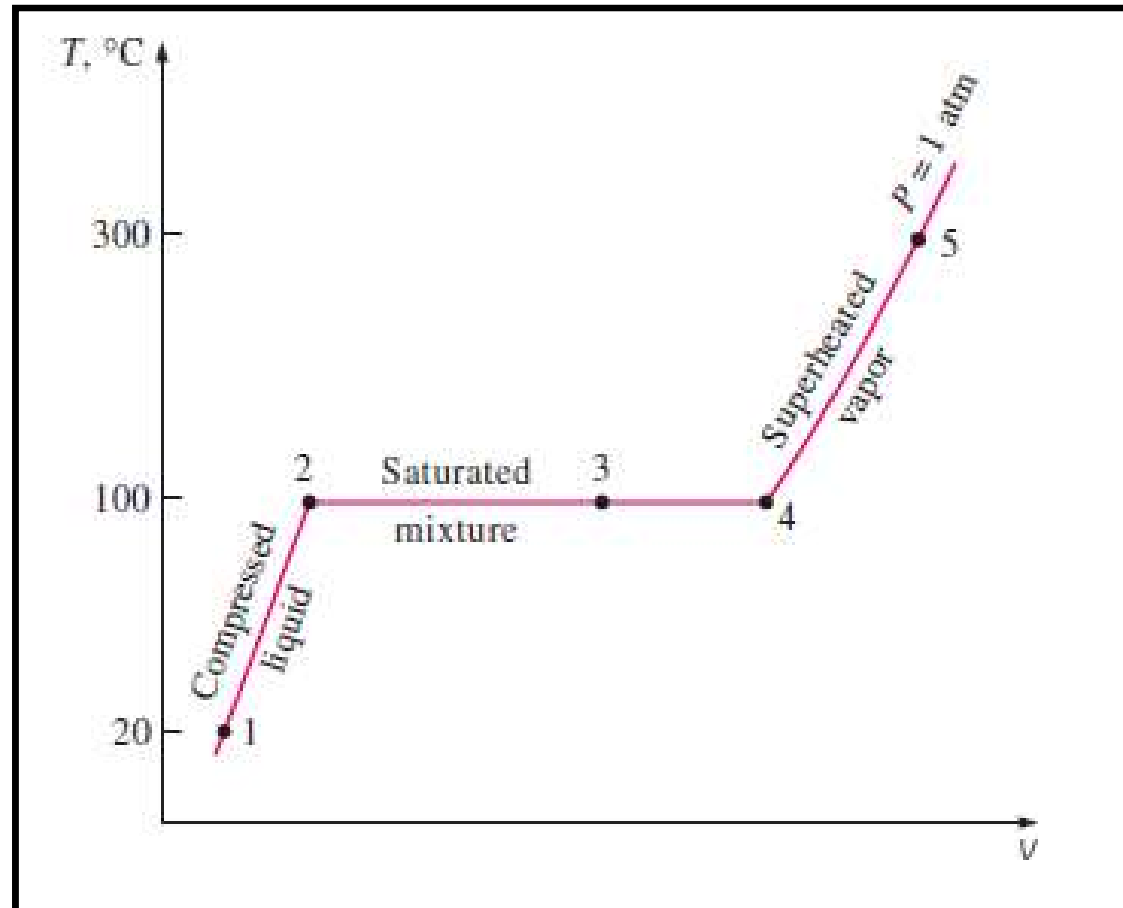
- Any heat loss from this vapor will cause some of the vapor to condense (phase change from vapor to liquid).

- A vapor that is *about to condense is called a **saturated vapor.***

- *Therefore, **state 4 is a saturated** vapor state*.

- A substance at states between 2 and 4 is referred to as a **saturated liquid–vapor mixture** since the *liquid and vapor phases coexist in* equilibrium at these states.

# Superheated Vapor

- Once the phase-change process is completed, then it will be a single phase region again (this time vapor only).

- Further transfer of heat results in an increase in both the temperature and the specific volume (Fig. 5).

- At state 5, the temperature of the vapor is, let us say, 300°C; and if we transfer some heat from the vapor, the temperature may drop somewhat but no condensation will take place as long as the temperature remains above 100°C (for *P = 1 atm*).
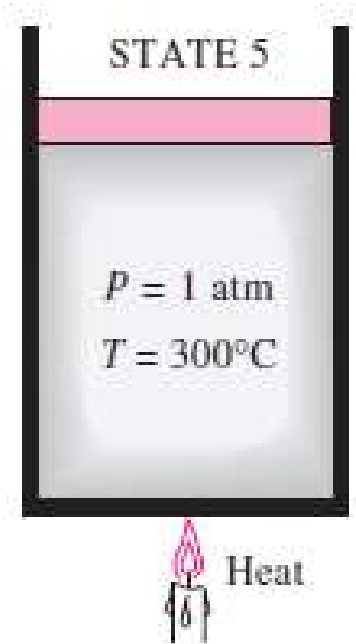


As more heat is transferred, the temperature of the vapor starts to rise (*superheated vapor*).

- A vapor that is not about to condense (i.e., not a saturated vapor) is called a **superheated vapor.**

- Therefore, **water at state 5 is a** superheated vapor.

- This constant-pressure phase-change process can be illustrated on a T-v diagram.

# T-V diagram for the heating process of water at constant pressure
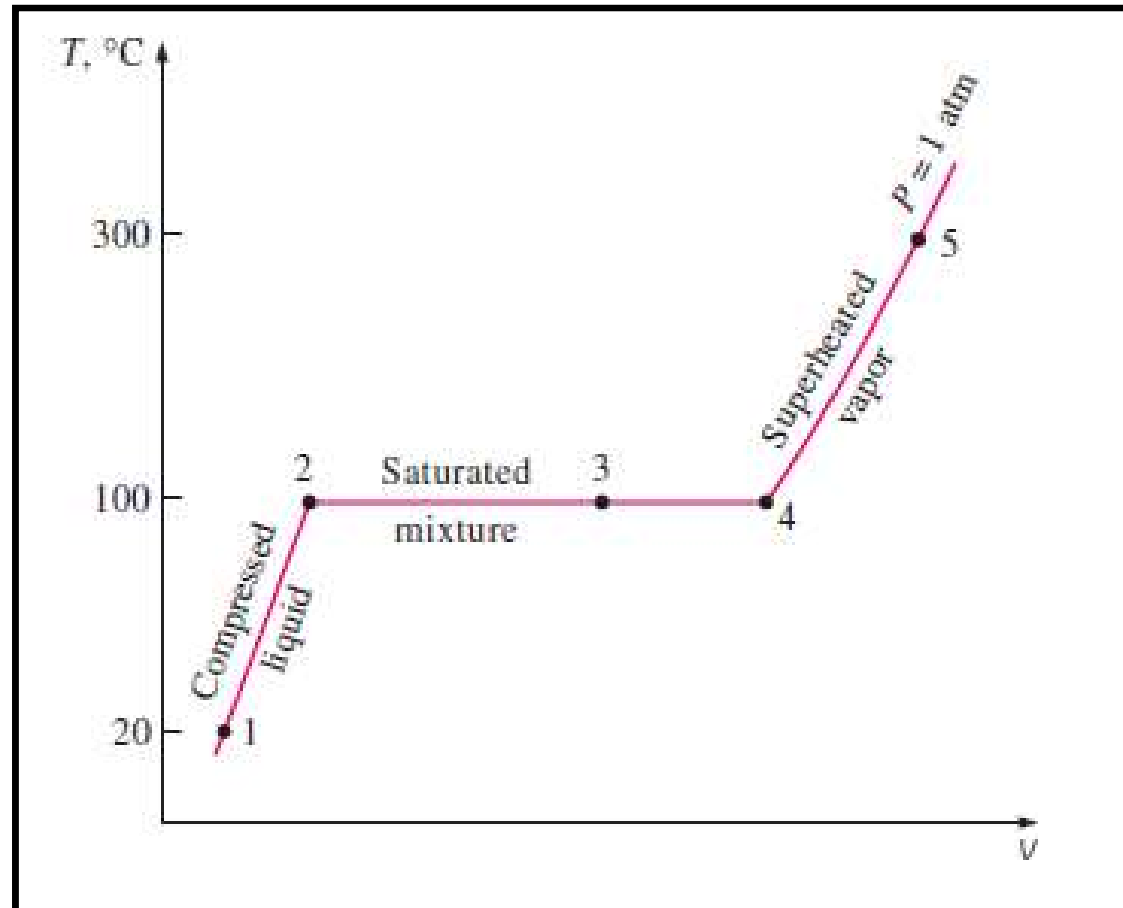
- If the entire process described here is reversed by cooling the water while maintaining the pressure at the same value,
    - the water will go back to state 1, retracing the same path,
    - and in so doing,
    - the amount of heat released will exactly match the amount of heat added during the heating process.

- In our daily life, water implies liquid water and steam implies water vapor.

- In thermodynamics, however, both water and steam usually mean only one thing: $H_2O$.

# Saturation Temperature and Saturation Pressure

- At a given pressure, the temperature at which a pure substance changes phase is called the **saturation temperature** $T_{\text{sat}}$.

- At a given temperature, the pressure at which a pure substance changes phase is called the **saturation pressure** $P_{\text{sat}}$.

- At a pressure of 101.325 kPa, $T_{\text{sat}}$ is 100°C.
- At a temperature of 100°C, $P_{\text{sat}}$ is 101.325 kPa.

- 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.

- That is, *the temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.*

# Saturation Temperature and Saturation Pressure of Water

| Temperature, T, °C | Saturation pressure, $P_{sat}$, kPa |
|:---:|:---:|
| − 10 | 0.26 |
| − 5 | 0.40 |
| 0 | 0.61 |
| 5 | 0.87 |
| 10 | 1.23 |
| 15 | 1.71 |
| 20 | 2.34 |
| 25 | 3.17 |
| 30 | 4.25 |
| 40 | 7.39 |
| 50 | 12.35 |
| 100 | 101.325 |
| 150 | 476.2 |
| 200 | 1555 |
| 250 | 3976 |
| 300 | 8588 |

[Saturation (boiling) pressure of water at various temperatures]

The liquid–vapor saturation curve of a pure substance (numerical values are for water)
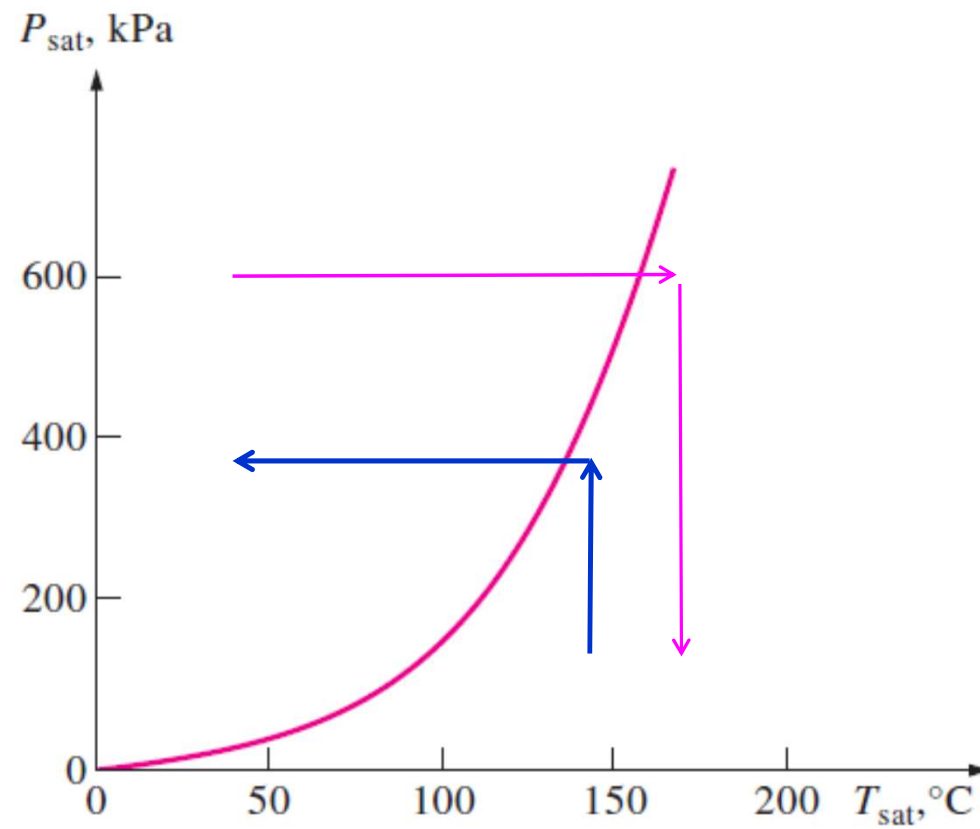
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# *Thank you for your Patience*