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
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Announcements:  
Dr. Walid’s e-mail and Office Hours 
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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). 

Text book: 
Thermodynamics An Engineering Approach 
Yunus A. Cengel & Michael A. Boles 
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.
3–1 PURE SUBSTANCE

A substance that has a fixed chemical composition throughout is called 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

Phases

- Gas
- Liquid
- Solid
Consider a piston–cylinder device containing liquid water at 20°C and 1 atm pressure (state 1). Under these conditions, water exists in the liquid phase, and it is called 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°C, water exists as 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.

As more heat is transferred, part of the saturated liquid vaporizes (saturated liquid–vapor mixture).
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 amount of heat released will exactly match the amount of heat added during the heating process.
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.
Variations of properties during phase-change processes are best studied and understood with the help of property diagrams (T-v, P-v, and P-T diagrams for pure substances).
1 The $T$-$\nu$ Diagram

Critical point

Saturation line

Saturated liquid

Saturated vapor

$P = 25$ MPa

$P = 22.06$ MPa

$P = 15$ MPa

$P = 8$ MPa

$P = 1$ MPa

$P = 0.1$ MPa

$P = 0.01$ MPa
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; \( T_{cr} \), critical pressure \( p_{cr} \), and critical specific volume \( v_{cr} \). The critical-point properties of water are \( p_{cr} = 22.06 \) MPa, \( T_{cr} = 373.95^\circ \)C, and \( v_{cr} = 0.003106 \) m\(^3\)/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 **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 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.
2 The $p$-$v$ Diagram

$p$-$v$ diagram of a pure substance.
Specific enthalpy, given the symbol $h$; is defined as:

$$h = u + Pv$$

(kJ/kg)  \hfill (3-1)
Hence, total enthalpy, $H$, is defined as:

$$H = U + PV \quad (kJ)$$ (3-2)
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.

\[ \begin{align*} v_f &= \text{specific volume of saturated liquid} \\ v_g &= \text{specific volume of saturated vapor} \\ v_{fg} &= \text{difference between } v_g \text{ and } v_f \\ &= v_g - v_f \end{align*} \]
<table>
<thead>
<tr>
<th>Temp. press.</th>
<th>Specific volume m³/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>Sat. press. kPa</td>
</tr>
<tr>
<td>T</td>
<td>P_{sat}</td>
</tr>
<tr>
<td>85</td>
<td>57.868</td>
</tr>
<tr>
<td>90</td>
<td>70.183</td>
</tr>
<tr>
<td>95</td>
<td>84.609</td>
</tr>
</tbody>
</table>

From Table A–4

- Specific temperature
- Specific volume of saturated liquid
- Corresponding saturation pressure
- Specific volume of saturated vapor
EXAMPLE 3–1 Pressure of Saturated Liquid in a Tank

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

Solution

\[ T, ^\circ C \quad T = 90^\circ C \text{ Sat. L} \]
From Table A–4 (As shown in Slide 30)

\( p_{sat} \) at 90°C = 70.183 kPa.

\( \nu_{sat} \) Liquid at 90°C = \( \nu_f \) at 90°C = 0.001036 m\(^3\)/kg.

But, \( \nu = V/m \). Hence, \( V = \nu \times m = 0.001036 \text{ m}^3/\text{kg} \times 50 \text{ kg} = 0.0518 \text{ m}^3 \)
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

\( a) \ v_f \text{ at } 100 \text{ kPa} = 0.001043 \text{ m}^3/\text{kg.} \)

\( v_g \text{ at } 100 \text{ kPa} = 1.6941 \text{ m}^3/\text{kg.} \)

\( v_{fg} = v_g - v_f = 1.6941 \text{ m}^3/\text{kg} - 0.001043 \text{ m}^3/\text{kg} \)

\( v_{fg} = v_g - v_f = 1.6931 \text{ m}^3/\text{kg} \)

\( \Delta v = m \times v_{fg} = (200/1000) \text{ kg} \times 1.6931 \text{ m}^3/\text{kg} = 0.3386 \text{ m}^3 \)
(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** $h_{fg}$ (at $p=100$ kPa) = 2257.5 kJ/kg

Thus, the amount of energy transferred is

$$E = m \times h_{fg} = \frac{200}{1000} \text{ kg} \times 2257.5 \text{ kJ/kg} = 451.5 \text{ kJ}$$
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:
where,

\[ x = \frac{m_{\text{vapor}}}{m_{\text{total}}} \]  \hspace{1cm} (3-3)
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).
By definition:

\[ x = \frac{AB}{AC} \]

Hence,

\[ x = \frac{v - v_f}{v_{fg}} \]

Hence,

\[ v = v_f + x v_{fg} = v_f + x (v_g - v_f) \text{ m}^3/\text{kg} \]
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)

\[ x = \frac{m_{\text{Vapor}}}{m_{\text{total}}} = \frac{(m_{\text{total}} - m_{\text{liquid}})}{m_{\text{total}}} \]

i.e. \[ x = \frac{(10 \text{ kg} - 8 \text{ kg})}{10 \text{ kg}} = 0.2 \]
It is clear that the tank contains mixture of Liquid an vapor

From Table A-4

\[ p = p_{sat} \text{ at } 90^\circ C = 70.183 \text{ kPa}. \]

\[ v_f \text{ at } 90^\circ C = 0.001036 \text{ m}^3/\text{kg}. \]

\[ v_g \text{ at } 90^\circ C = 2.3593 \text{ m}^3/\text{kg}. \]

But

\[ v = v_f + x \quad v_{fg} = v_f + x ( \quad v_g - v_f \quad ) \text{ m}^3/\text{kg} \]
Hence,

\[ v = 0.001036 + 0.2 (2.3593 - 0.001036) \]
\[ \text{m}^3/\text{kg} = 0.473 \text{ m}^3/\text{kg} \]

\[ V = m \times v = 10 \text{ kg} \times 0.473 \text{ m}^3/\text{kg} = 4.73 \text{ m}^3 \]
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

\[ V = 80 \text{ L} = \frac{80}{1000} \text{ m}^3 = 0.08 \]

\[ \nu = \frac{V}{m} = \frac{0.08 \text{ m}^3}{4 \text{ kg}} = 0.02 \text{ m}^3/\text{kg} \]
R-134a

$P = 160$ kPa

$m = 4$ kg

$v_f = 0.0007437$

$v_g = 0.12348$

$v$, m$^3$/kg

$h_f = 31.21$

$h_g = 241.11$

$h$, kJ/kg

$T = -15.60^\circ$C
From Table A-12

\( \nu_f \ (\text{at } p_{sat} = 160 \text{ kPa}) = 0.0007437 \text{ m}^3/\text{kg.} \)

\( \nu_g \ (\text{at } p_{sat} = 160 \text{ kPa}) = 0.12348 \text{ m}^3/\text{kg.} \)

It is clear that \( \nu_f \ (= 0.0007437 \text{ m}^3/\text{kg}) \)

\(< \nu \ (= 0.02 \text{ m}^3/\text{kg}) \)< \( \nu_g \ (= 0.12348 \text{ m}^3/\text{kg}). \)

**Hence, 134a refrigerant is in the Saturated Liquid–Vapor Mixture**
(a) The temperature:
Hence, \( T = T_{\text{sat}} \) (at \( p_{\text{sat}} = 160 \text{ kPa} \)) = \(-15.60^\circ\text{C}\).

(b) Quality:
\[
x = \left( v - v_f \right) / v_{fg} = \left( 0.02 - 0.0007437 \right) / \left( 0.12348 - 0.0007437 \right) = 0.157
\]

(c) The enthalpy of the refrigerant,
From Table A–12 : \( h_f \) (At 160 kPa) = 31.21 kJ/kg and \( h_{fg} \) (@ \( p=160 \text{ kPa} \)) = 209.90 kJ/kg.
\[ h = h_f + (x \times h_{fg}) = 31.21 \text{ kJ/kg} + (0.157 \times 209.90 \text{ kJ/kg}) = 64.2 \text{ kJ/kg} \]

(d) Volume occupied by the vapor phase,

\[ x = \frac{m_g}{m_t}, \text{ Hence} \]

\[ m_g = x \times m_t = 0.157 \times 4 \text{ kg} = 0.628 \text{ kg} \]

\[ V_g = m_g \times v_g = 0.628 \text{ kg} \times 0.12348 \text{ m}^3/\text{kg} = 0.0775 \text{ m}^3 \text{ (or 77.5 l)} \]
2 Superheated Vapor (single-phase 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.
The format of the superheated vapor tables is illustrated in the following figure.

See the previous two figures

(A partial listing of Table A–6).
Compared to saturated vapor, superheated vapor is characterized by
-Lower pressures \((p < p_{\text{sat}} \text{ at a given } T)\)
-Higher temperatures \((T > T_{\text{sat}} \text{ at a given } p)\)
-Higher specific volumes \((v > v_{g} \text{ at a given } p \text{ or } T)\)
-Higher internal energies \((u > u_{g} \text{ at a given } p \text{ or } T)\)
-Higher enthalpies \((h > h_{g} \text{ at a given } p \text{ or } T)\)
EXAMPLE 3–7 Temperature of Superheated Vapor

Determine the temperature of water at a state of $p = 0.5 \text{ MPa}$ and $h = 2890 \text{ kJ/kg}$.

Solution

From Table A-5

$T_{sat} \ (\ @ \ p = 0.5 \text{ Mpa}) = 151.83 \ ^\circ\text{C}$

$h_f \ (\ @ \ p = 0.5 \text{ Mpa}) = 640.09 \ \text{kJ/kg}$

$h_g \ (\ @ \ p = 0.5 \text{ Mpa}) = 2748.1 \ \text{kJ/kg}$

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, \( at \ p = 0.5 \ Mpa \)

<table>
<thead>
<tr>
<th>( T \ (\ ^\circ C) )</th>
<th>( h, \ kJ/kg )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>2855.8</td>
</tr>
<tr>
<td>( T )</td>
<td>2890</td>
</tr>
<tr>
<td>250</td>
<td>2961.0</td>
</tr>
</tbody>
</table>
Hence, by interpolation

\[
\frac{(T-200)}{(250-200)} = \frac{(2890-2855.8)}{(2961.0-2855.8)}
\]

\[T = 216.255 \, ^{\circ}C\]
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.
$v \approx v_f$,  
$u \approx u_f$,  
$h \approx h_f$  

$v_f, u_f, h_f \ (T_{sat})$  

$T_{sat} = T$
In general Compressed liquid *is characterized by:*

- Higher pressures \((P > P_{\text{sat}} \text{ at a given } T)\)
- Lower temperatures \((T < T_{\text{sat}} \text{ at a given } P)\)
- Lower specific volumes \((\nu < \nu_f \text{ at a given } P \text{ or } T)\)
- Lower internal energies \((u < u_f \text{ at a given } P \text{ or } T)\)
- Lower enthalpies \((h < h_f \text{ at a given } P \text{ or } T)\)
\[ T_{\text{sat}} = T \]

\[ v \approx v_f, \quad u \approx u_f, \quad v_f, u_f, h_f \ (T_{\text{sat}}) \]

\[ h \approx h_f \]
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°C) < $T_{sat}$ ( p = 5MPa) = 263.94°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 \( p = 5 \text{MPa} \) & \( T = 80^\circ \text{C} \), \( u = 333.82 \text{ kJ/kg} \)

(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 \( u \) = \[
\left(\frac{u_{\text{approx}} - u_{\text{exact}}}{u_{\text{exact}}}\right) \times 100\%
\]

= \[
\left(\frac{334.97 - 333.82}{333.82}\right) \times 100\% = 0.3445\%
\]
**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:

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T, °C</td>
<td>P, kPa</td>
<td>u, kJ/kg</td>
<td>x</td>
<td>Phase description</td>
</tr>
<tr>
<td>(a)</td>
<td>200</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td>125</td>
<td>1600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c)</td>
<td>1000</td>
<td>2950</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d)</td>
<td>75</td>
<td>500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(e)</td>
<td>850</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Solution

(a) Saturated Liquid–Vapor Mixture

\[ p = 200 \text{ kPa} \quad \& \quad x = 0.6 \]

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

\[ u = (u_f + x \cdot u_{fg}) = [504.5 \text{ kJ/kg} + (0.6 \cdot 2024.6 \text{ kJ/kg})] = 1719.26 \text{ kJ/kg} \]
(b) $T = 125 \, ^\circ C, \ u = 1600 \, kJ/kg$

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

It is clear that for $T = T_{\text{sat}} (= 125 ^\circ C)$,

$u_f (= 524.83 \, kJ/kg) < u (= 1600 \, kJ/kg) < u_g (= 2534.3 \, kJ/kg)$

Hence, water is *saturated liquid–vapor mixture*
\[ p = p \left( T_{sat} = 125^\circ C \right) = 232.23 \text{ kPa} \]

\[ x = \frac{(u-u_f)}{u_{fg}} = \frac{(1600 - 524.83)}{2009.5} \]

i.e. \[ x = \frac{(u-u_f)}{u_{fg}} = \frac{(1600 - 524.83)}{2009.5} \]

i.e. \[ x = 0.535 \]
(c) $p = 1000$ kPa, $u = 2950$ kJ/kg

From Table A-5

$T_{sat} \ (at \ p = 1000 \ kPa) = 179.88 \ ^\circ C$

$u_f \ (at \ p = 1000 \ kPa) = 761.39 \ \text{kJ/kg}$

$u_g \ (at \ p = 1000 \ kPa) = 2582.8 \ \text{kJ/kg}$

*It is clear that* $u \ (\ = 2950 \ \text{kJ/kg})$ $> u_g \ (\ = 2582.8 \ \text{kJ/kg})$
Hence, water is superheated steam.

From Table A-6, at $p = 1000 \text{ kPa}$

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>$u$, kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>2875.7</td>
</tr>
<tr>
<td>$T$</td>
<td>2950</td>
</tr>
<tr>
<td>400</td>
<td>2957.9</td>
</tr>
</tbody>
</table>

Hence, by interpolation

\[
\frac{(T - 350)}{(400 - 350)} = \frac{(2950 - 2875.7)}{(2957.9 - 2875.7)}
\]

\[T = 395.2 \, ^\circ \text{C}\]
$p = 1000 \text{ kPa}$
We would leave the quality column blank in this case since quality has no meaning for a superheated vapor.
(d) $T = 75 \, ^\circ C$, $p = 500 \, kPa$

\[ T_{\text{sat}} = 151.83 \, ^\circ C \]

$p = 500 \, kPa$
From Table A-5

\[ T_{\text{sat}} \ (\text{at} \ p = 500 \ \text{kPa}) = 151.83 \ ^\circ \text{C} \]

It is clear that \( T (= 75 \ ^\circ \text{C}) < T_{\text{sat}} = 151.83 \ ^\circ \text{C} \)

Hence, water is compressed liquid

From Table A-7 [for compressed liquid water] at \( p = 500 \text{kPa} \ & T = 75 \ ^\circ \text{C} \) {No data in Table A-7 corresponding to \( p = 500 \ \text{kPa} \)}

Hence, \( u \approx u_f (T_{\text{sat}} = T = 75 \ ^\circ \text{C}) = 313.99 \ \text{kJ/kg} \)
(e) $x = 0, p = 850 \text{ kPa}$
Hence, water is saturated liquid

From Table A-5 [for saturated water-Pressure table] at $p_{sat} = 850 \text{ kPa}$,
$T = T_{sat} = 172.94 \degree \text{C}, u_f = 731.0 \text{ kJ/kg}$
<table>
<thead>
<tr>
<th></th>
<th>$T$, °C</th>
<th>$P$, kPa</th>
<th>$u$, kJ/kg</th>
<th>$x$</th>
<th>Phase description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>120.21</td>
<td>200</td>
<td>1719.26</td>
<td>0.6</td>
<td>Saturated L–V Mixture</td>
</tr>
<tr>
<td>(b)</td>
<td>125</td>
<td>232.2</td>
<td>1600</td>
<td>0.535</td>
<td>Saturated L–V Mixture</td>
</tr>
<tr>
<td>(c)</td>
<td>395.2</td>
<td>1000</td>
<td>2950</td>
<td>-</td>
<td>Superheated steam</td>
</tr>
<tr>
<td>(d)</td>
<td>75</td>
<td>500</td>
<td>313.99</td>
<td>-</td>
<td>compressed L</td>
</tr>
<tr>
<td>(e)</td>
<td>172.94</td>
<td>850</td>
<td>731.0</td>
<td>0.0</td>
<td>Saturated L</td>
</tr>
</tbody>
</table>
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

\[
p v = R T \quad \text{or} \quad p / \rho = R T \quad \text{(3-10)}
\]

or \( p V = m R T \)
\[ R = \frac{R_u}{M} \quad R_u = 8.31447 \text{ kJ/kmol.K} \]

**Universal gas constant**

Gas constants for different gases; Table A-1

<table>
<thead>
<tr>
<th>Substance</th>
<th>Formula</th>
<th>Molar mass, ( M ) (kg/kmol)</th>
<th>( R ) (kJ/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>-</td>
<td>28.97</td>
<td>0.287</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>4.003</td>
<td>2.0769</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>39.948</td>
<td>0.2081</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N(_2)</td>
<td>28.013</td>
<td>0.2968</td>
</tr>
</tbody>
</table>
**EXAMPLE 3–10 Mass of Air in a Room**

Determine the mass of the air in a room whose dimensions are 4 m × 5 m × 6 m at 100 kPa and 25°C.
**Solution**

\[ p \, V = m \, R \, T \]

\[ p = 100 \text{ kPa} \]

\[ T = 25°C = 25 + 273 = 298\text{K} \]

\[ V = 4 \text{ m} \times 5 \text{ m} \times 6 \text{ m} = 120 \text{ m}^3 \]

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

*Hence, \( m = 140.3 \text{ kg} \)*
Homework

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