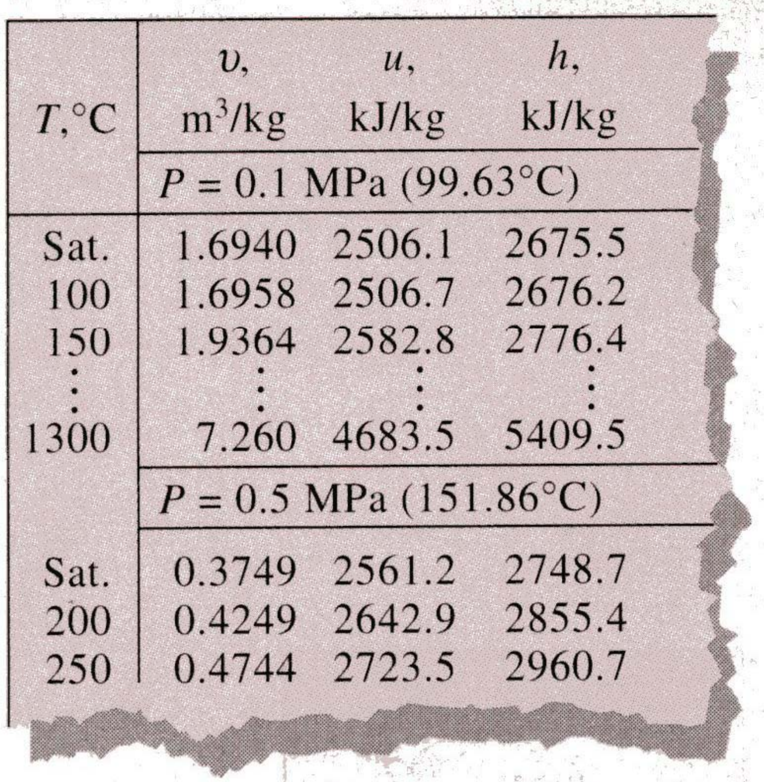
2 Superheated Vapor



T,°C	v, m^3/kg	u, kJ/kg	h, kJ/kg
	P = 0.1 MPa (99.63°C)		
Sat.	1.6940	2506.1	2675.5
100	1.6958	2506.7	2676.2
150	1.9364	2582.8	2776.4
⋮	⋮	⋮	⋮
1300	7.260	4683.5	5409.5
	P = 0.5 MPa (151.86°C)		
Sat.	0.3749	2561.2	2748.7
200	0.4249	2642.9	2855.4
250	0.4744	2723.5	2960.7

FIGURE 2–40

A partial listing of Table A–6.

Superheated vapor is characterized

Lower pressure ($P<P_{sat}$ at a given T)

Higher temperatures ($T>T_{sat}$ at a given P or T)

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)

2 Superheated Vapor

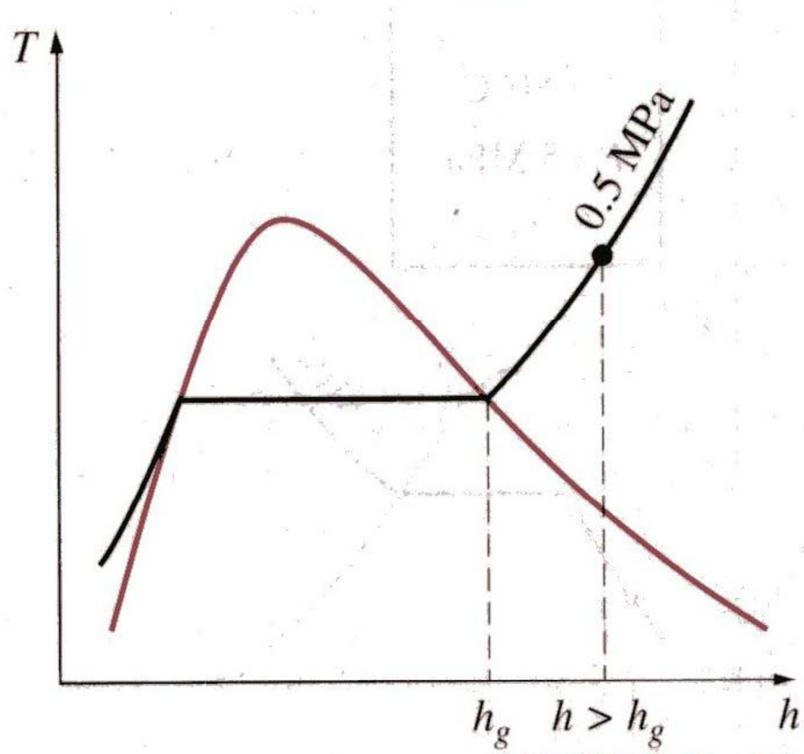


FIGURE 2–41

At a specified P, superheated vapor exists at a higher h than the saturated vapor (Example 2–7).

EXAMPLE 2-7

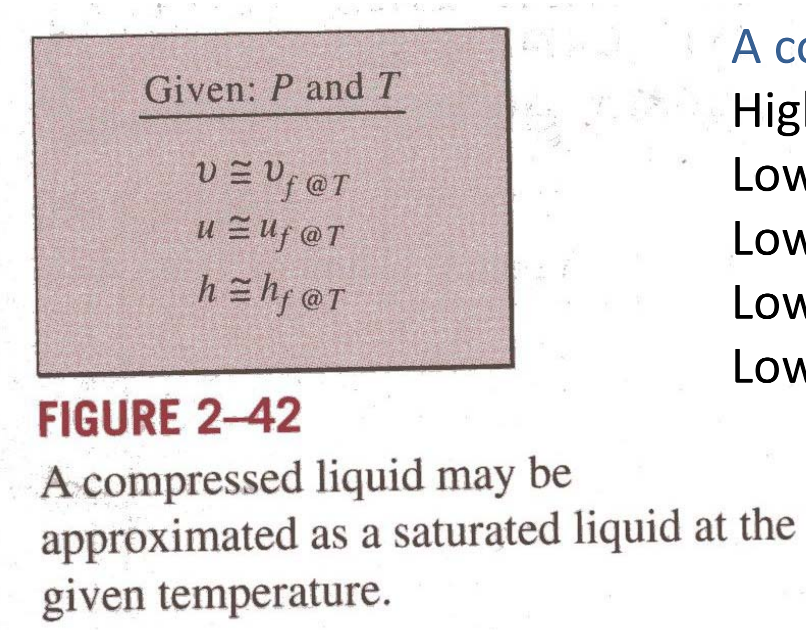
Determine the temperature of water at a state of P=0.5 Mpa and h=2890 kJ/kg.

Solution

$T, {}^{o}C$	$h, kJ/kg$
200	2855.4
250	2960.7

$$\boxed{T = 216.4\ {}^{o}C}$$

3 Compressed Liquid



Given: P and T

$v \cong v_{f\,@T}$

$u \cong u_{f\,@T}$

$h \cong h_{f\,@T}$

FIGURE 2–42

A compressed liquid may be approximated as a saturated liquid at the given temperature.

A compressed liquid is characterized

Higher pressure ($P>P_{sat}$ at a given T)

Lower temperatures ($T<T_{sat}$ 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)

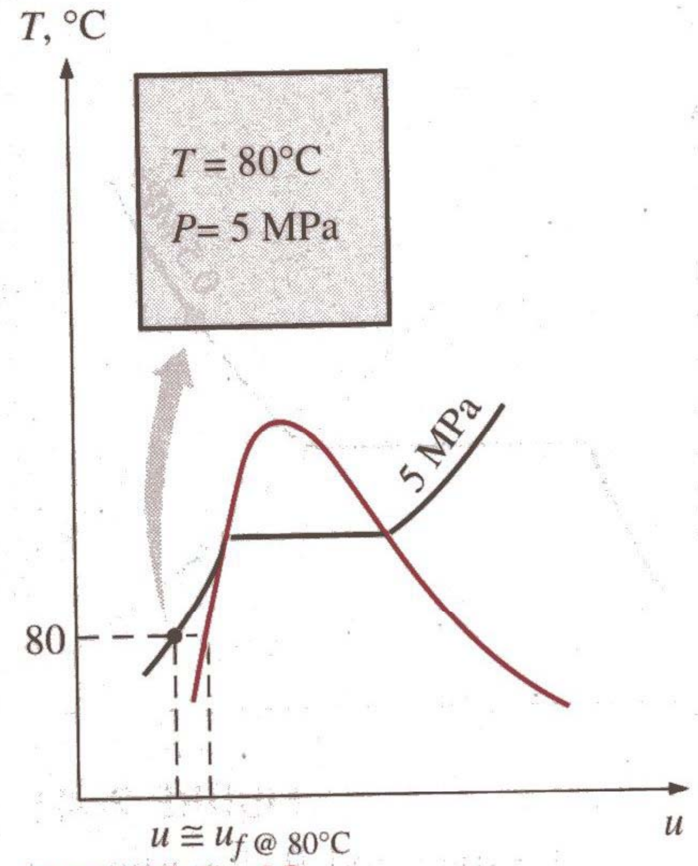


FIGURE 2–43

Schematic and T-u diagram for Example 2–8.

EAMPLE 2-8

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

(a) from table A-7

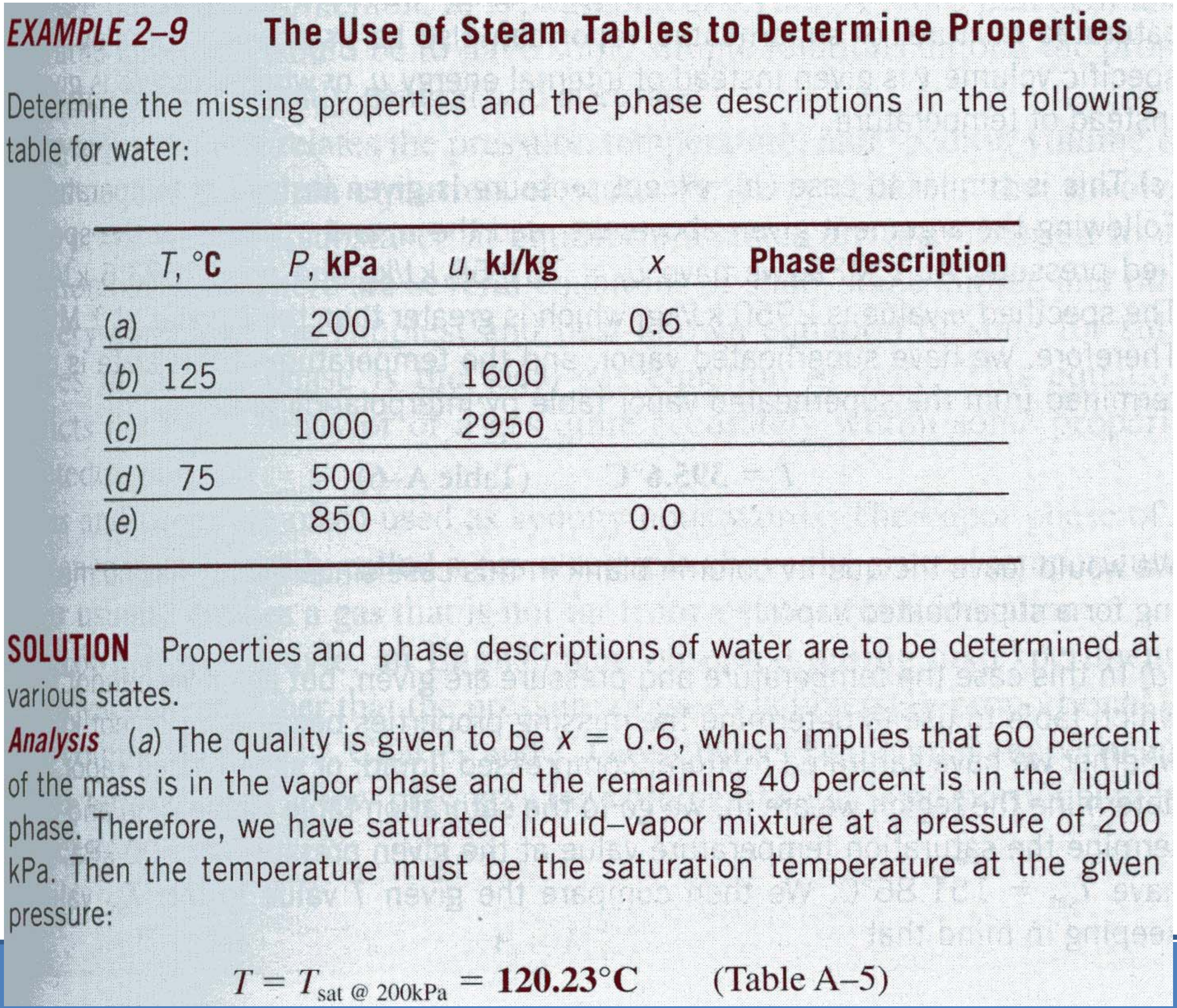
$$\boxed{\left.\begin{array}{l} P = 5\,MPa \\ T = 80^{o}C \end{array}\right\} \quad u = 333.72\,kJ/kg}$$

(b) from table A-4

$$\boxed{u \cong u_{f@80^{o}C} = 334.86\text{kJ/kg}}$$

$$\boxed{\frac{334.86 - 333.72}{333.72} \times 100 = 0.34\%}$$

Reference State and Reference Values



EXAMPLE 2–9 **The Use of Steam Tables to Determine Properties**

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

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

SOLUTION Properties and phase descriptions of water are to be determined at various states.

Analysis (a) The quality is given to be $x = 0.6$, which implies that 60 percent of the mass is in the vapor phase and the remaining 40 percent is in the liquid phase. Therefore, we have saturated liquid–vapor mixture at a pressure of 200 kPa. Then the temperature must be the saturation temperature at the given pressure:

$$T = T_{\text{sat @ 200kPa}} = \mathbf{120.23°C} \qquad \text{(Table A–5)}$$

2-7. THE IDEAL-GAS EQUATION OF STATE

ลักษณะของแก๊สอุดมคติคือ เป็นแก๊สที่มีอิสระในการเคลื่อนไหว โมเลกุลแก๊สไม่มีปฏิกิริยาซึ่งกันและกัน ไม่อยู่ภายใต้แรงดึงดูดระหว่างกัน ตย. เช่น อากาศ ออกซิเจน ไนโตรเจน ไฮโดรเจนฯลฯ สำหรับน้ำธรรมดาไม่ถือว่าเป็นแก๊สอุดมคติ นอกจากกรณีที่มีอุณหภูมิสูงกว่าอุณหภูมิวิกฤติ หรือที่ความดันต่ำมากๆ

2-7. THE IDEAL-GAS EQUATION OF STATE

An equation that relates the pressure, temperature, and specific volume of a substance is called an equation of state.

$$\boxed{\begin{aligned} &P = R\frac{T}{v} \\ &Pv = RT \qquad (2-9) \end{aligned}}$$

R is called the gas constant

Equation (2-9) is called the ideal-gas equation of state

P is the absolute pressure,

T is the absolute temperature,

v is the specific volume.

2-7. THE IDEAL-GAS EQUATION OF STATE

$$\boxed{R = \frac{R_u}{M} \qquad [\mathrm{kJ/(kg \cdot K) or \ kPa \cdot m^3/(kg \cdot K)}]}$$

R_u is the gas universal constant

$$\boxed{R = \begin{cases} 8.314 \ \mathrm{kJ/(kmol \cdot K)} \\ 8.314 \ \mathrm{kPa \cdot m^3/(kmol \cdot K)} \\ 0.08314 \mathrm{bar \cdot m^3/(kmol \cdot K)} \\ 1.986 \mathrm{Btu/(lbmol \cdot R)} \\ 10.73 \mathrm{psia \cdot ft^3/(lbmol \cdot R)} \\ 1545 \mathrm{ft \ ibf/(lbmol \cdot R)} \end{cases}}$$

$$\boxed{m = MN \quad (kg)}$$

m = mass ,(kg)
M = Molar mass, (kg/kmol)
N = Number of moles, (kmol)

EQUATION OF STATE

$$\boxed{\begin{aligned} &V = mv \rightarrow PV = mRT \\ &mR = (MN)R = NR_u \rightarrow PV = NR_uT \\ &V = N\bar{v} \rightarrow P\bar{v} = R_uT \end{aligned}}$$

$\bar{v}$ is the molar specific volume, m^3/kmol

An ideal gas at two different states are related to each other

$$\boxed{\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}}$$

Example 2-10

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

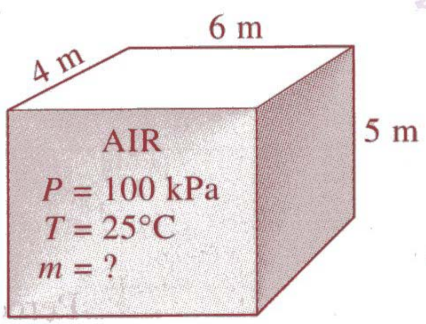


FIGURE 2–48
Schematic for Example 2–10.

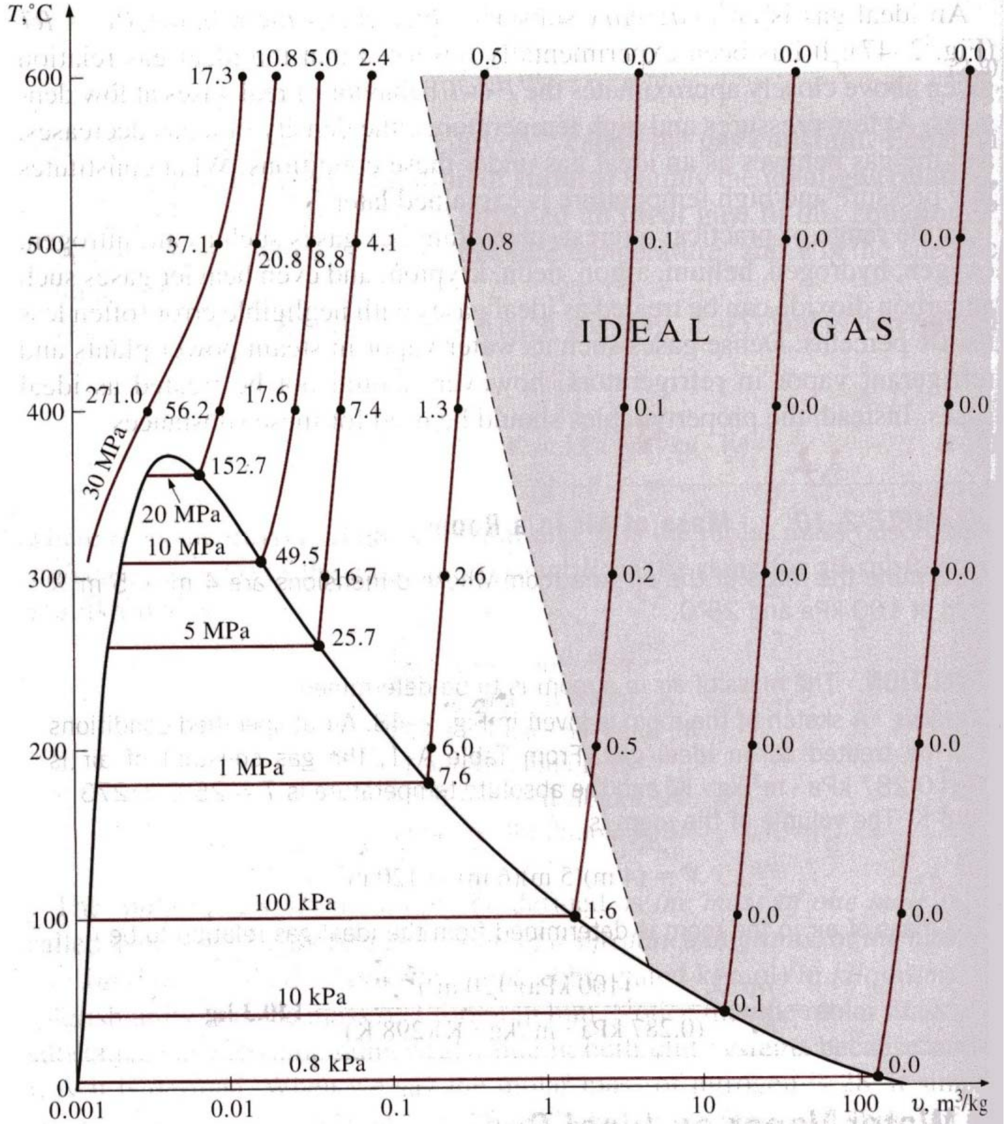
SOLUTION

$$\boxed{V = (4\text{m})(5\text{m})(6\ \text{m}) = 120\text{m}^3}$$

$$\boxed{m = \frac{PV}{RT} = \frac{(100\text{kPa})(1\ \ 20\text{m}^3)}{[0.287\text{kJ/(}\ \text{kg}\cdot\text{K)}](289\text{K})} = 140.3\text{kg}}$$

2-7. compressibility factor- a measure of deviation from ideal-gas behavior

No



ideal-gas behavior at a given temperature and pressure can accurately be accounted for by the introduction of a correction factor called the **compressibility factor** *Z* defined as

by Aj.Sanchai Ramphueiphad
Department of Mechanical Enginee

2-8. OTHER EQUATION OF STATE

No

2-9. SPECIFIC HEAT

The **specific heat** is defined as the energy required to raise the temperature of a unit mass of a substance by one degree

specific heat at constant volume, C_v

specific heat at constant pressure , C_p

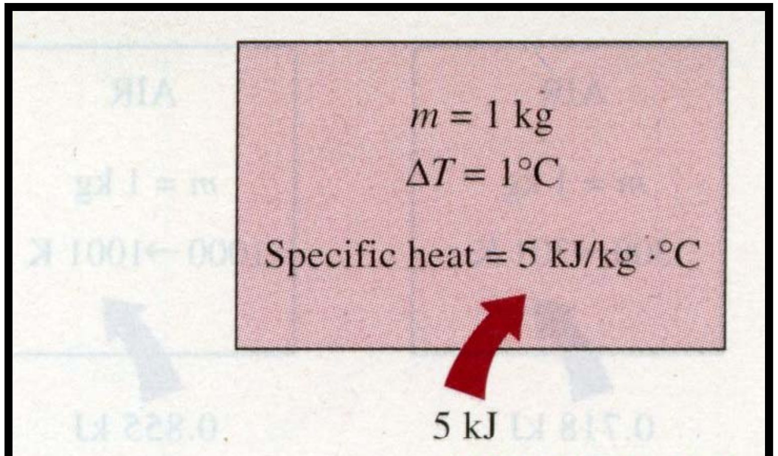


FIGURE 2–62

Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

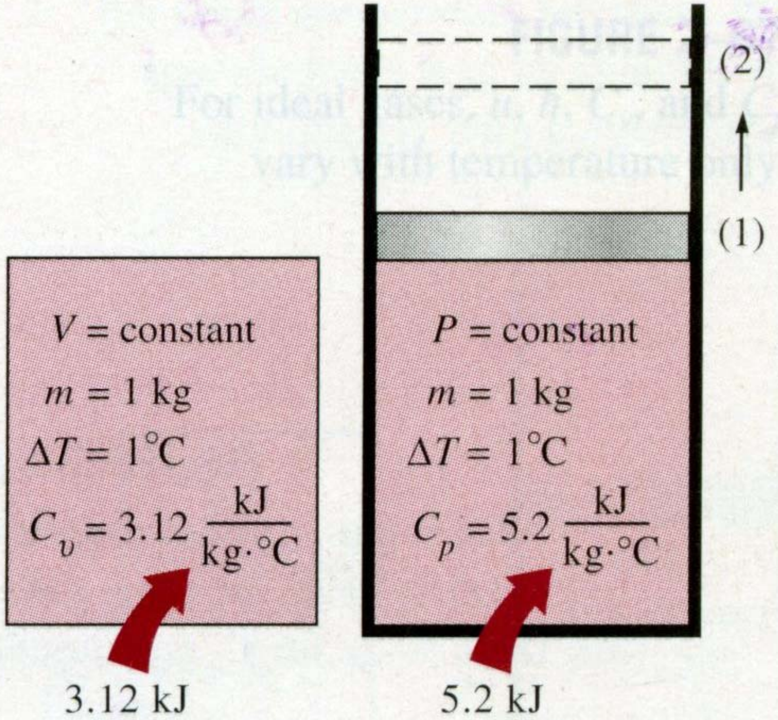


FIGURE 2–63

Constant-volume and constant-pressure specific heats C_v and C_p (values given are for helium gas).

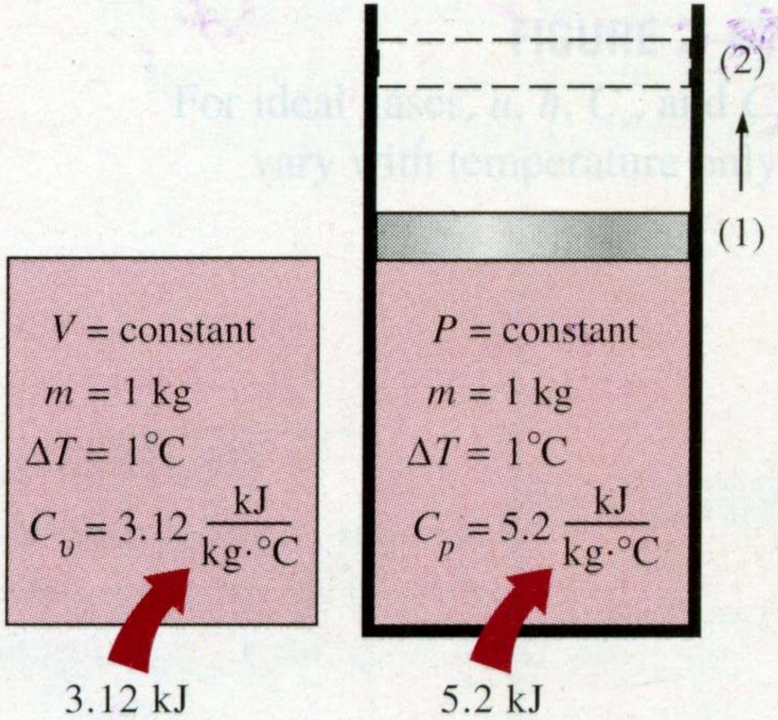
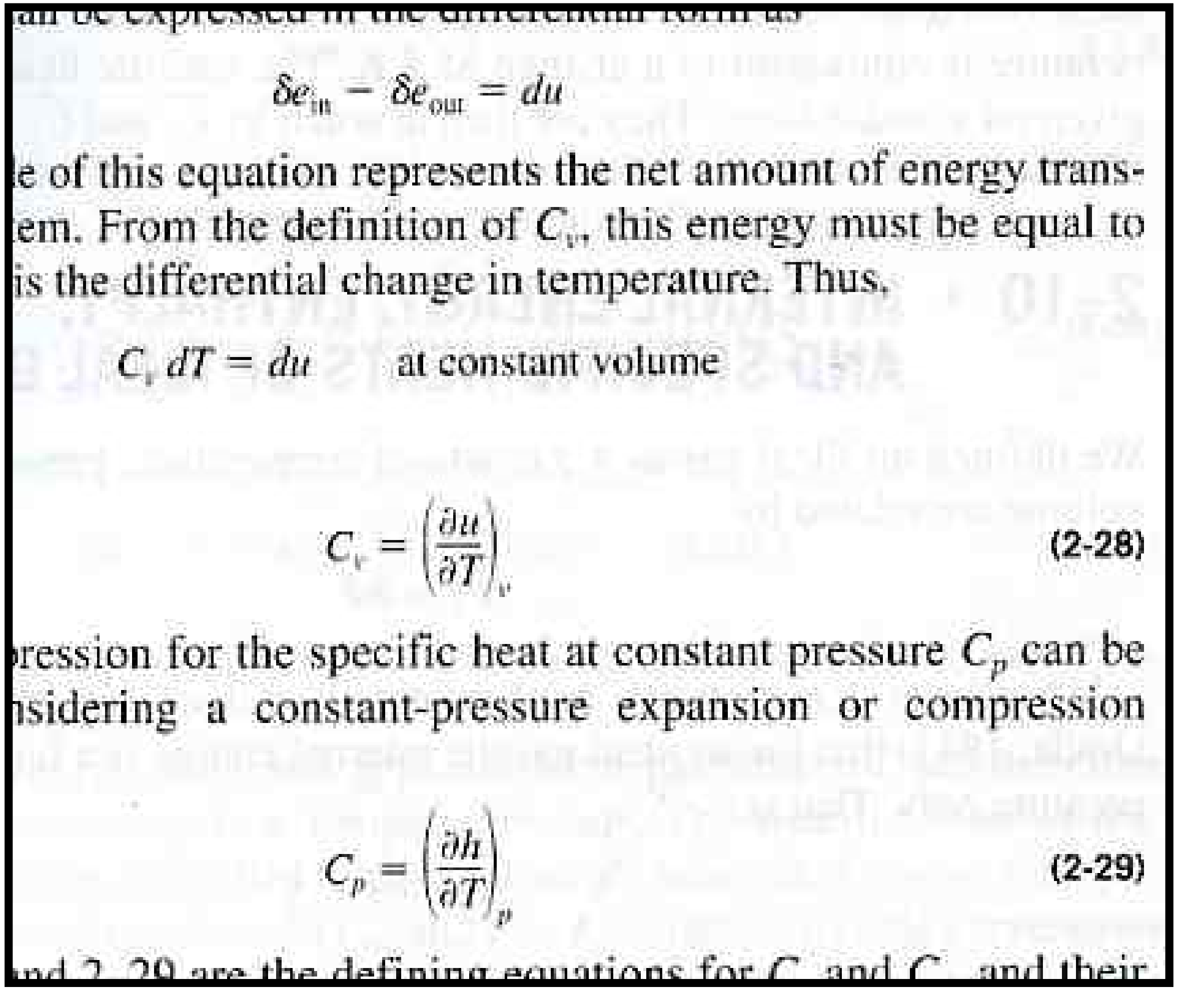


FIGURE 2–63

Constant-volume and constant-pressure specific heats C_v and C_p (values given are for helium gas).

The conservation of energy principle $e_{in} - e_{out} = \Delta e_{system}$



an be expressed in the differential form as

$$\delta e_{in} - \delta e_{out} = du$$

e of this equation represents the net amount of energy trans-
em. From the definition of C_v, this energy must be equal to
is the differential change in temperature. Thus,

$$C_v\,dT = du \qquad \text{at constant volume}$$

$$C_v = \left(\frac{\partial u}{\partial T}\right)_v \qquad (2\text{-}28)$$

ression for the specific heat at constant pressure C_p can be
nsidering a constant-pressure expansion or compression

$$C_p = \left(\frac{\partial h}{\partial T}\right)_p \qquad (2\text{-}29)$$

nd 2-29 are the defining equations for C_v and C_p, and their

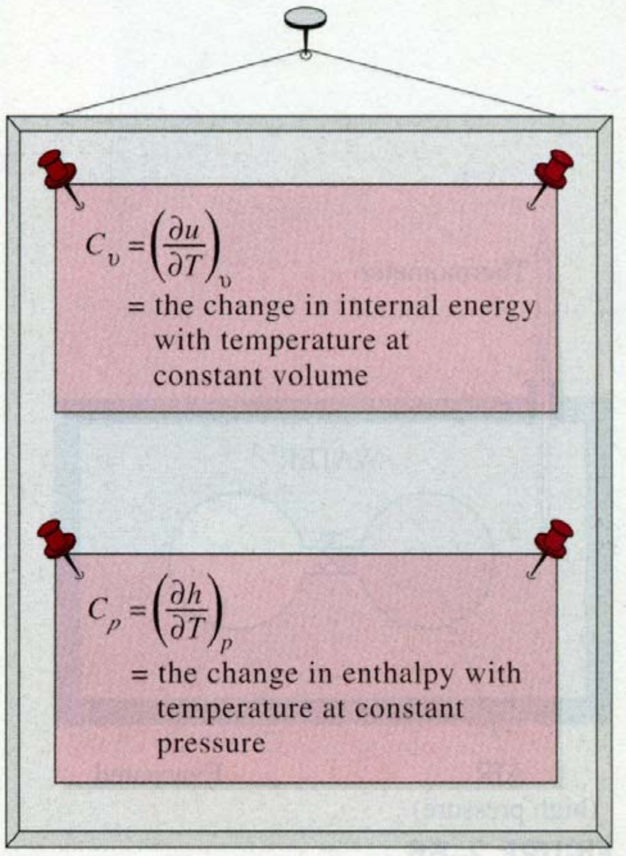


FIGURE 2–64
Formal definitions of C_v and C_p.

The conservation of energy principle $e_{in} - e_{out} = \Delta e_{system}$

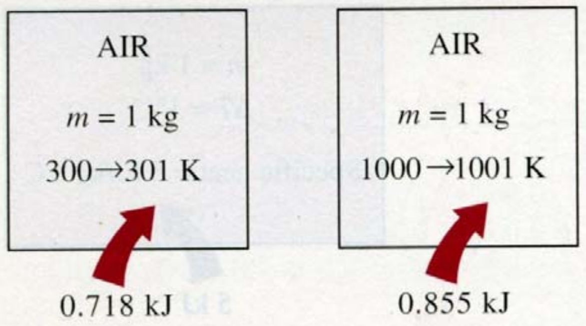


FIGURE 2–65
The specific heat of a substance changes with temperature.

2-10. Internal energy, Enthalpy, and Specific heats of ideal gases

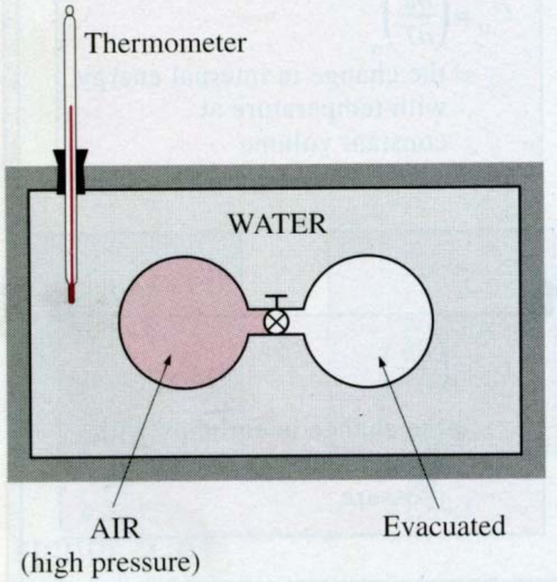
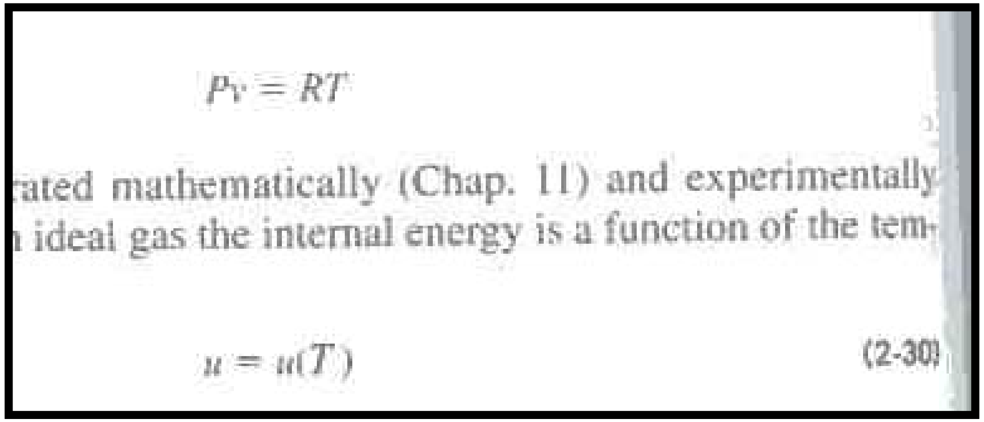


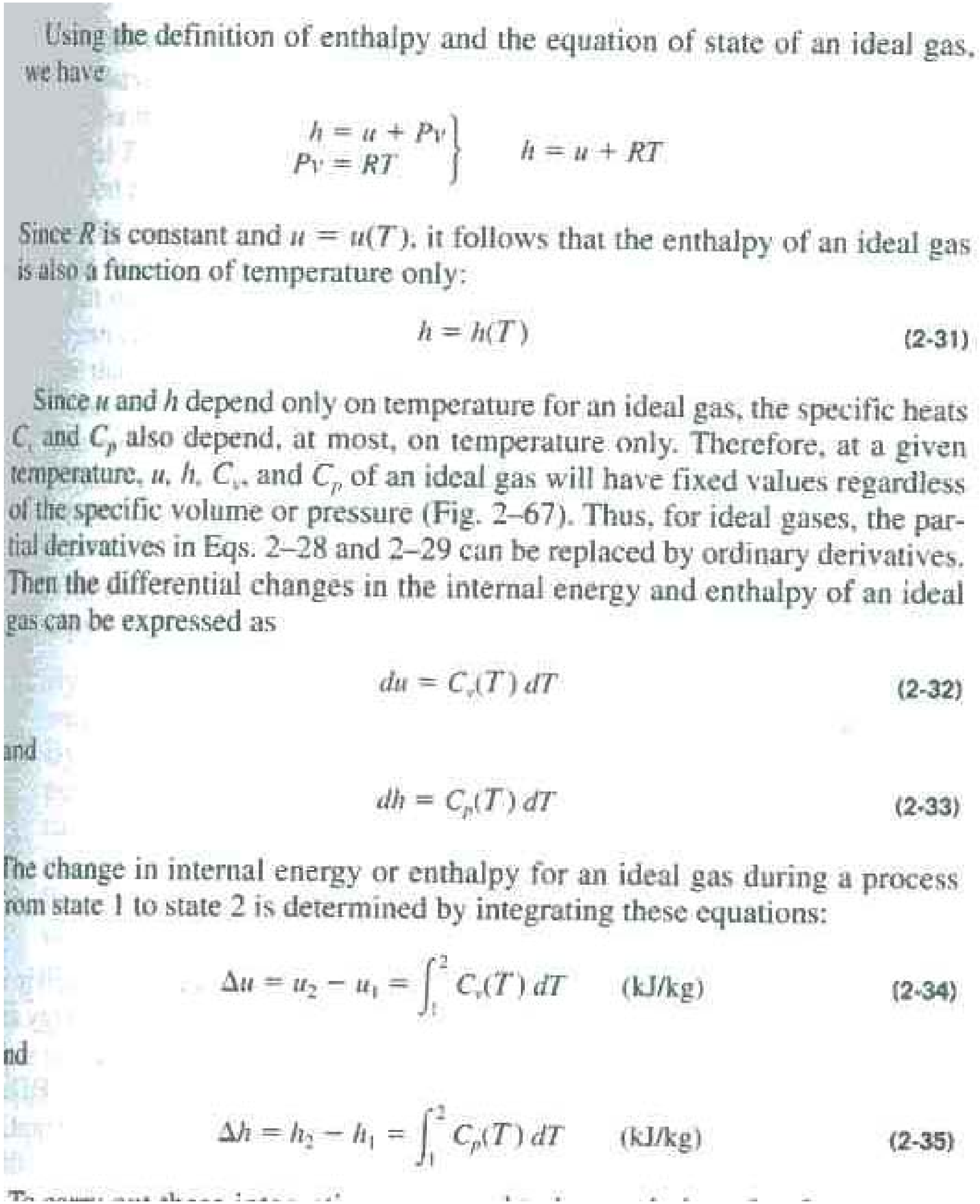
FIGURE 2–66
Schematic of the experimental apparatus used by Joule.



$$Pv = RT$$

ated mathematically (Chap. 11) and experimentally ideal gas the internal energy is a function of the tem-

$$u = u(T) \qquad (2\text{-}30)$$



Using the definition of enthalpy and the equation of state of an ideal gas, we have

$$\left.\begin{aligned} h &= u + Pv \\ Pv &= RT \end{aligned}\right\} \qquad h = u + RT$$

Since R is constant and $u = u(T)$, it follows that the enthalpy of an ideal gas is also a function of temperature only:

$$h = h(T) \tag{2-31}$$

Since u and h depend only on temperature for an ideal gas, the specific heats C_v and C_p also depend, at most, on temperature only. Therefore, at a given temperature, u, h, C_v, and C_p of an ideal gas will have fixed values regardless of the specific volume or pressure (Fig. 2–67). Thus, for ideal gases, the partial derivatives in Eqs. 2–28 and 2–29 can be replaced by ordinary derivatives. Then the differential changes in the internal energy and enthalpy of an ideal gas can be expressed as

$$du = C_v(T)\,dT \tag{2-32}$$

and

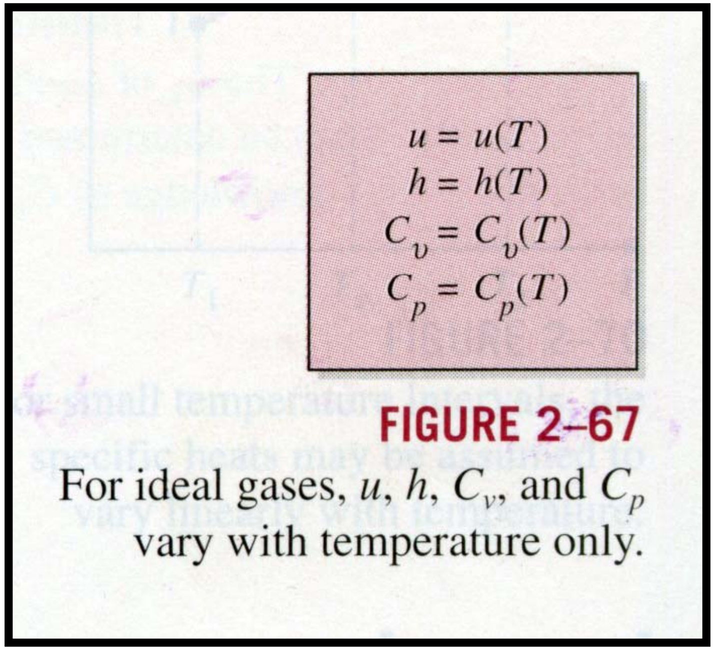
$$dh = C_p(T)\,dT \tag{2-33}$$

The change in internal energy or enthalpy for an ideal gas during a process rom state 1 to state 2 is determined by integrating these equations:

$$\Delta u = u_2 - u_1 = \int_1^2 C_v(T)\,dT \qquad \text{(kJ/kg)} \tag{2-34}$$

nd

$$\Delta h = h_2 - h_1 = \int_1^2 C_p(T)\,dT \qquad \text{(kJ/kg)} \tag{2-35}$$



$u = u(T)$
$h = h(T)$
$C_v = C_v(T)$
$C_p = C_p(T)$

FIGURE 2–67

For ideal gases, u, h, C_v, and C_p vary with temperature only.

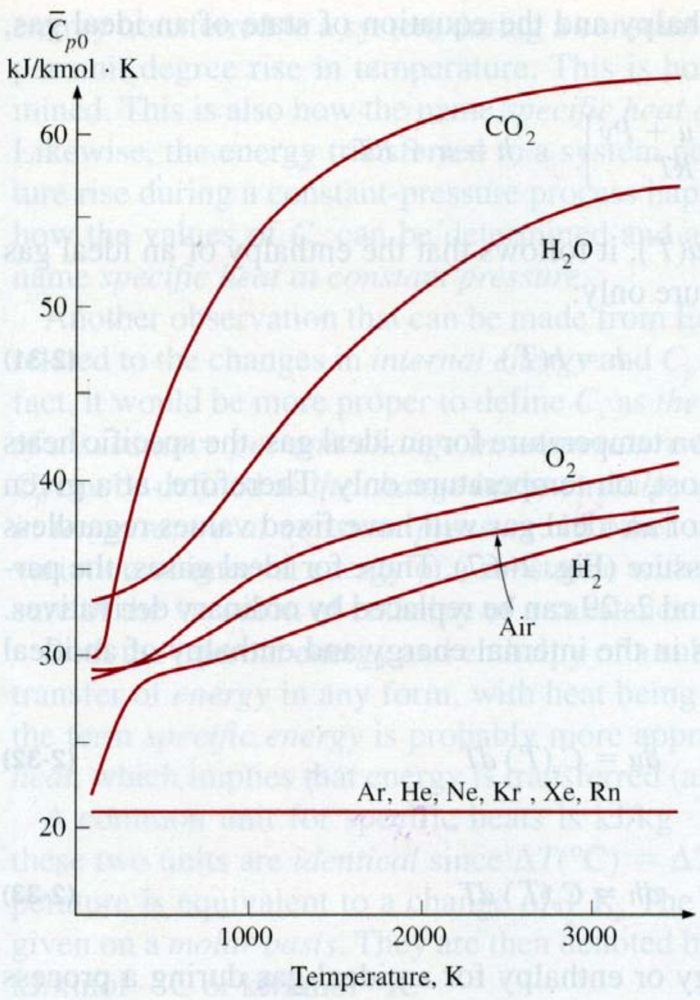
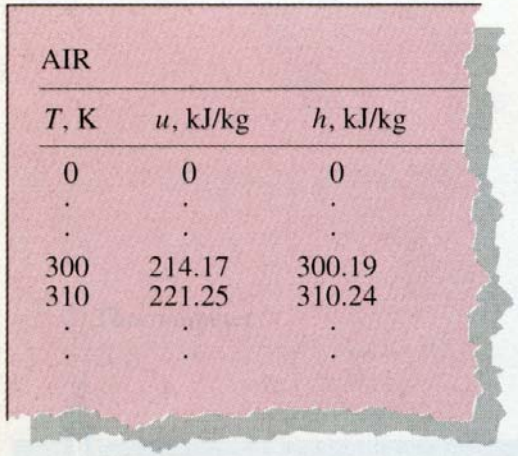


FIGURE 2–68

Ideal-gas constant-pressure specific heats for some gases (see Table A–2c for C_p equations).



AIR

T, K	u, kJ/kg	h, kJ/kg
0	0	0
.	.	.
.	.	.
300	214.17	300.19
310	221.25	310.24
.	.	.
.	.	.

FIGURE 2–69

In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

$$u_2 - u_1 = C_{v,av}(T_2 - T_1) \qquad \text{(kJ/kg)}$$

$$h_2 - h_1 = C_{p,av}(T_2 - T_1) \qquad \text{(kJ/kg)}$$

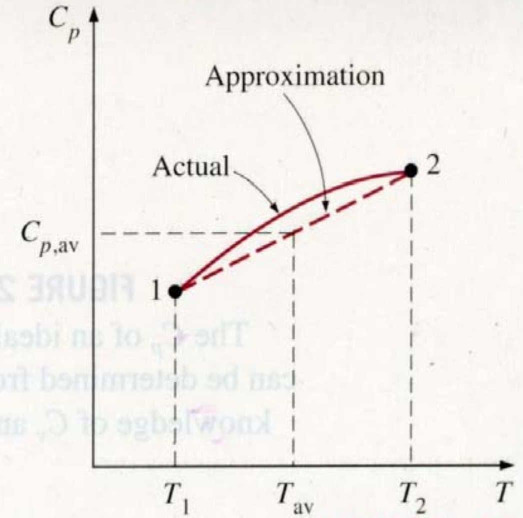


FIGURE 2–70

For small temperature intervals, the specific heats may be assumed to vary linearly with temperature.

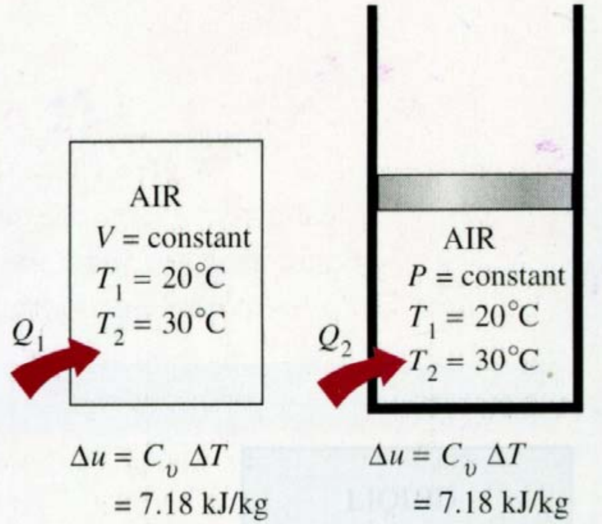


FIGURE 2–71

The relation $\Delta u = C_v \, \Delta T$ is valid for *any* kind of process, constant-volume or not.

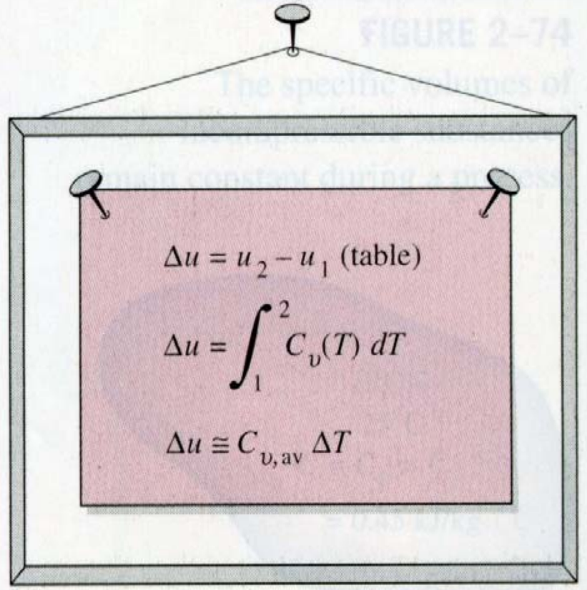
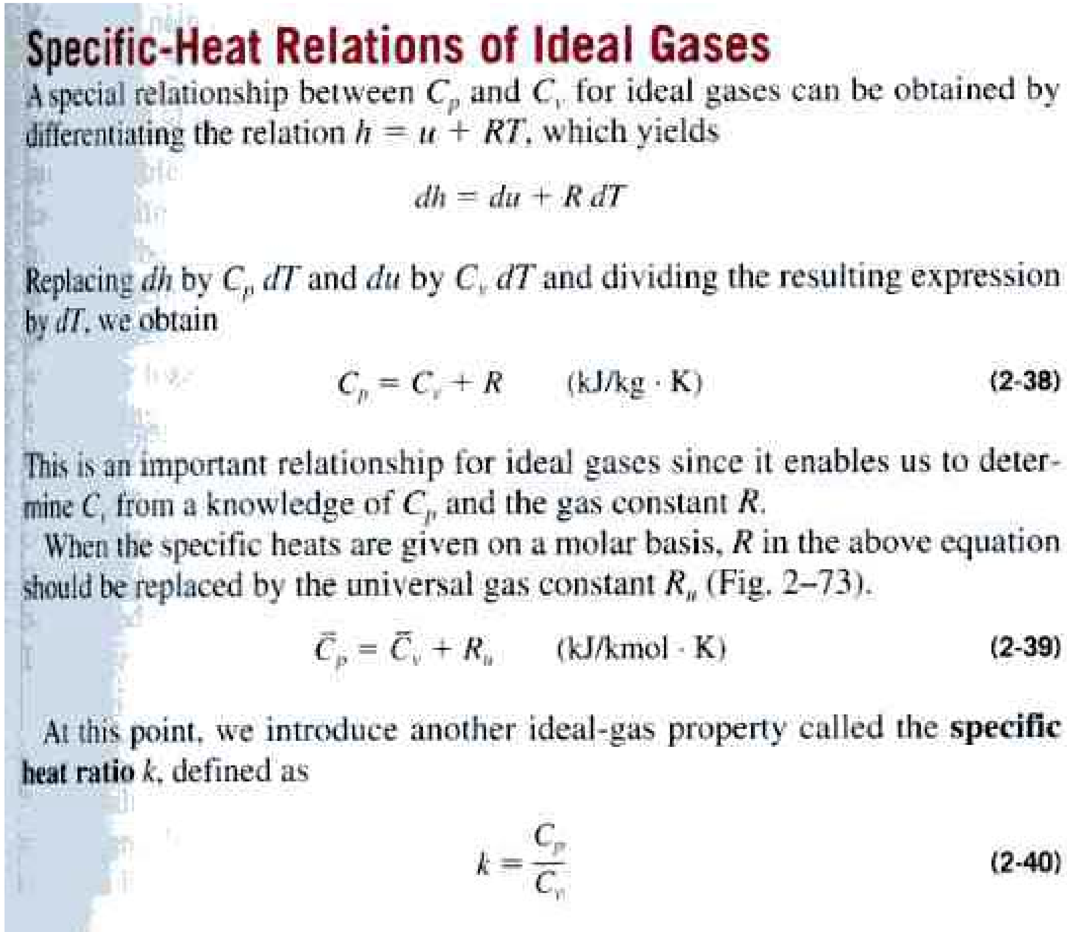


FIGURE 2–72

Three ways of calculating Δu.



Specific-Heat Relations of Ideal Gases

A special relationship between C_p and C_v for ideal gases can be obtained by differentiating the relation $h = u + RT$, which yields

$$dh = du + R\,dT$$

Replacing dh by $C_p\,dT$ and du by $C_v\,dT$ and dividing the resulting expression by dT, we obtain

$$C_p = C_v + R \qquad (\text{kJ/kg}\cdot\text{K}) \tag{2-38}$$

This is an important relationship for ideal gases since it enables us to determine C_v from a knowledge of C_p and the gas constant R.

When the specific heats are given on a molar basis, R in the above equation should be replaced by the universal gas constant R_u (Fig. 2–73).

$$\bar{C}_p = \bar{C}_v + R_u \qquad (\text{kJ/kmol}\cdot\text{K}) \tag{2-39}$$

At this point, we introduce another ideal-gas property called the **specific heat ratio** k, defined as

$$k = \frac{C_p}{C_v} \tag{2-40}$$

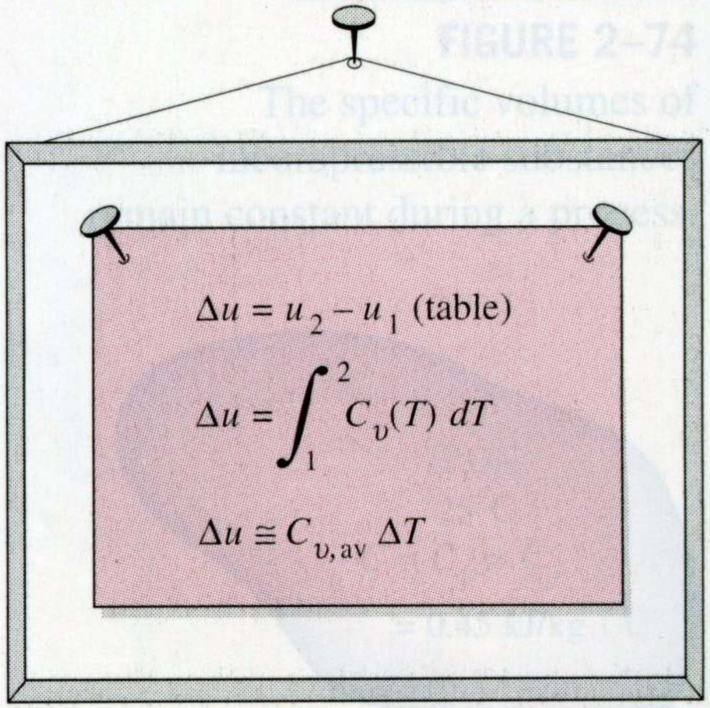


FIGURE 2–72

Three ways of calculating Δu.

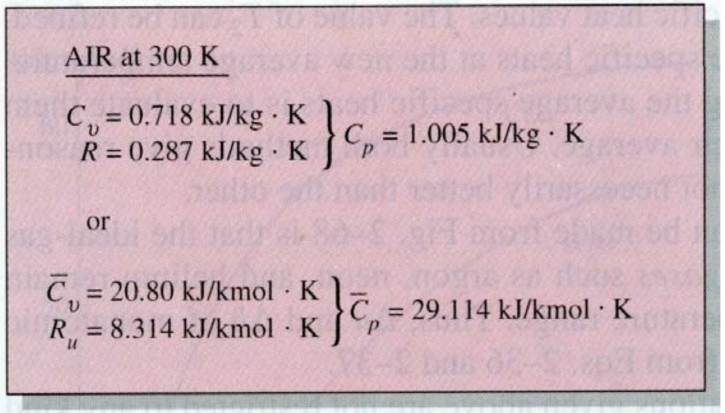


FIGURE 2–73

The C_p of an ideal gas can be determined from a knowledge of C_v and R.

EXAMPLE 2–14 Evaluation of the Δu of an Ideal Gas

Air at 300 K and 200 kPa is heated at constant pressure to 600 K. Determine the change in internal energy of air per unit mass, using (*a*) data from the air table (Table A–17), (*b*) the functional form of the specific heat (Table A–2*c*), and (*c*) the average specific heat value (Table A–2*b*).

SOLUTION The internal energy change of air is to be determined in three different ways.

Analysis At specified conditions, air can be considered to be an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. The internal energy change Δu of ideal gases depends on the initial and final temperatures only, and not on the type of process. Thus, the solution given below is valid for any kind of process.

(*a*) One way of determining the change in internal energy of air is to read the u values at T_1 and T_2 from Table A–17 and take the difference:

$$u_1 = u_{@\,300\text{K}} = 214.07 \text{ kJ/kg}$$
$$u_2 = u_{@\,600\text{K}} = 434.78 \text{ kJ/kg}$$

Thus,

$$\Delta u = u_2 - u_1 = (434.78 - 214.07) \text{ kJ/kg} = 220.71 \text{ kJ/kg}$$

(*b*) The $\bar{C}_p(T)$ of air is given in Table A–2*c* in the form of a third-degree polynomial expressed as

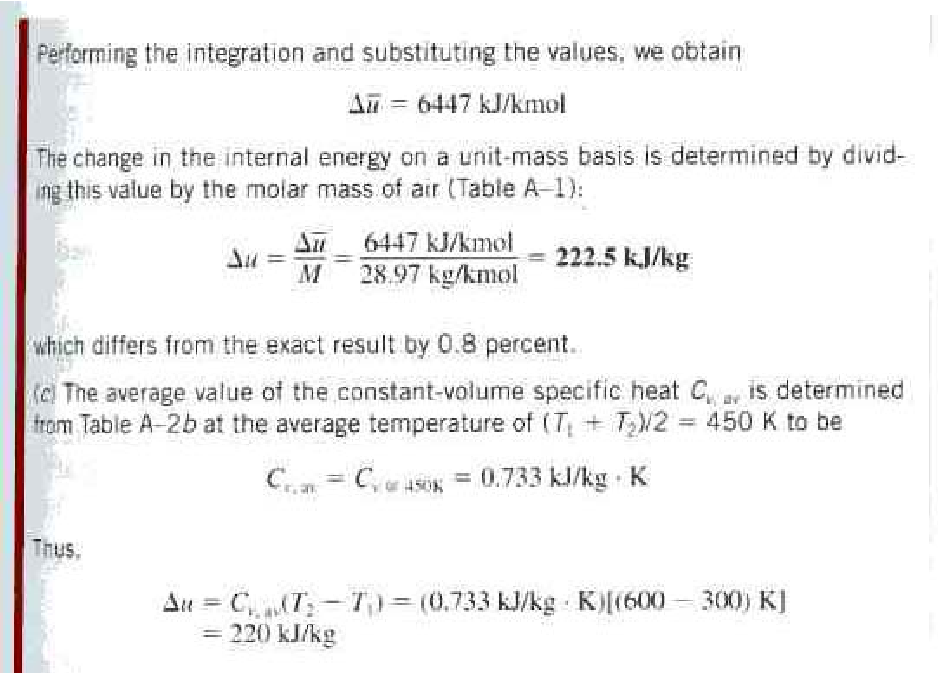
$$\bar{C}_p(T) = a + bT + cT^2 + dT^3$$

where $a = 28.11$, $b = 0.1967 \times 10^{-2}$, $c = 0.4802 \times 10^{-5}$, and $d = -1.966 \times 10^{-9}$. From Eq. 2–39,

$$\bar{C}_v(T) = \bar{C}_p - R_u = (a - R_u) + bT + cT^2 + dT^3$$

From Eq. 2–34,

$$\Delta \bar{u} = \int_1^2 \bar{C}_v(T)\,dT = \int_{T_1}^{T_2} [(a - R_u) + bT + cT^2 + dT^3]\,dT$$



Performing the integration and substituting the values, we obtain

$$\Delta\bar{u} = 6447\ \text{kJ/kmol}$$

The change in the internal energy on a unit-mass basis is determined by dividing this value by the molar mass of air (Table A–1):

$$\Delta u = \frac{\Delta\bar{u}}{M} = \frac{6447\ \text{kJ/kmol}}{28.97\ \text{kg/kmol}} = \mathbf{222.5\ kJ/kg}$$

which differs from the exact result by 0.8 percent.

(*c*) The average value of the constant-volume specific heat $C_{v,\,av}$ is determined from Table A–2*b* at the average temperature of $(T_1 + T_2)/2 = 450$ K to be

$$C_{v,\,av} = C_{v\ @\ 450\text{K}} = 0.733\ \text{kJ/kg}\cdot\text{K}$$

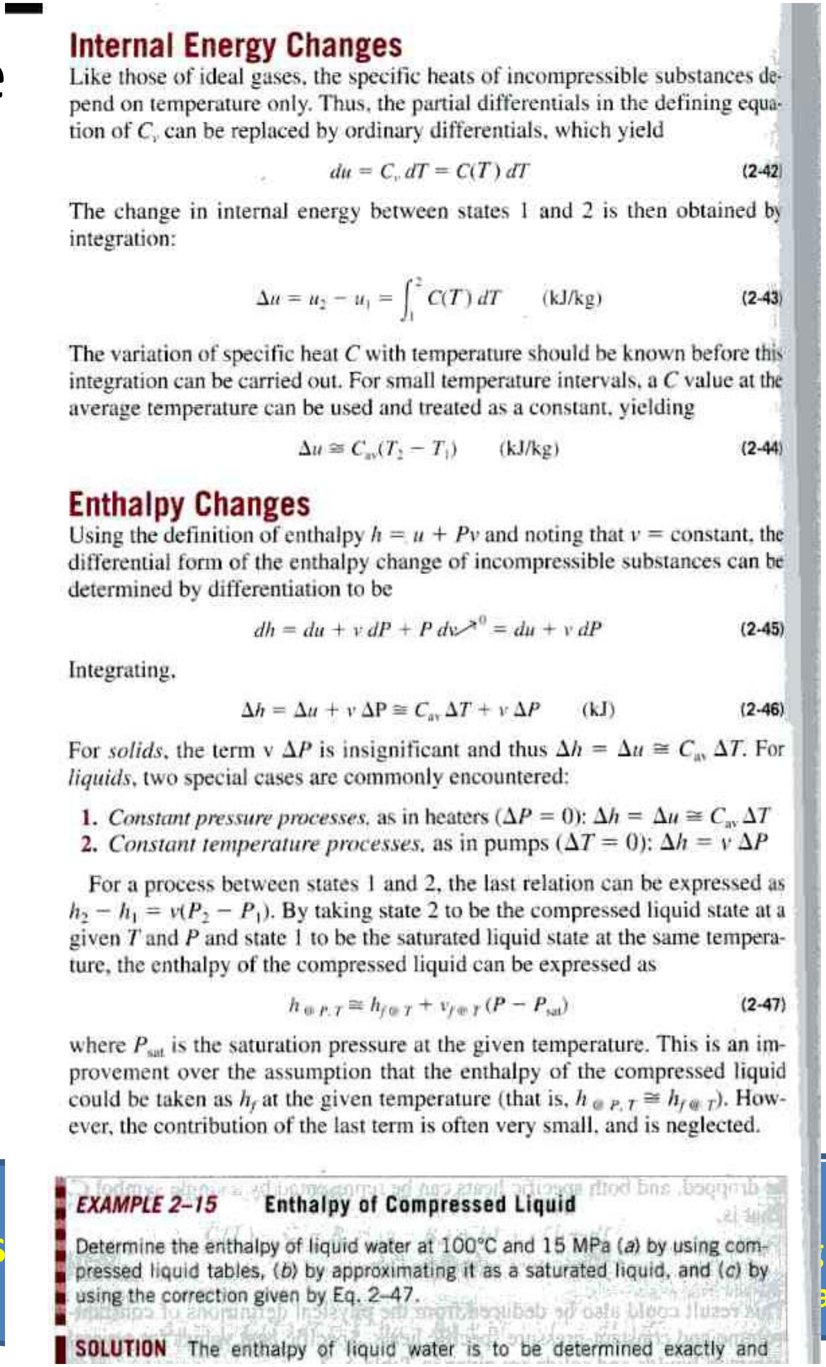
Thus,

$$\Delta u = C_{v,\,av}(T_2 - T_1) = (0.733\ \text{kJ/kg}\cdot\text{K})[(600 - 300)\ \text{K}]$$
$$= 220\ \text{kJ/kg}$$

2-11. Internal energy

$$C_p = C_v = C \qquad (2\text{-}41)$$

Internal ene



Internal Energy Changes

Like those of ideal gases, the specific heats of incompressible substances depend on temperature only. Thus, the partial differentials in the defining equation of C_v can be replaced by ordinary differentials, which yield

$$du = C_v\,dT = C(T)\,dT \qquad \text{(2-42)}$$

The change in internal energy between states 1 and 2 is then obtained by integration:

$$\Delta u = u_2 - u_1 = \int_1^2 C(T)\,dT \qquad \text{(kJ/kg)} \qquad \text{(2-43)}$$

The variation of specific heat C with temperature should be known before this integration can be carried out. For small temperature intervals, a C value at the average temperature can be used and treated as a constant, yielding

$$\Delta u \cong C_{av}(T_2 - T_1) \qquad \text{(kJ/kg)} \qquad \text{(2-44)}$$

Enthalpy Changes

Using the definition of enthalpy $h = u + Pv$ and noting that $v =$ constant, the differential form of the enthalpy change of incompressible substances can be determined by differentiation to be

$$dh = du + v\,dP + P\,\cancelto{0}{dv} = du + v\,dP \qquad \text{(2-45)}$$

Integrating,

$$\Delta h = \Delta u + v\,\Delta P \cong C_{av}\,\Delta T + v\,\Delta P \qquad \text{(kJ)} \qquad \text{(2-46)}$$

For *solids*, the term $v\,\Delta P$ is insignificant and thus $\Delta h = \Delta u \cong C_{av}\,\Delta T$. For *liquids*, two special cases are commonly encountered:

1. *Constant pressure processes*, as in heaters ($\Delta P = 0$): $\Delta h = \Delta u \cong C_{av}\,\Delta T$
2. *Constant temperature processes*, as in pumps ($\Delta T = 0$): $\Delta h = v\,\Delta P$

For a process between states 1 and 2, the last relation can be expressed as $h_2 - h_1 = v(P_2 - P_1)$. By taking state 2 to be the compressed liquid state at a given T and P and state 1 to be the saturated liquid state at the same temperature, the enthalpy of the compressed liquid can be expressed as

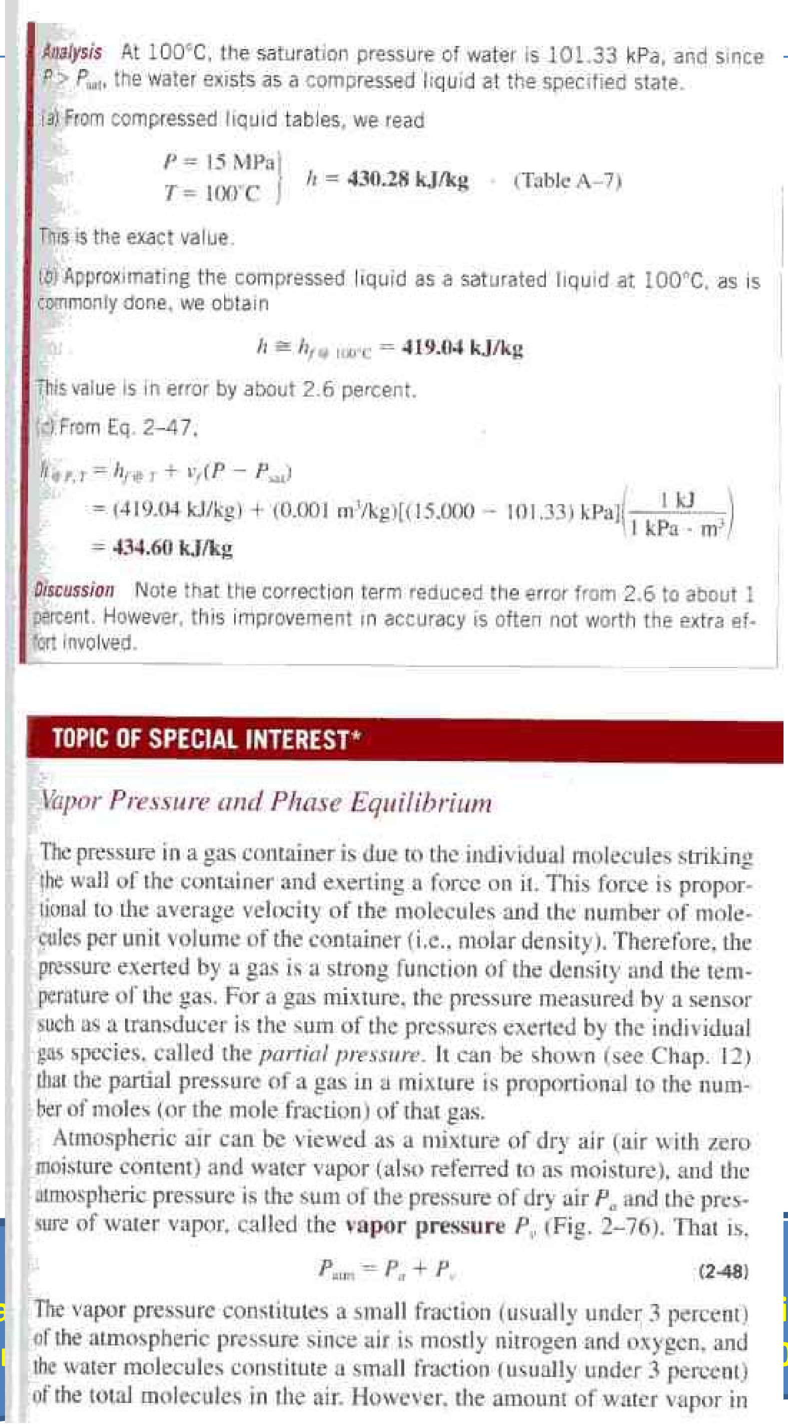
$$h_{@\,P,T} \cong h_{f\,@\,T} + v_{f\,@\,T}\,(P - P_{sat}) \qquad \text{(2-47)}$$

where P_{sat} is the saturation pressure at the given temperature. This is an improvement over the assumption that the enthalpy of the compressed liquid could be taken as h_f at the given temperature (that is, $h_{@\,P,T} \cong h_{f\,@\,T}$). However, the contribution of the last term is often very small, and is neglected.

EXAMPLE 2–15 **Enthalpy of Compressed Liquid**

Determine the enthalpy of liquid water at 100°C and 15 MPa (*a*) by using compressed liquid tables, (*b*) by approximating it as a saturated liquid, and (*c*) by using the correction given by Eq. 2–47.

SOLUTION The enthalpy of liquid water is to be determined exactly and



Analysis At 100°C, the saturation pressure of water is 101.33 kPa, and since $P > P_{sat}$, the water exists as a compressed liquid at the specified state.

(a) From compressed liquid tables, we read

$$\left.\begin{array}{l} P = 15\ \text{MPa} \\ T = 100^\circ\text{C} \end{array}\right\} \quad h = \mathbf{430.28\ kJ/kg} \qquad \text{(Table A–7)}$$

This is the exact value.

(b) Approximating the compressed liquid as a saturated liquid at 100°C, as is commonly done, we obtain

$$h \cong h_{f\,@\,100^\circ\text{C}} = \mathbf{419.04\ kJ/kg}$$

This value is in error by about 2.6 percent.

(c) From Eq. 2–47,

$$\begin{aligned} h_{@\,P,T} &= h_{f\,@\,T} + v_f(P - P_{sat}) \\ &= (419.04\ \text{kJ/kg}) + (0.001\ \text{m}^3/\text{kg})[(15{,}000 - 101.33)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right) \\ &= \mathbf{434.60\ kJ/kg} \end{aligned}$$

Discussion Note that the correction term reduced the error from 2.6 to about 1 percent. However, this improvement in accuracy is often not worth the extra effort involved.

TOPIC OF SPECIAL INTEREST*

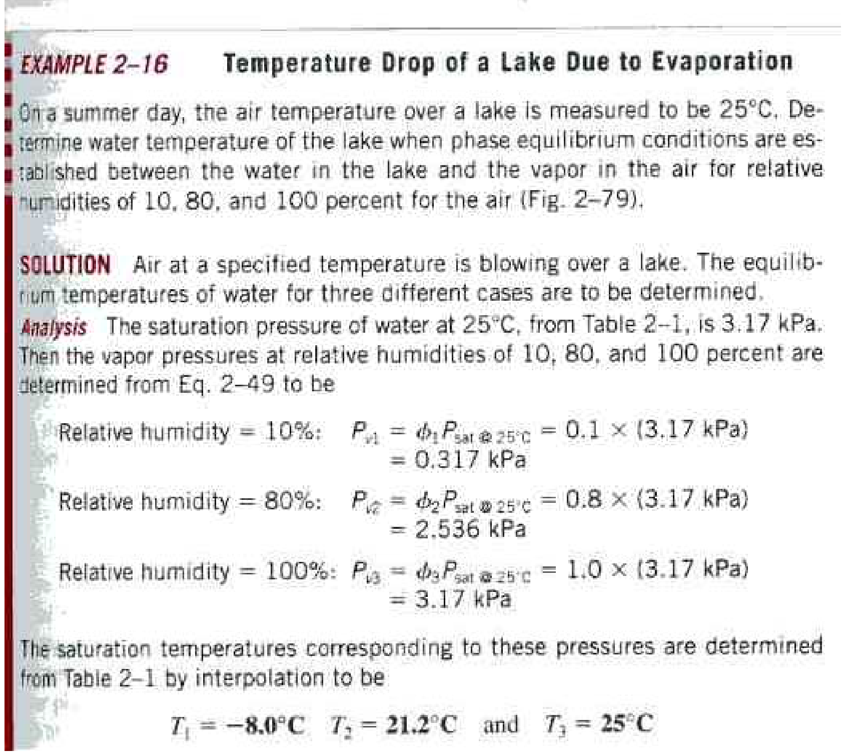
Vapor Pressure and Phase Equilibrium

The pressure in a gas container is due to the individual molecules striking the wall of the container and exerting a force on it. This force is proportional to the average velocity of the molecules and the number of molecules per unit volume of the container (i.e., molar density). Therefore, the pressure exerted by a gas is a strong function of the density and the temperature of the gas. For a gas mixture, the pressure measured by a sensor such as a transducer is the sum of the pressures exerted by the individual gas species, called the *partial pressure*. It can be shown (see Chap. 12) that the partial pressure of a gas in a mixture is proportional to the number of moles (or the mole fraction) of that gas.

Atmospheric air can be viewed as a mixture of dry air (air with zero moisture content) and water vapor (also referred to as moisture), and the atmospheric pressure is the sum of the pressure of dry air P_a and the pressure of water vapor, called the **vapor pressure** P_v (Fig. 2–76). That is,

$$P_{atm} = P_a + P_v \tag{2-48}$$

The vapor pressure constitutes a small fraction (usually under 3 percent) of the atmospheric pressure since air is mostly nitrogen and oxygen, and the water molecules constitute a small fraction (usually under 3 percent) of the total molecules in the air. However, the amount of water vapor in



EXAMPLE 2–16 Temperature Drop of a Lake Due to Evaporation

On a summer day, the air temperature over a lake is measured to be 25°C. Determine water temperature of the lake when phase equilibrium conditions are established between the water in the lake and the vapor in the air for relative humidities of 10, 80, and 100 percent for the air (Fig. 2–79).

SOLUTION Air at a specified temperature is blowing over a lake. The equilibrium temperatures of water for three different cases are to be determined.

Analysis The saturation pressure of water at 25°C, from Table 2–1, is 3.17 kPa. Then the vapor pressures at relative humidities of 10, 80, and 100 percent are determined from Eq. 2–49 to be

$$\text{Relative humidity} = 10\%: \quad P_{v1} = \phi_1 P_{\text{sat @ }25^\circ\text{C}} = 0.1 \times (3.17\text{ kPa}) = 0.317\text{ kPa}$$

$$\text{Relative humidity} = 80\%: \quad P_{v2} = \phi_2 P_{\text{sat @ }25^\circ\text{C}} = 0.8 \times (3.17\text{ kPa}) = 2.536\text{ kPa}$$

$$\text{Relative humidity} = 100\%: \quad P_{v3} = \phi_3 P_{\text{sat @ }25^\circ\text{C}} = 1.0 \times (3.17\text{ kPa}) = 3.17\text{ kPa}$$

The saturation temperatures corresponding to these pressures are determined from Table 2–1 by interpolation to be

$$T_1 = \mathbf{-8.0^\circ C} \quad T_2 = \mathbf{21.2^\circ C} \quad \text{and} \quad T_3 = \mathbf{25^\circ C}$$

PROBLEMS

2-52 **A 0.5-m³ vessel contains 10 kg of refrigerant-134a at -20 ° C . Determine (a) the pressure (b) the total internal energy, and (c) the volume occupied by the liquid phase. (a) 132.99 kPa (b) 889.5 kJ (c) 0.00487 m³**

2-71 **The air in an automobile tire with a volume of 0.015 m³ is at 32 ° C and 140 kPa gage. Determine the amount of air that must be added to raise the pressure to the reccommended value of 207 kPa gage. Assume the atmospheric pressure to be 100.66 kPa and temperture and the volume to remain constant. (0.012 kg)**