$$Q_{net,in} - W_{net,out} = \Delta E_{system} \quad \text{or} \quad Q - W = \Delta E$$

$$Q = Q_{net,in} = Q_{in} - Q_{out}$$

$$W = W_{net,out} = W_{out} - W_{in}$$

Energy balance when sign convention is used: (i.e., heat input and work output are positive; heat output and work input are negative).
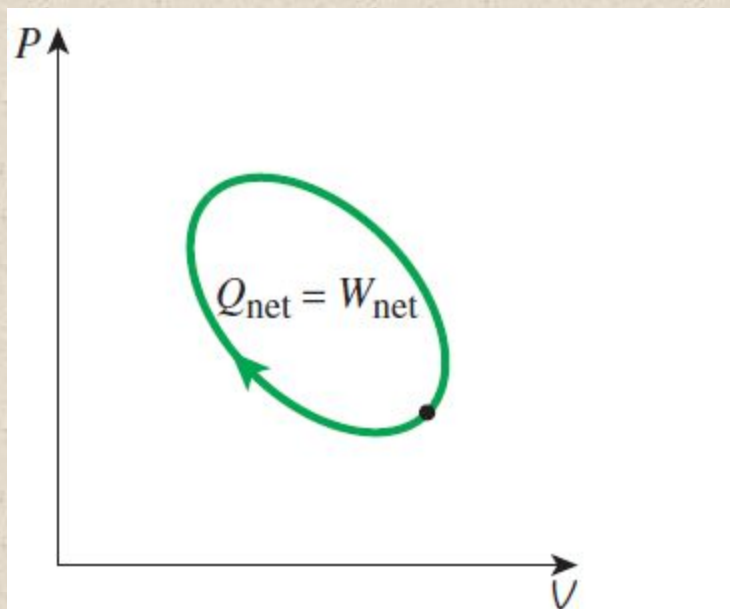

FIGURE 4–11
For a cycle $\Delta E = 0$, thus $Q = W$.

General $\quad Q - W = \Delta E$

Stationary systems $\quad Q - W = \Delta U$

Per unit mass $\quad q - w = \Delta e$

Differential form $\quad \delta q - \delta w = de$

Various forms of the first-law relation for closed systems when sign convention is used.

The first law cannot be proven mathematically, but no process in nature is known to have violated the first law, and this should be taken as sufficient proof.

Energy balance for a constant-pressure expansion or compression process

General analysis for a closed system undergoing a quasi-equilibrium constant-pressure process. *Q* is *to* the system and *W* is *from* the system.

$$E_{in} - E_{out} = \Delta E_{system}$$

Net energy transfer by heat, work, and mass

Change in internal, kinetic, potential, etc., energies

$$Q - W = \Delta U + \Delta KE^{0} + \Delta PE^{0}$$

$$Q - W_{other} - W_b = U_2 - U_1$$

$$Q - W_{other} - P_0(V_2 - V_1) = U_2 - U_1$$

$$Q - W_{other} = (U_2 + P_2 V_2) - (U_1 + P_1 V_1)$$
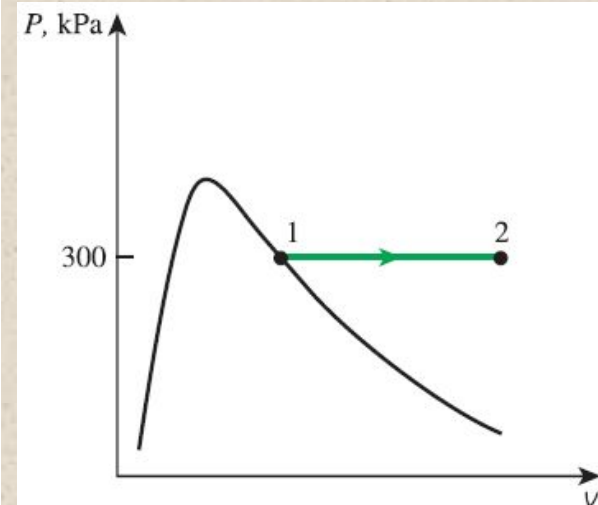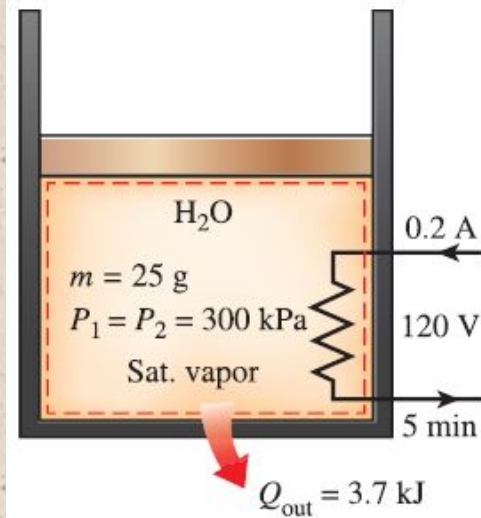
$$H = U + PV$$

$$Q - W_{other} = H_2 - H_1$$

For a constant-pressure expansion or compression process:

$$\Delta U + W_b = \Delta H$$

An example of constant-pressure process

$$W_{e,in} - Q_{out} - W_b = \Delta U$$

$$W_{e,in} - Q_{out} = \Delta H = m(h_2 - h_1)$$

H_2O
$m = 25$ g
$P_1 = P_2 = 300$ kPa
Sat. vapor
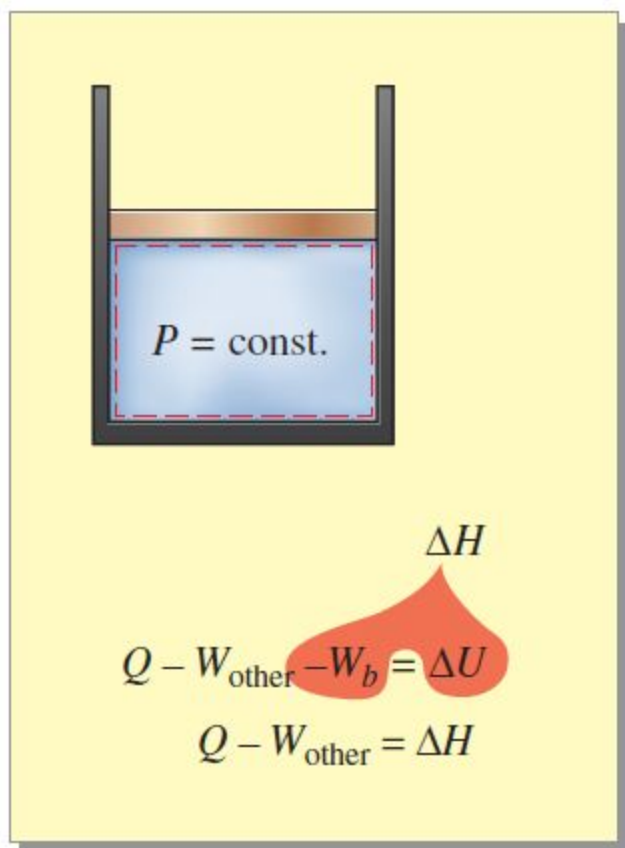0.2 A
120 V
5 min
$Q_{out} = 3.7$ kJ

P, kPa
300
1
2
V

FIGURE 4–14

For a closed system undergoing a quasi-equilibrium, $P =$ constant process, $\Delta U + W_b = \Delta H$. Note that this relation is NOT valid for closed systems processes during which pressure DOES NOT remain constant.
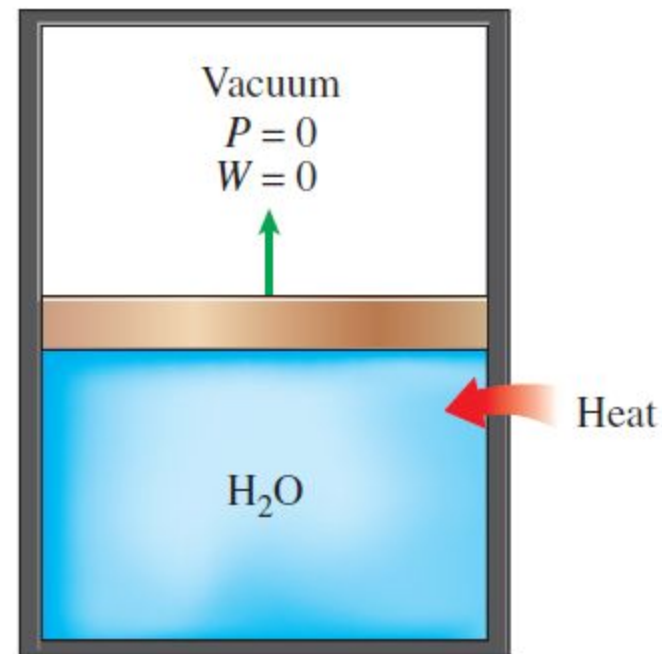
Equations shown in figure:

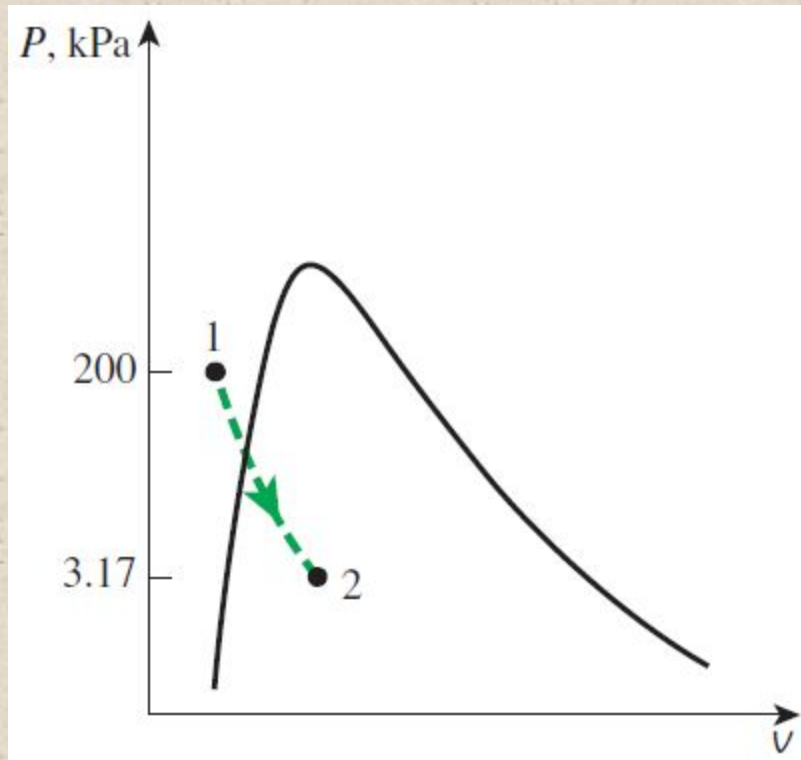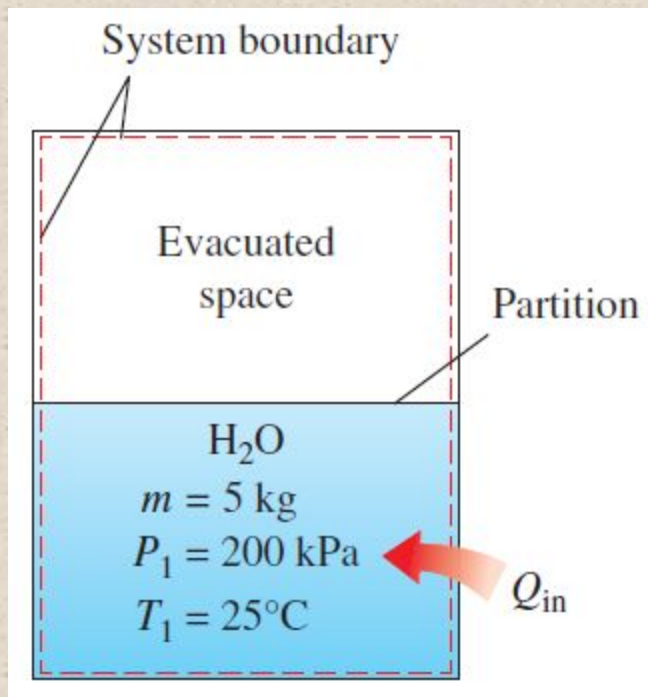$$Q - W_{other} - W_b = \Delta U$$

$$Q - W_{other} = \Delta H$$

$P = \text{const.}$

ΔH

FIGURE 4–16

Expansion against a vacuum involves no work and thus no energy transfer.

Labels in figure:

Vacuum
$P = 0$
$W = 0$

Heat

H_2O

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

$$Q_{in} = \Delta U = m(u_2 - u_1)$$

Unrestrained Expansion of Water

System boundary

Evacuated space

Partition

H_2O
$m = 5$ kg
$P_1 = 200$ kPa
$T_1 = 25°C$

Q_{in}

P, kPa

200

1

3.17

2

v

4

SPECIFIC HEATS

Specific heat at constant volume, c_v: The energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

Specific heat at constant pressure, c_p: The energy required to raise the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.

1 kg
Iron
$20 \rightarrow 30°C$

4.5 kJ

1 kg
Water
$20 \rightarrow 30°C$

41.8 kJ

FIGURE 4–17
It takes different amounts of energy to raise the temperature of different substances by the same amount.

$m = 1$ kg
$\Delta T = 1°C$

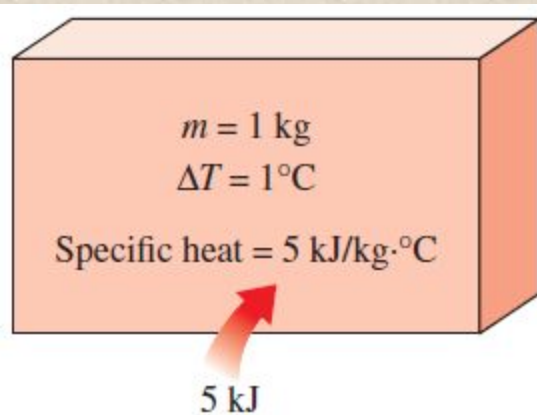Specific heat $= 5$ kJ/kg·°C

5 kJ

FIGURE 4–18
Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

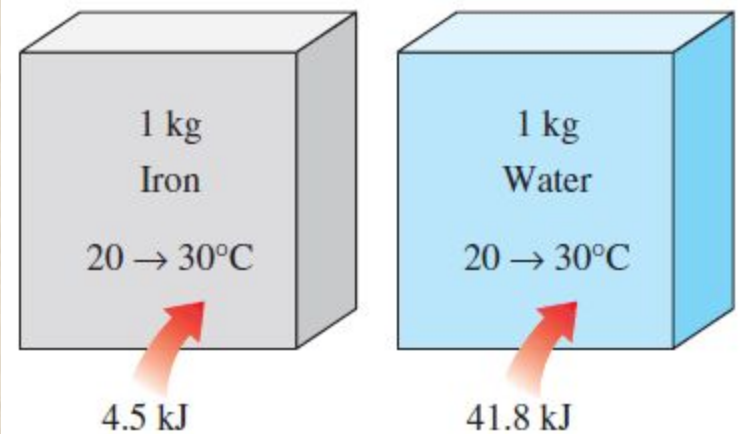Constant-volume and constant-pressure specific heats c_v and c_p (values are for helium gas).
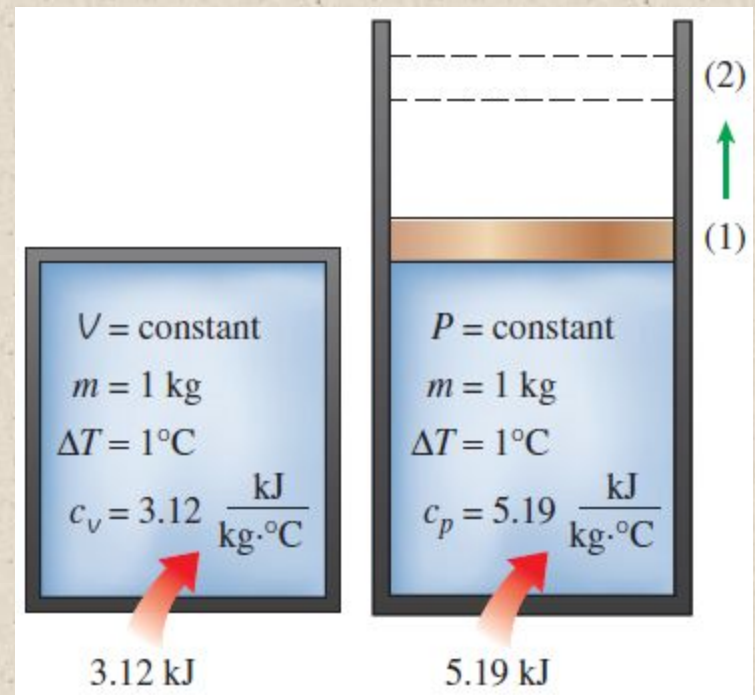

$V =$ constant
$m = 1$ kg
$\Delta T = 1°C$
$c_v = 3.12 \dfrac{kJ}{kg·°C}$

3.12 kJ

$P =$ constant
$m = 1$ kg
$\Delta T = 1°C$
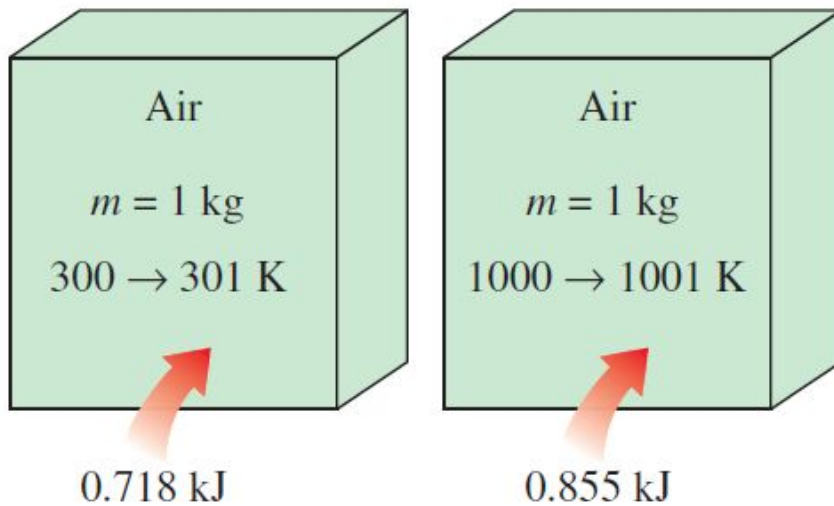$c_p = 5.19 \dfrac{kJ}{kg·°C}$

5.19 kJ

(2)

(1)

FIGURE 4–21
The specific heat of a substance changes with temperature.

- The equations are valid for *any* substance undergoing *any* process.
- c_v and c_p are properties.
- c_v is related to the changes in *internal energy* and c_p to the changes in *enthalpy*.
- A common unit for specific heats is kJ/kg·°C or kJ/kg·K. **Are these units identical?**

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v$$

= the change in internal energy with temperature at constant volume

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

= the change in enthalpy with temperature at constant pressure

Formal definitions of c_v and c_p.

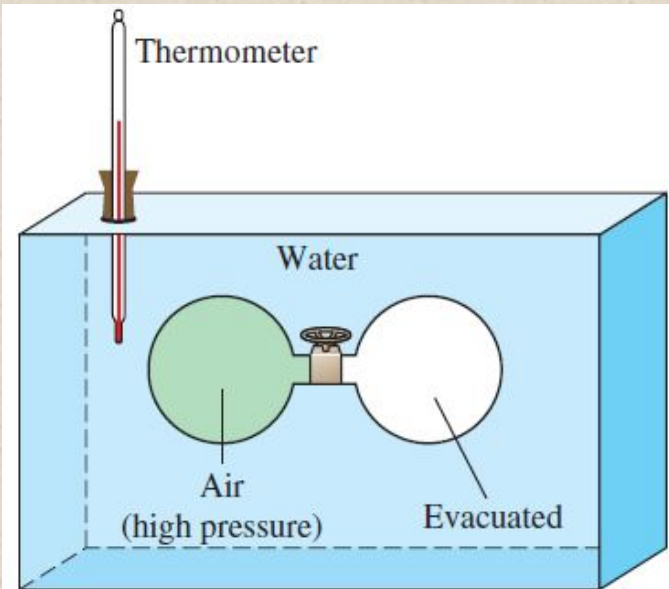# INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF IDEAL GASES

FIGURE 4–22

Schematic of the experimental apparatus used by Joule.

$$h = u + Pv$$
$$Pv = RT$$
$$\Biggr\} \quad h = u + RT$$

$$u = u(T) \quad h = h(T)$$

$$du = c_v(T)\, dT \quad dh = c_p(T)\, dT$$

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)\, dT$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)\, dT$$

Joule showed using this experimental apparatus that $u = u(T)$

$$u = u(T)$$
$$h = h(T)$$
$$c_v = c_v(T)$$
$$c_p = c_p(T)$$

For ideal gases, u, h, c_v, and c_p vary with temperature only.

Internal energy and enthalpy change of an ideal gas

7

- At low pressures, all real gases approach ideal-gas behavior, and therefore their specific heats depend on temperature only.
- The specific heats of real gases at low pressures are called *ideal-gas specific heats*, or *zero-pressure specific heats*, and are often denoted c_{p0} and c_{v0}.

- u and h data for a number of gases have been tabulated.
- These tables are obtained by choosing an arbitrary reference point and performing the integrations by treating state 1 as the reference state.
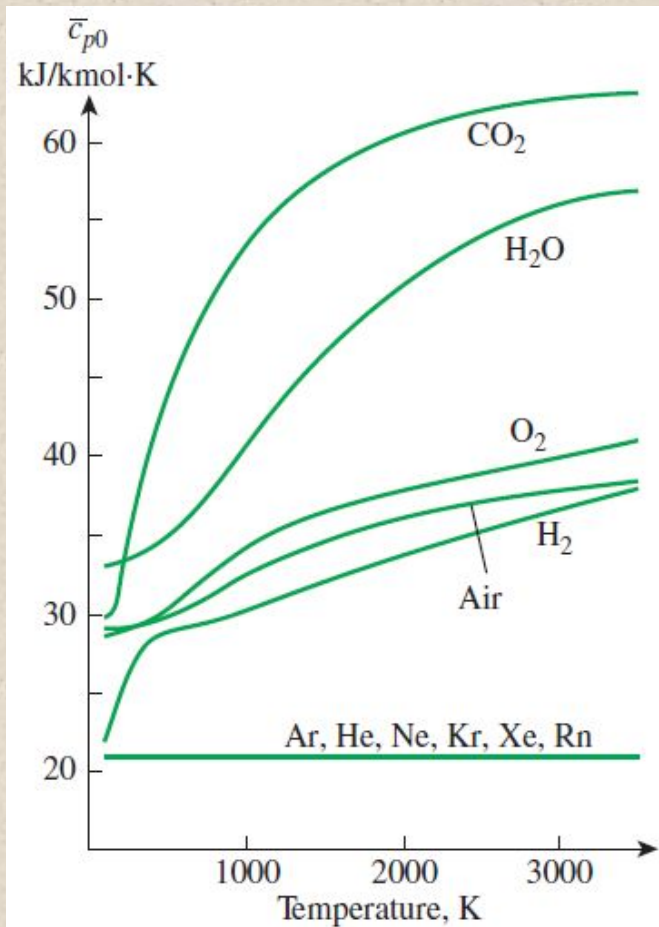
Ideal-gas constant-pressure specific heats for some gases (see Table A–2c for c_p equations).

Air		
T, K	u, kJ/kg	h, kJ/kg
0	0	0
.	.	.
.	.	.
300	214.07	300.19
310	221.25	310.24

Table A-17. In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

Internal energy and enthalpy change when specific heat is taken constant at an average value

$$u_2 - u_1 = c_{v,\text{avg}}(T_2 - T_1)$$

$$h_2 - h_1 = c_{p,\text{avg}}(T_2 - T_1)$$ (kJ/kg)

Air
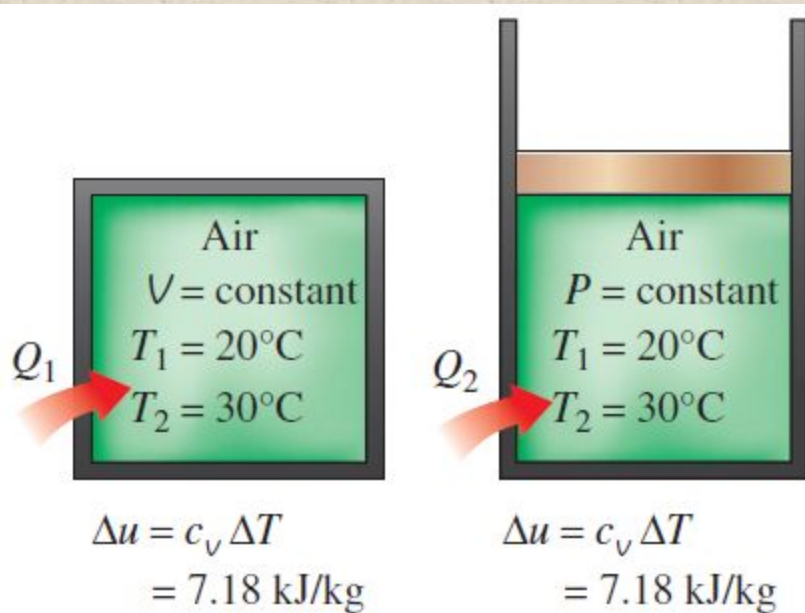$V = \text{constant}$
$T_1 = 20°C$
Q_1
$T_2 = 30°C$

$\Delta u = c_v \, \Delta T$
$= 7.18 \text{ kJ/kg}$

Air
$P = \text{constant}$
$T_1 = 20°C$
Q_2
$T_2 = 30°C$

$\Delta u = c_v \, \Delta T$
$= 7.18 \text{ kJ/kg}$

FIGURE 4–27
The relation $\Delta u = c_v \, \Delta T$ is valid for *any* kind of process, constant-volume or not.

Approximation

Actual

$c_{p,\text{avg}}$

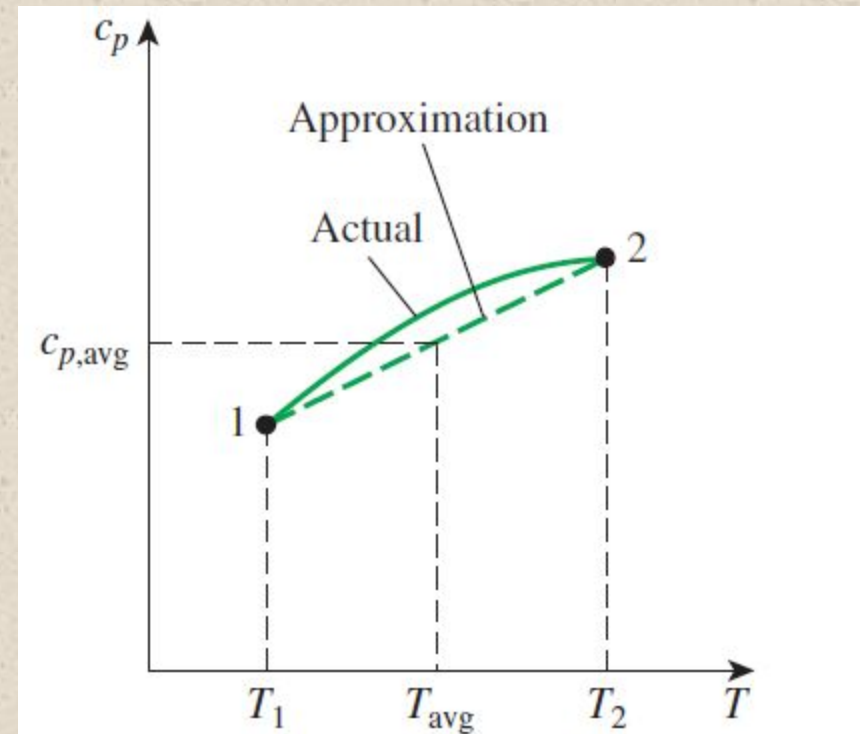T_1 T_{avg} T_2 T

FIGURE 4–26
For small temperature intervals, the specific heats may be assumed to vary linearly with temperature.

9

Three ways of calculating Δ*u and* Δ*h*

1. By using the tabulated *u* and *h* data (Table A-17). This is the easiest and **most accurate** way when tables are readily available.

2. By using the c_v or c_p relations (Table A-2c) as a function of temperature and performing the integrations. This is very inconvenient for hand calculations but quite desirable for computerized calculations. The results obtained are **very accurate**.

3. By using average specific heats. This is very simple and certainly very convenient when property tables are not available. The results obtained are **reasonably accurate** if the temperature interval is not very large.

$$\Delta u = u_2 - u_1 \text{ (table)}$$

$$\Delta u = \int_1^2 c_v (T) \, dT$$

$$\Delta u \cong c_{v,\text{avg}} \Delta T$$

Three ways of calculating Δ*u*.

Specific Heat Relations of Ideal Gases

$$h = u + RT$$

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

$dh = c_p dT$ and $du = c_v dT$

The relationship between c_p, c_v and R

$$c_p = c_v + R \qquad (\text{kJ/kg} \cdot \text{K})$$

On a molar basis

$$\bar{c}_p = \bar{c}_v + R_u \qquad (\text{kJ/kmol} \cdot \text{K})$$

$$k = \frac{c_p}{c_v}$$ Specific heat ratio

Air at 300 K

$$\left. \begin{array}{l} c_v = 0.718 \text{ kJ/kg·K} \\ R = 0.287 \text{ kJ/kg·K} \end{array} \right\} c_p = 1.005 \text{ kJ/kg·K}$$

or

$$\left. \begin{array}{l} \bar{c}_v = 20.80 \text{ kJ/kmol·K} \\ R_u = 8.314 \text{ kJ/kmol·K} \end{array} \right\} \bar{c}_p = 29.114 \text{ kJ/kmol·K}$$

The c_p of an ideal gas can be determined from a knowledge of c_v and R.

- The specific heat ratio varies with temperature, but this variation is very mild.
- For monatomic gases (helium, argon, etc.), its value is essentially constant at 1.667.
- Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

Heating of a Gas in a Tank by Stirring

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

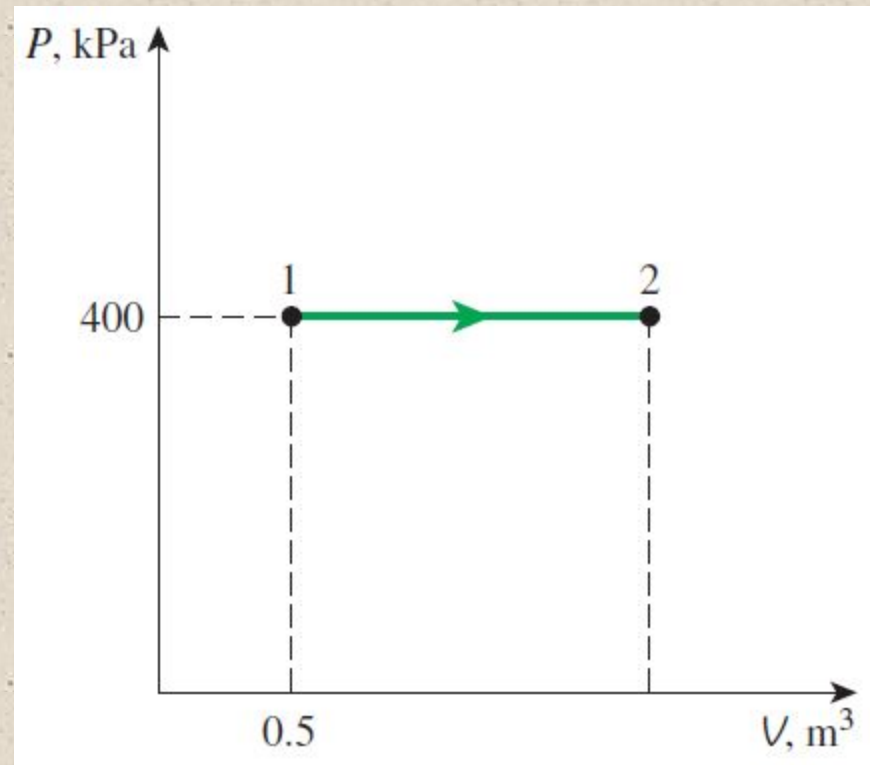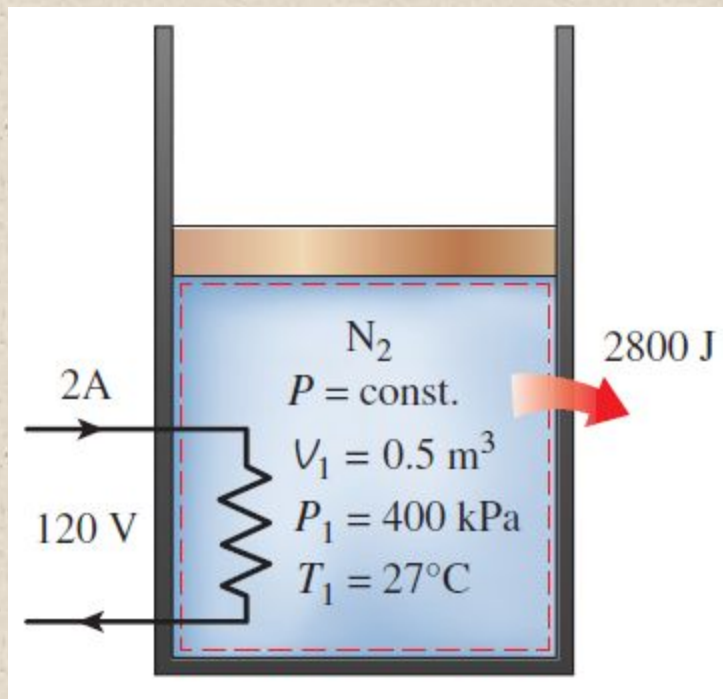$$W_{sh,in} = \Delta U = m(u_2 - u_1) = mc_{v,avg}(T_2 - T_1)$$

He

$m = 1.5$ lbm

$T_1 = 80°F$

$P_1 = 50$ psia

W_{sh}

P, psia

P_2 ─────── • 2

50 ─────── • 1

$V_2 = V_1$ V
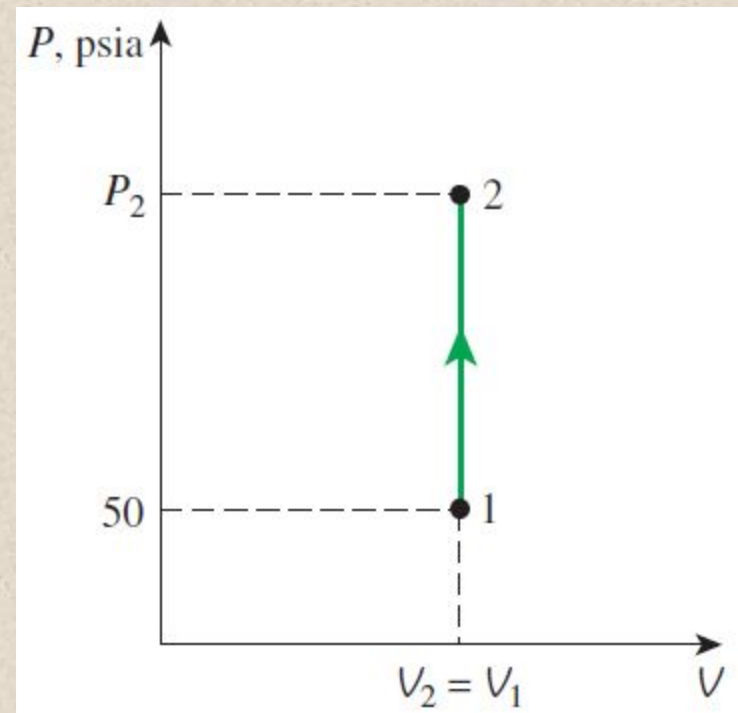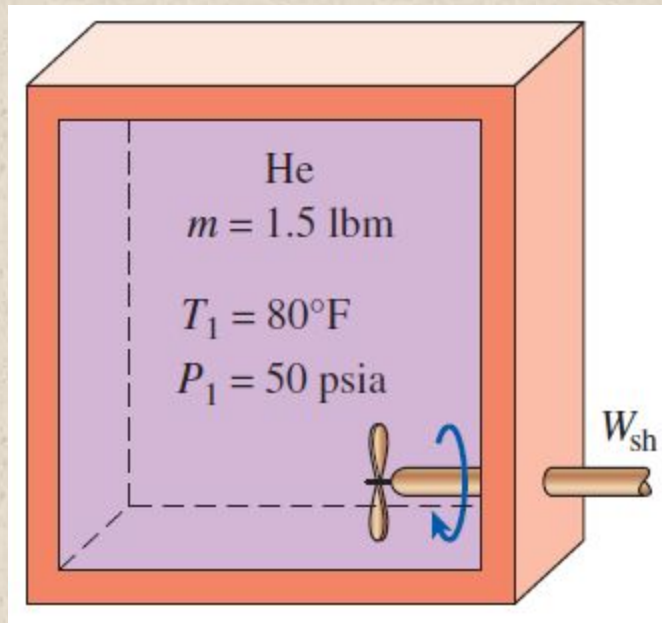
Heating of a Gas by a Resistance Heater

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

$$W_{e,in} - Q_{out} - W_{b,out} = \Delta U$$

$$W_{e,in} - Q_{out} = \Delta H = m(h_2 - h_1) = mc_p(T_2 - T_1)$$

2A

120 V

N$_2$
P = const.
$V_1 = 0.5 \text{ m}^3$
$P_1 = 400 \text{ kPa}$
$T_1 = 27°C$

2800 J

P, kPa

400

1   2

0.5 V, m^3

Heating of a Gas at Constant Pressure

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}}$$

$$Q_{in} - W_{b,out} = \Delta U = m(u_3 - u_1)$$

Air

$V_1 = 400 \text{ L}$
$P_1 = 150 \text{ kPa}$
$T_1 = 27°C$

Q

P, kPa

350 ---- 2 →→ 3

A

1
150 ----

0.4   0.8   V, m³