

Thermodynamics: An Engineering Approach, 5<sup>th</sup> Edition  
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# Chapter 1

## INTRODUCTION AND BASIC CONCEPTS

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# INTRODUCTION AND BASIC CONCEPTS

- 1-1 Thermodynamics and Energy
  - Application Areas of Thermodynamics
- 1-2 Importance of Dimensions and Units
  - Some SI and English Units
  - Dimensional Homogeneity
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SI Birimleriyle  
Yedinci Baskı

SI Birimleriyle Yedinci Baskı

TERMODİNAMİK  
MÜHENDİSLİK YAKLAŞIMIYLA

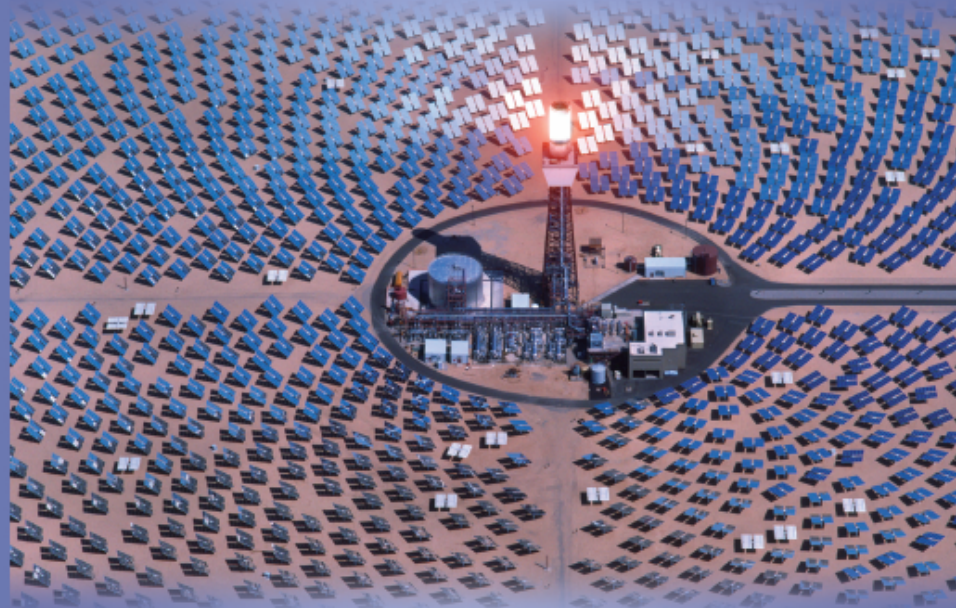
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PINARBAŞI



PALME  
YAYINCILIK

TERMODİNAMİK  
MÜHENDİSLİK YAKLAŞIMIYLA



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PALME YAYINCILIK

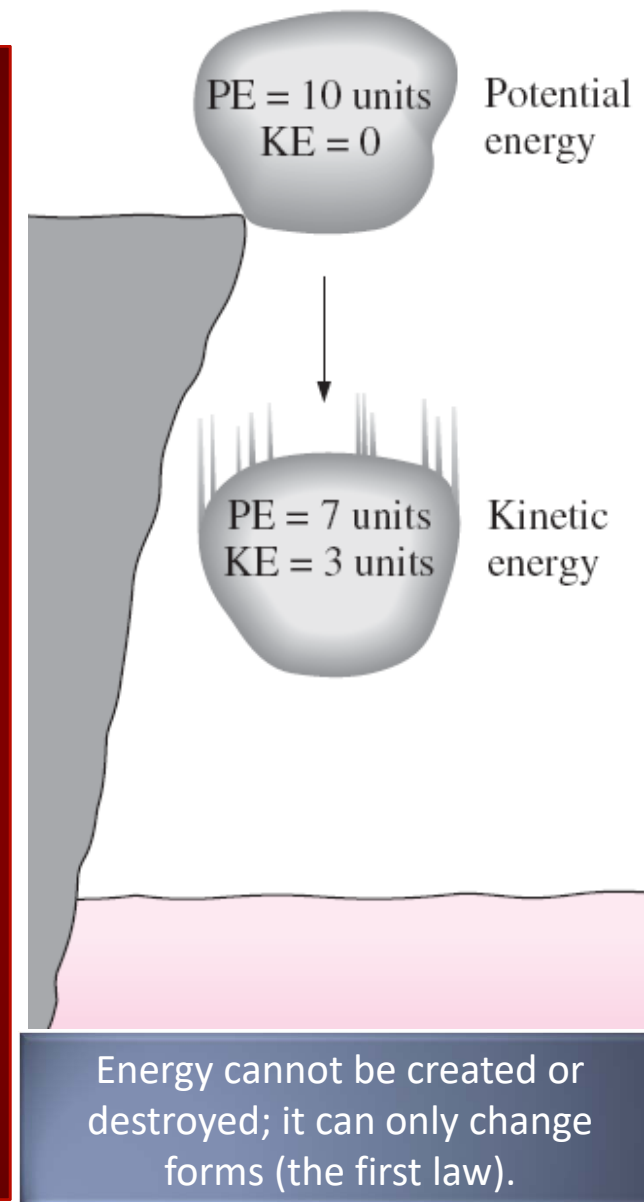
# Objectives

- Identify the unique vocabulary associated with thermodynamics through the precise definition of basic concepts to form a sound foundation for the development of the principles of thermodynamics.
- Review the metric SI and the English unit systems.
- Explain the basic concepts of thermodynamics such as **system**, **state**, **state postulate**, **equilibrium**, **process**, and **cycle**.
- Review concepts of temperature, temperature scales, pressure, and absolute and gage pressure.
- Introduce an intuitive systematic problem-solving technique.

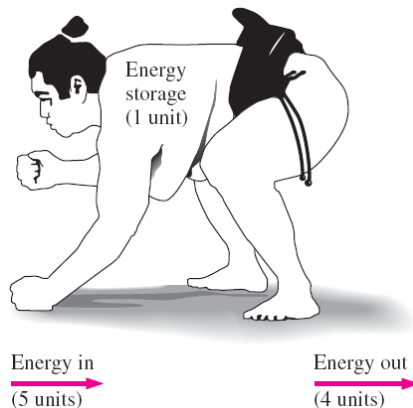


# THERMODYNAMICS AND ENERGY

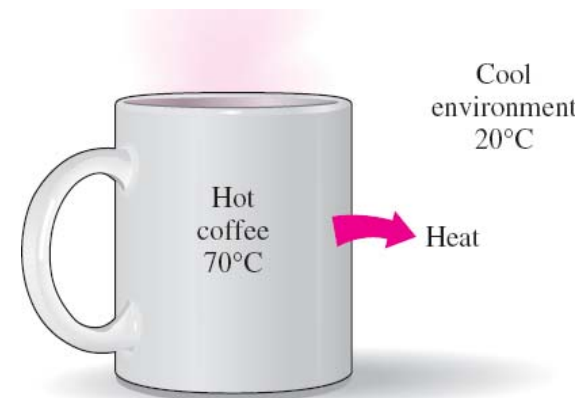
- **Thermodynamics:** The science of *energy*.
- **Energy:** The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle:** During an interaction, energy can change from one form to another but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics:** An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.



- **The second law of thermodynamics:** It asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.
- **Classical thermodynamics:** A *macroscopic approach* to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
- It provides a direct and easy way to the solution of engineering problems and it is used in this text.
- **Statistical thermodynamics:** A *microscopic approach*, based on the average behavior of large groups of individual particles.
- It is used in this text only in the supporting role.

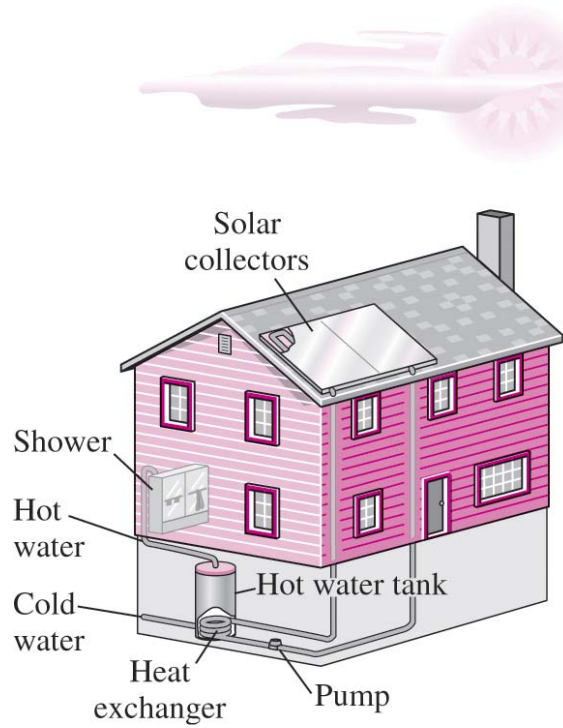


Conservation of energy principle for the human body.



Heat flows in the direction of decreasing temperature.

# APPLICATION AREAS OF THERMODYNAMICS



# IMPORTANCE OF DIMENSIONS AND UNITS

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to the dimensions are called **units**.
- Some basic dimensions such as mass  $m$ , length  $L$ , time  $t$ , and temperature  $T$  are selected as **primary** or **fundamental dimensions**, while others such as velocity  $V$ , energy  $E$ , and volume  $V$  are expressed in terms of the primary dimensions and are called **secondary dimensions**, or **derived dimensions**.
- Metric SI system**: A simple and logical system based on a decimal relationship between the various units.
- English system**: It has no apparent systematic numerical base, and various units in this system are related to each other rather arbitrarily.

| The seven fundamental (or primary) dimensions and their units in SI |               |
|---|---------------|
| Dimension   | Unit          |
| Length  | meter (m)     |
| Mass  | kilogram (kg) |
| Time  | second (s)    |
| Temperature   | kelvin (K)    |
| Electric current  | ampere (A)    |
| Amount of light   | candela (cd)  |
| Amount of matter  | mole (mol)    |

| Standard prefixes in SI units |              |
|-------------------------------|--------------|
| Multiple                      | Prefix       |
| $10^{12}$                     | tera, T      |
| $10^9$                        | giga, G      |
| $10^6$                        | mega, M      |
| $10^3$                        | kilo, k      |
| $10^2$                        | hecto, h     |
| $10^1$                        | deka, da     |
| $10^{-1}$                     | deci, d      |
| $10^{-2}$                     | centi, c     |
| $10^{-3}$                     | milli, m     |
| $10^{-6}$                     | micro, $\mu$ |
| $10^{-9}$                     | nano, n      |
| $10^{-12}$                    | pico, p      |



## SOME SI AND ENGLISH UNITS

$$1 \text{ lbm} = 0.45359 \text{ kg}$$

$$1 \text{ ft} = 0.3048 \text{ m}$$

Work = Force  $\times$  Distance

$$1 \text{ J} = 1 \text{ N}\cdot\text{m}$$

$$1 \text{ cal} = 4.1868 \text{ J}$$

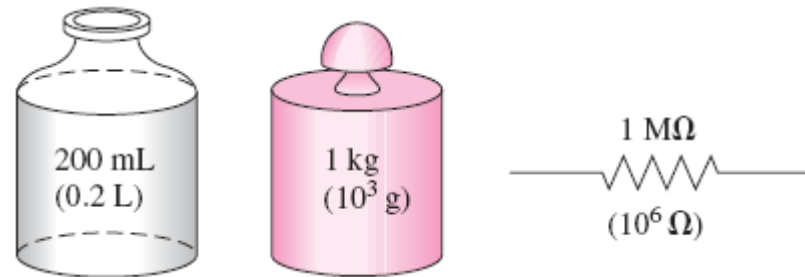
$$1 \text{ Btu} = 1.0551 \text{ kJ}$$

Force = (Mass)(Acceleration)

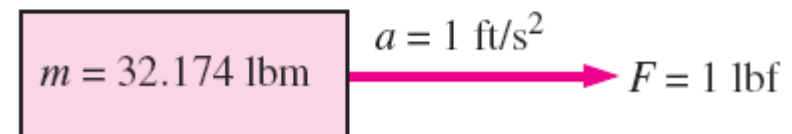
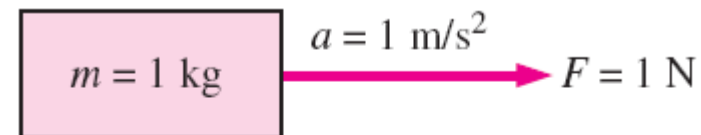
$$F = ma$$

$$1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2$$

$$1 \text{ lbf} = 32.174 \text{ lbm} \cdot \text{ft/s}^2$$



The SI unit prefixes are used in all branches of engineering.



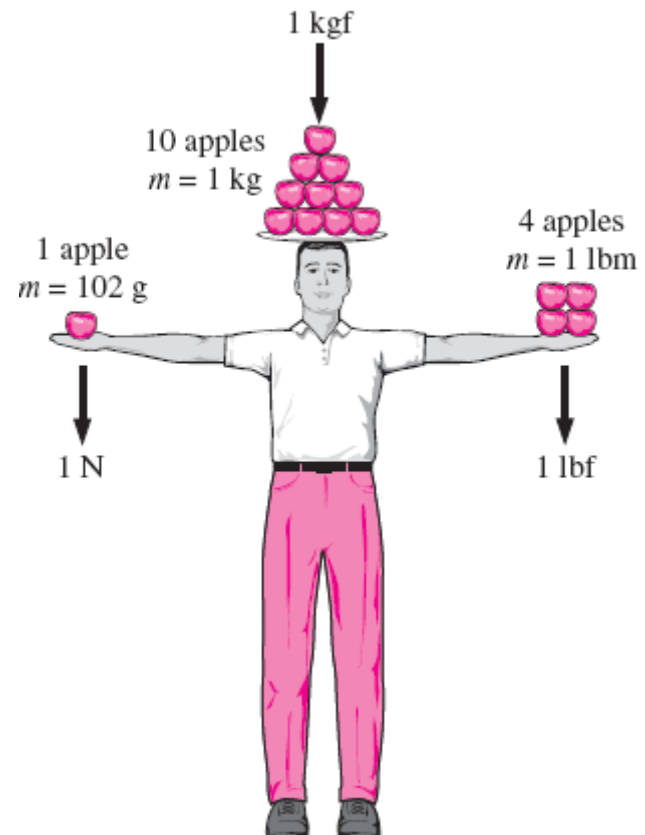
The definition of the force units.



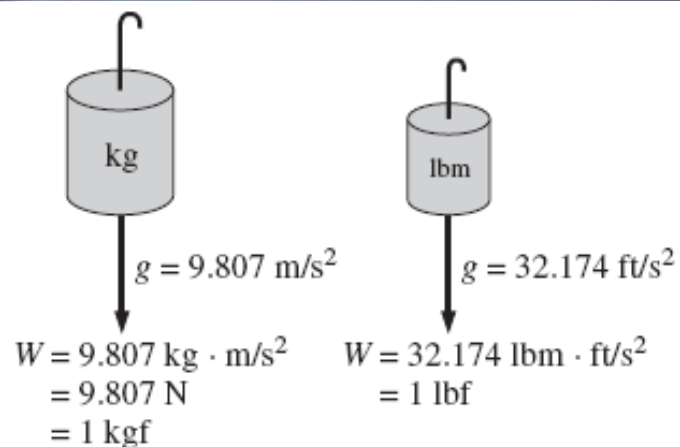


$$W = mg \quad (\text{N})$$

**W** weight  
**m** mass  
**g** gravitational  
 acceleration



A body weighing 60 kgf on earth will weigh only 10 kgf on the moon.



The weight of a unit mass at sea level.

The relative magnitudes of the force units newton (N), kilogram-force (kgf), and pound-force (lbf).

# Dimensional homogeneity

All equations must be dimensionally **homogeneous**.

## UNITY CONVERSION RATIOS

All nonprimary units (secondary units) can be formed by combinations of primary units. Force units, for example, can be expressed as

$$N = \text{kg} \frac{\text{m}}{\text{s}^2} \quad \text{and} \quad \text{lbf} = 32.174 \text{ lbm} \frac{\text{ft}}{\text{s}^2}$$

They can also be expressed more conveniently as **unity conversion ratios** as

$$\frac{N}{\text{kg} \cdot \text{m}/\text{s}^2} = 1 \quad \text{and} \quad \frac{\text{lbf}}{32.174 \text{ lbm} \cdot \text{ft}/\text{s}^2} = 1$$

Unity conversion ratios are identically equal to 1 and are unitless, and thus such ratios (or their inverses) can be inserted conveniently into any calculation to properly convert units.



To be dimensionally homogeneous, all the terms in an equation must have the same unit.

### EXAMPLE 1-1

While solving a problem, a person ended up with the following equation at some stage:

$E = 25 \text{ kJ} \pm 7 \text{ kJ/kg}$  where  $E$  is the total energy and has the unit of kilojoules. Determine the error that may have caused it.

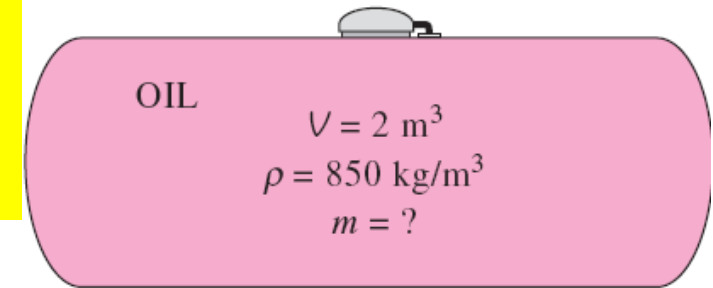
**Solution** During an analysis, a relation with inconsistent units is obtained. The probable cause of it is to be determined.

**Analysis** The two terms on the right-hand side do not have the same units, and therefore they cannot be added to obtain the total energy. Multiplying the last term by mass will eliminate the kilograms in the denominator, and the whole equation will become dimensionally homogeneous; that is, every term in the equation will have the same unit.

**Discussion** Obviously this error was caused by forgetting to multiply the last term by mass at an earlier stage.

### EXAMPLE 1-2

A tank is filled with oil whose density is  $\rho = 850 \text{ kg/m}^3$ . If the volume of the tank is  $V = 2 \text{ m}^3$ , determine the amount of mass  $m$  in the tank.



**Solution** The volume of an oil tank is given. The mass of oil is to be determined.

**Assumptions** Oil is an incompressible substance and thus its density is constant

$$\rho = 850 \text{ kg/m}^3 \quad \text{and} \quad V = 2 \text{ m}^3$$

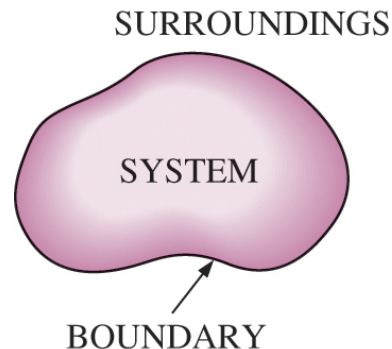
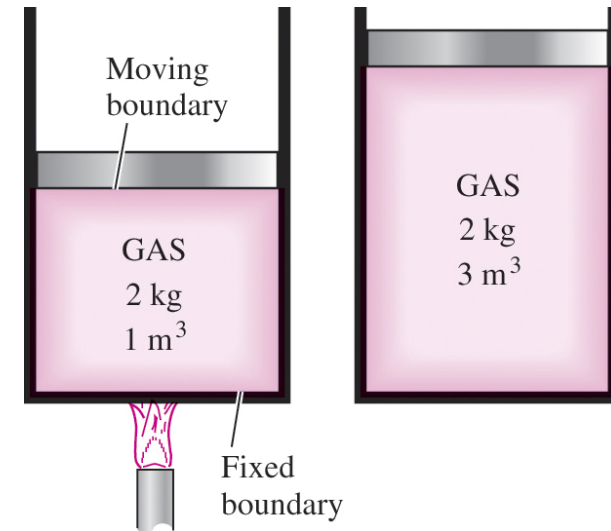
$$m = \rho V$$

$$m = (850 \text{ kg/m}^3)(2 \text{ m}^3) = \mathbf{1700 \text{ kg}}$$

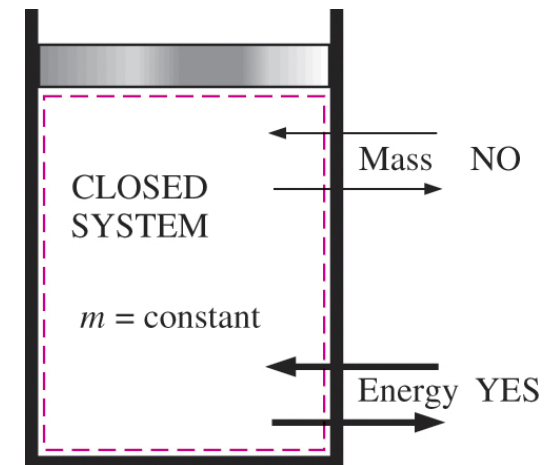
**Discussion** Note that this approach may not work for more complicated formulas.

# SYSTEMS AND CONTROL VOLUMES

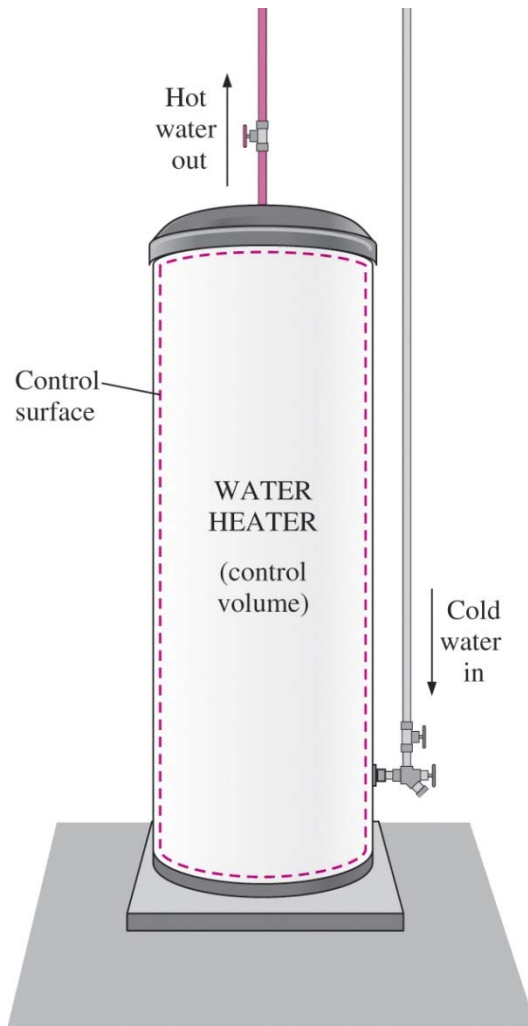
- **System:** A quantity of matter or a region in space chosen for study.
- **Surroundings:** The mass or region outside the system
- **Boundary:** The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable*.
- Systems may be considered to be *closed* or *open*.



**Closed system (Control mass):** A fixed Amount of mass, and no mass can cross its boundary.

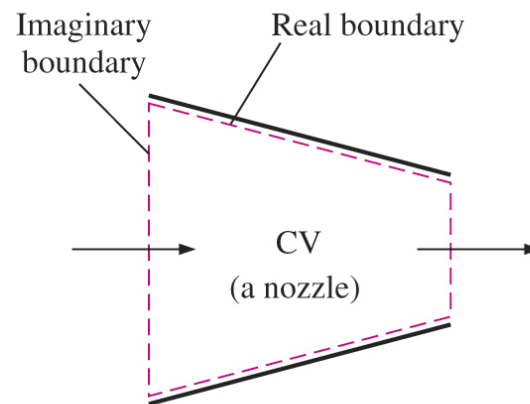




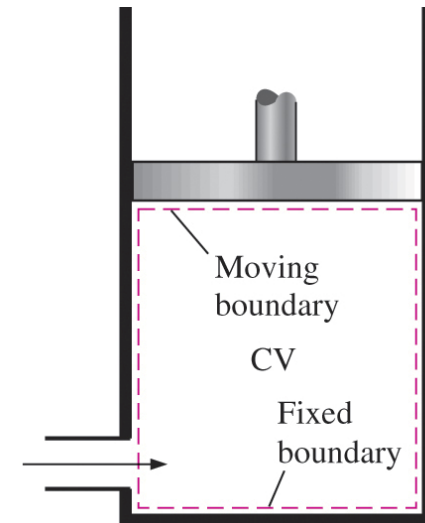


An open system (a control volume) with one inlet and one exit.

- **Open system (control volume):** A properly selected region in space.
- It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Both mass and energy can cross the boundary of a control volume.
- **Control surface:** The boundaries of a control volume. It can be real or imaginary.



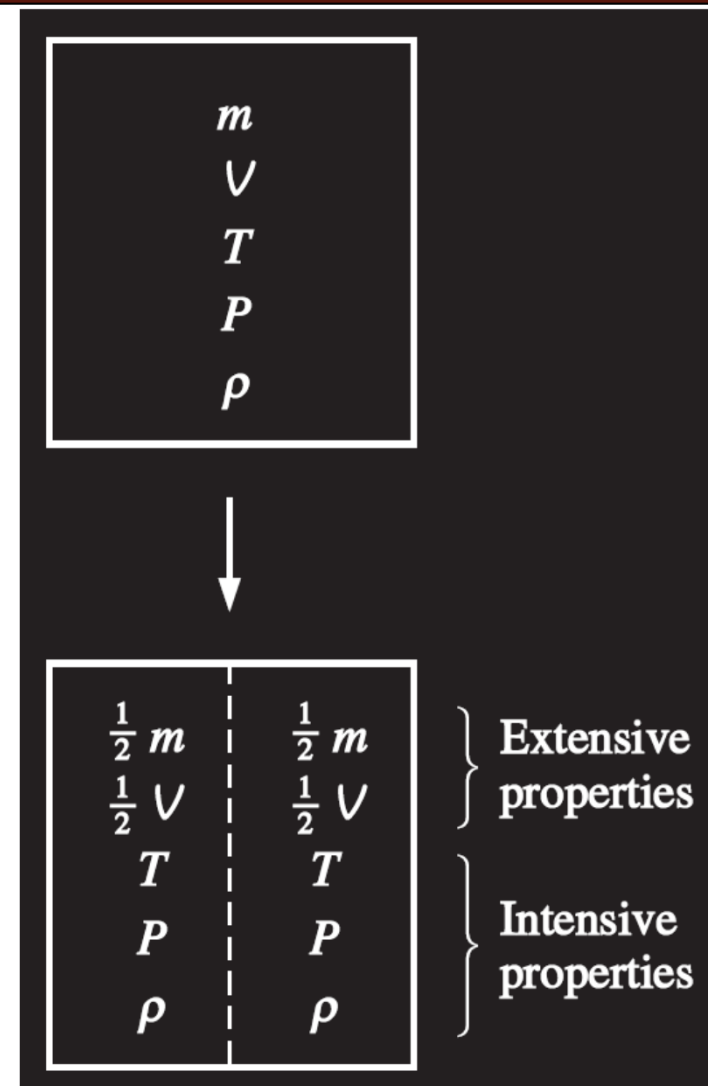
(a) A control volume with real and imaginary boundaries



(b) A control volume with fixed and moving boundaries

# PROPERTIES OF A SYSTEM

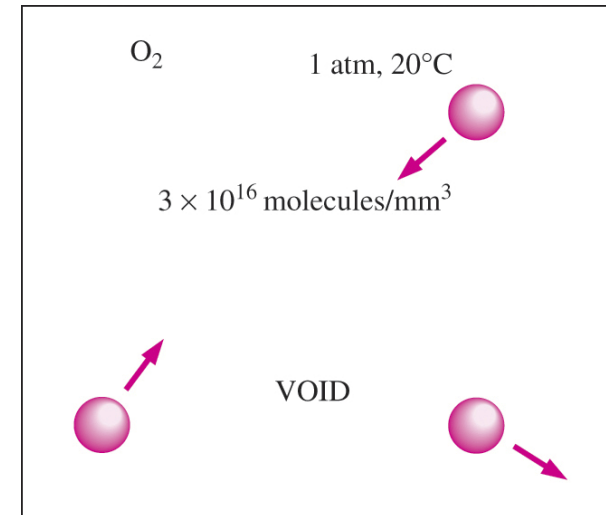
- **Property:** Any characteristic of a system.
- Some familiar properties are pressure  $P$ , temperature  $T$ , volume  $V$ , and mass  $m$ .
- Properties are considered to be either *intensive* or *extensive*.
- **Intensive properties:** Those that are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties:** Those whose values depend on the size-or extent-of the system.
- **Specific properties:** Extensive properties per unit mass.



Criterion to differentiate intensive and extensive properties.

# CONTINUUM

- Matter is made up of atoms that are widely spaced in the gas phase.
- It is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is, a **continuum**.
- The continuum idealization allows us to treat properties as point functions and to assume the properties vary continually in space with no jump discontinuities.
- This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules.
- This is the case in practically all problems.
- In this text we will limit our consideration to substances that can be modeled as a continuum.



Despite the large gaps between molecules, a substance can be treated as a continuum because of the very large number of molecules even in an extremely small volume.

# DENSITY AND SPECIFIC GRAVITY

## Density

Density is mass per unit volume; specific volume is volume per unit mass.

$$\rho = \frac{m}{V} \quad (\text{kg/m}^3)$$

$$\begin{aligned} V &= 12 \text{ m}^3 \\ m &= 3 \text{ kg} \\ \downarrow \\ \rho &= 0.25 \text{ kg/m}^3 \\ \nu &= \frac{1}{\rho} = 4 \text{ m}^3/\text{kg} \end{aligned}$$

## Specific volume

$$\nu = \frac{V}{m} = \frac{1}{\rho}$$

**Specific weight:** The weight of a unit volume of a substance.

$$\gamma_s = \rho g \quad (\text{N/m}^3)$$

**Specific gravity:** The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$SG = \frac{\rho}{\rho_{\text{H}_2\text{O}}}$$

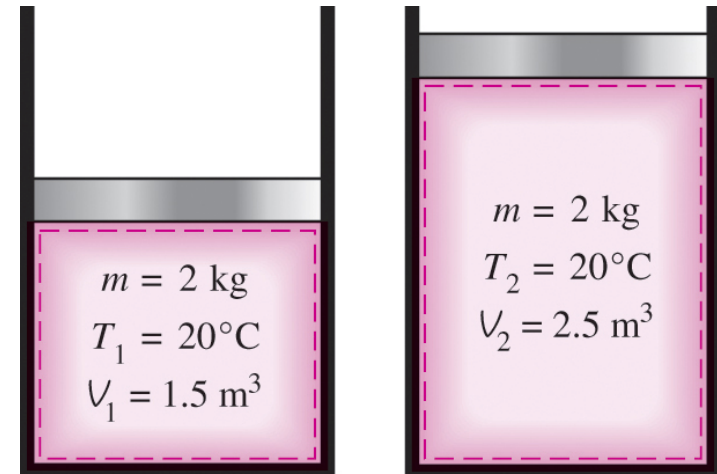
Specific gravities of some substances at 0°C

| Substance      | SG      |
|----------------|---------|
| Water          | 1.0     |
| Blood          | 1.05    |
| Seawater       | 1.025   |
| Gasoline       | 0.7     |
| Ethyl alcohol  | 0.79    |
| Mercury        | 13.6    |
| Wood           | 0.3–0.9 |
| Gold           | 19.2    |
| Bones          | 1.7–2.0 |
| Ice            | 0.92    |
| Air (at 1 atm) | 0.0013  |

# STATE AND EQUILIBRIUM

Thermodynamics deals with **equilibrium** states.

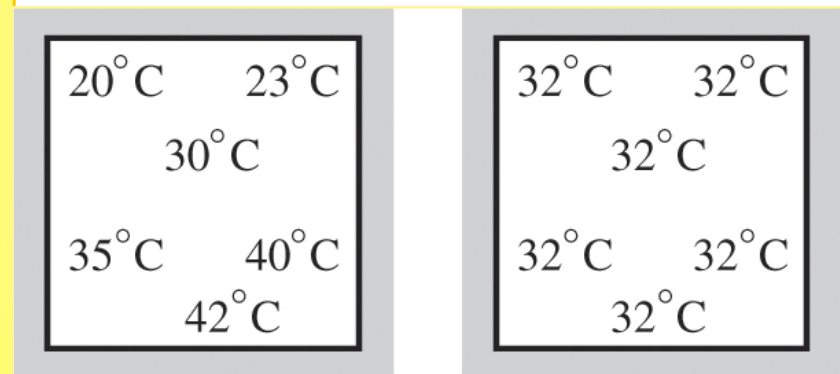
- **Equilibrium:** A state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium:** If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.



(a) State 1

(b) State 2

A system at two different states.



(a) Before

(b) After

A closed system reaching thermal equilibrium.



# THE STATE POSTULATE

- The number of properties required to fix the state of a system is given by the **state postulate**:  
*The state of a simple compressible system is completely specified by two independent, intensive properties.*
- **Simple compressible system**: If a system involves no electrical, magnetic, gravitational, motion, and surface tension effects.



The state of nitrogen is fixed by two independent, intensive properties.

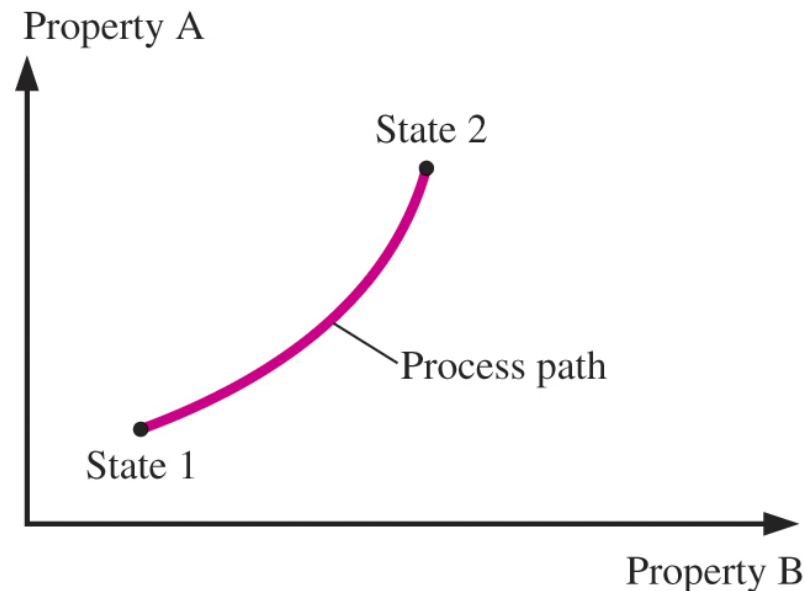
# PROCESSES AND CYCLES

**Process:** Any change that a system undergoes from one equilibrium state to another.

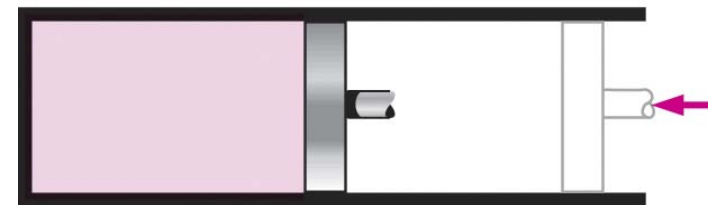
**Path:** The series of states through which a system passes during a process.

**To describe a process completely, one should specify the initial and final states, as well as the path it follows, and the interactions with the surroundings.**

**Quasistatic or quasi-equilibrium process:** When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.

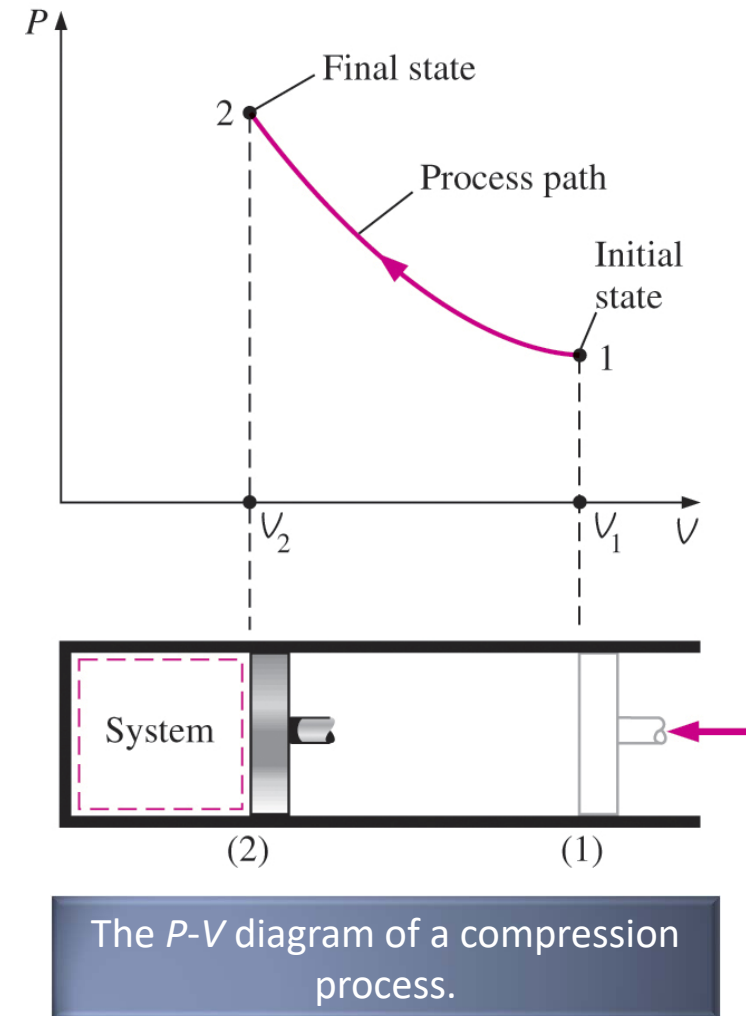


(a) Slow compression  
(quasi-equilibrium)



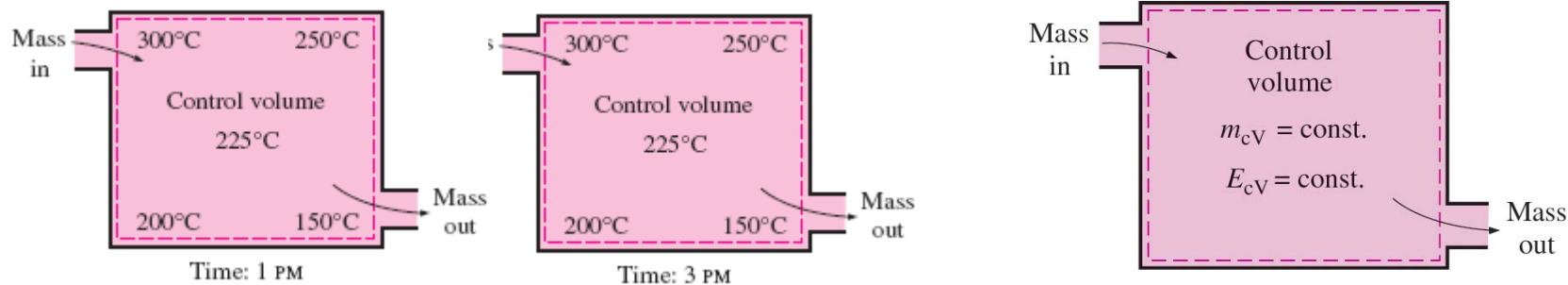
(b) Very fast compression  
(nonquasi-equilibrium)

- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature  $T$ , pressure  $P$ , and volume  $V$  (or specific volume  $v$ ).
- The prefix **iso-** is often used to designate a process for which a particular property remains constant.
- Isothermal process:** A process during which the temperature  $T$  remains constant.
- Isobaric process:** A process during which the pressure  $P$  remains constant.
- Isochoric (or isometric) process:** A process during which the specific volume  $v$  remains constant.
- Cycle:** A process during which the initial and final states are identical.



# THE STEADY-FLOW PROCESS

- The term **steady** implies **no change with time**. The opposite of steady is **unsteady**, or **transient**.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as **steady-flow devices**.
- **Steady-flow process**: A process during which a fluid flows through a control volume steadily.
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as **turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems**.



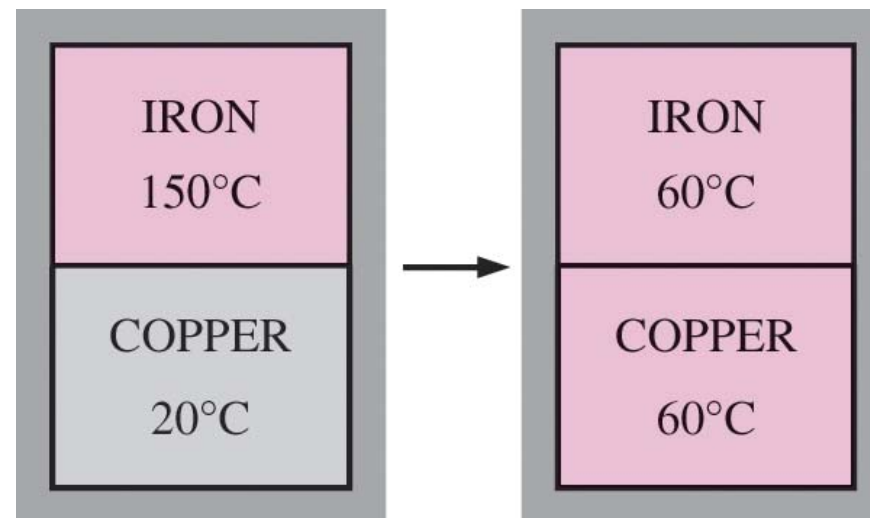
During a steady-flow process, fluid properties within the control volume may change with position but not with time.

Under steady-flow conditions, the mass and energy contents of a control volume remain constant

# TEMPERATURE AND THE ZEROth LAW OF THERMODYNAMICS

- **The zeroth law of thermodynamics:** If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as

*two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact.*

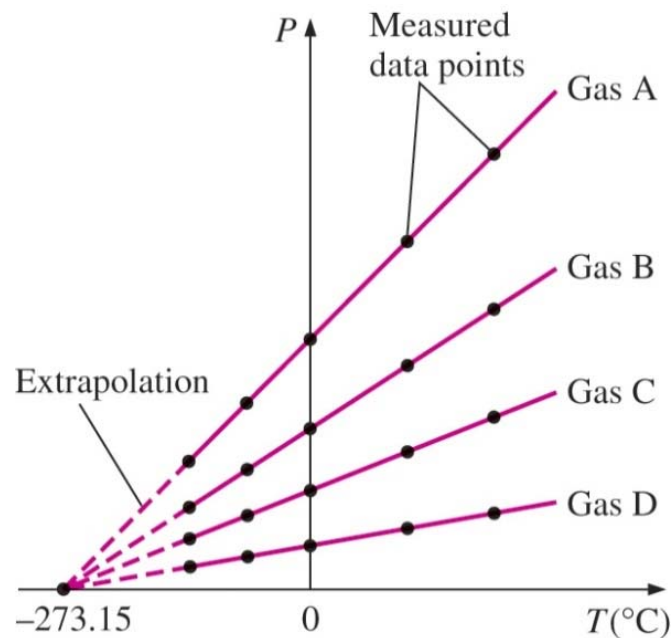


Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

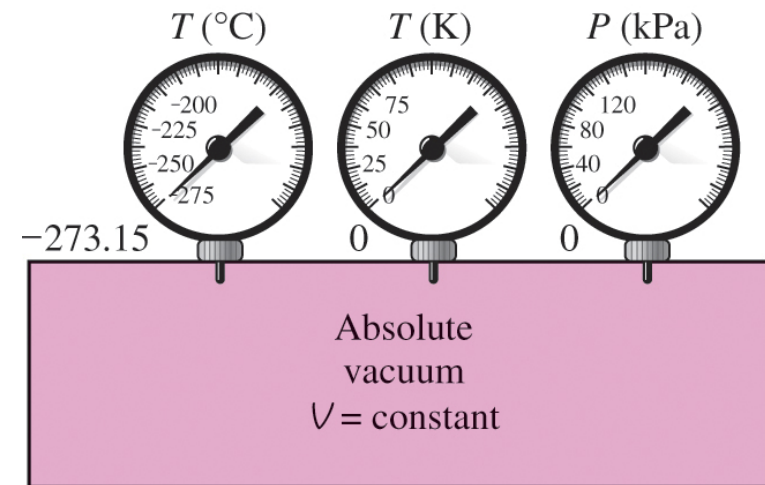


# TEMPERATURE SCALES

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point*.
- **Ice point:** A mixture of ice and water that is in equilibrium with air saturated with vapor at 1 atm pressure (0°C or 32°F).
- **Steam point:** A mixture of liquid water and water vapor (with no air) in equilibrium at 1 atm pressure (100°C or 212°F).
- **Celsius scale:** in SI unit system
- **Fahrenheit scale:** in English unit system
- **Thermodynamic temperature scale:** A temperature scale that is independent of the properties of any substance.
- **Kelvin scale** (SI) **Rankine scale** (E)
- A temperature scale nearly identical to the Kelvin scale is the **ideal-gas temperature scale**. The temperatures on this scale are measured using a **constant-volume gas thermometer**.



$P$  versus  $T$  plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.



A constant-volume gas thermometer would read  $273.15\text{ }^{\circ}\text{C}$  at absolute zero pressure.

$$T(\text{K}) = T(^{\circ}\text{C}) + 273.15$$

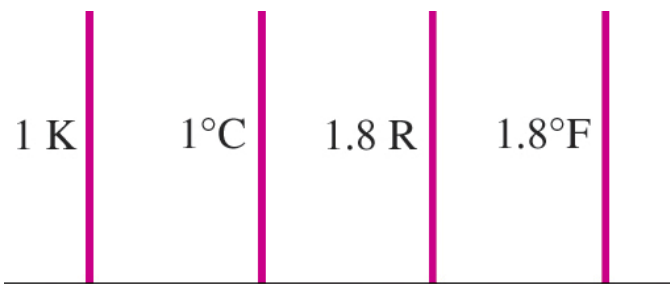
$$T(\text{R}) = T(^{\circ}\text{F}) + 459.67$$

$$T(\text{R}) = 1.8T(\text{K})$$

$$T(^{\circ}\text{F}) = 1.8T(^{\circ}\text{C}) + 32$$

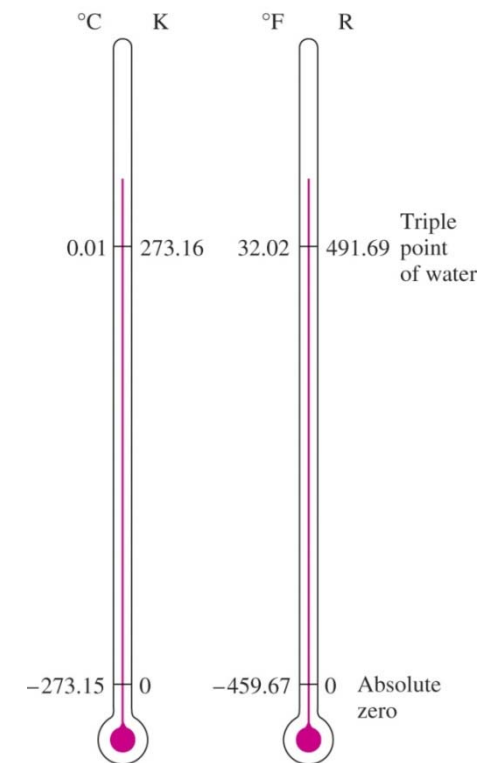
$$\Delta T(\text{K}) = \Delta T(^{\circ}\text{C})$$

$$\Delta T(\text{R}) = \Delta T(^{\circ}\text{F})$$



Comparison of magnitudes of various temperature units.

- The reference temperature in the original Kelvin scale was the **ice point**, 273.15 K, which is the temperature at which water freezes (or ice melts).
- The reference point was changed to a much more precisely reproducible point, the **triple point** of water (the state at which all three phases of water coexist in equilibrium), which is assigned the value 273.16 K.



Comparison of temperature scales.

# PRESSURE

**Pressure:** A normal force exerted by a fluid per unit area

$$1 \text{ Pa} = 1 \text{ N/m}^2$$

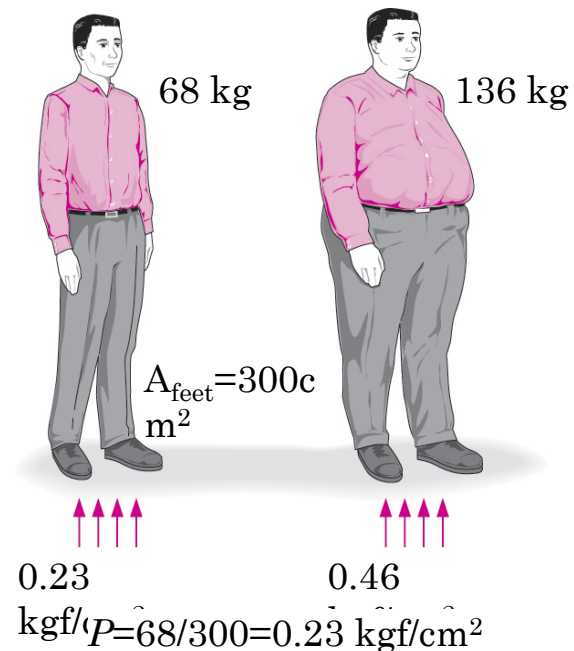
$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa} = 100 \text{ kPa}$$

$$1 \text{ atm} = 101,325 \text{ Pa} = 101.325 \text{ kPa} = 1.01325 \text{ bars}$$

$$\begin{aligned} 1 \text{ kgf/cm}^2 &= 9.807 \text{ N/cm}^2 = 9.807 \times 10^4 \text{ N/m}^2 = 9.807 \times 10^4 \text{ Pa} \\ &= 0.9807 \text{ bar} \\ &= 0.9679 \text{ atm} \end{aligned}$$

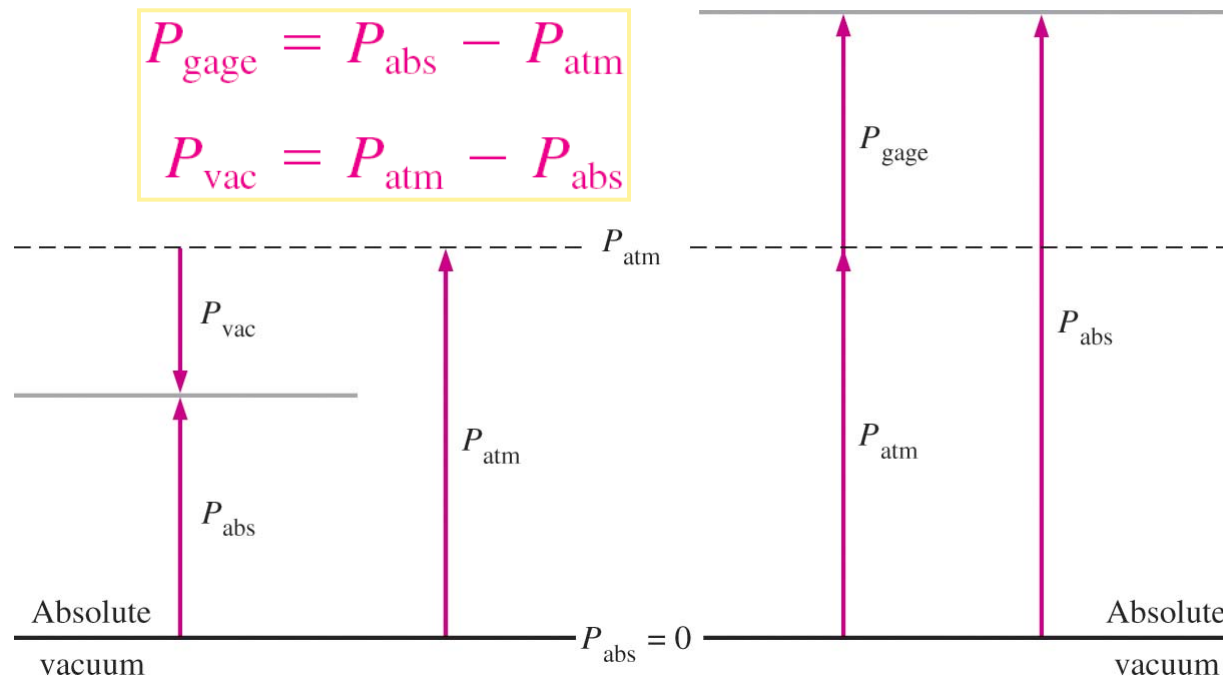


Some basic pressure gages.



The normal stress (or “pressure”) on the feet of a chubby person is much greater than on the feet of a slim person.

- **Absolute pressure:** The actual pressure at a given position. It is measured relative to absolute vacuum (i.e., absolute zero pressure).
- **Gage pressure:** The difference between the absolute pressure and the local atmospheric pressure. Most pressure-measuring devices are calibrated to read zero in the atmosphere, and so they indicate gage pressure.
- **Vacuum pressures:** Pressures below atmospheric pressure.



Throughout this text, the pressure  $P$  will denote **absolute pressure** unless specified otherwise.

### EXAMPLE 1-5

A vacuum gage connected to a chamber reads 40 kPa at a location where the atmospheric pressure is 100 kPa. Determine the absolute pressure in the chamber.

**Solution** The gage pressure of a vacuum chamber is given. The absolute pressure in the chamber is to be determined.

**Analysis** The absolute pressure is easily determined from.

$$P_{\text{abs}} = P_{\text{atm}} - P_{\text{vac}} = 100 - 40 = 60 \text{ kPa}$$

**Discussion** Note that the local value of the atmospheric pressure is used when determining the absolute pressure.



# VARIATION OF PRESSURE WITH DEPTH

Assuming the density of the fluid to be constant,  
a force balance in the vertical z-direction gives;

$$\sum F_z = ma_z = 0: \quad P_2 \Delta x - P_1 \Delta x - \rho g \Delta x \Delta z = 0$$

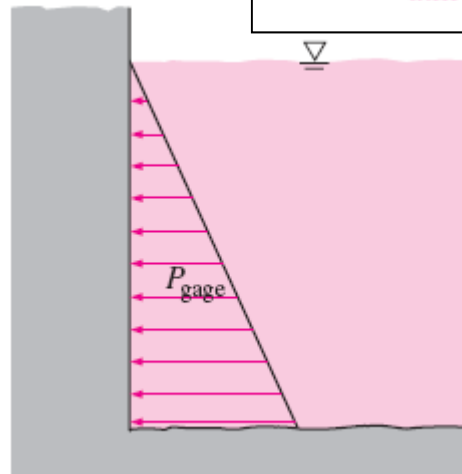
$$W = mg = \rho g \Delta x \Delta z$$

$$\Delta P = P_2 - P_1 = \rho g \Delta z = \gamma_s \Delta z$$

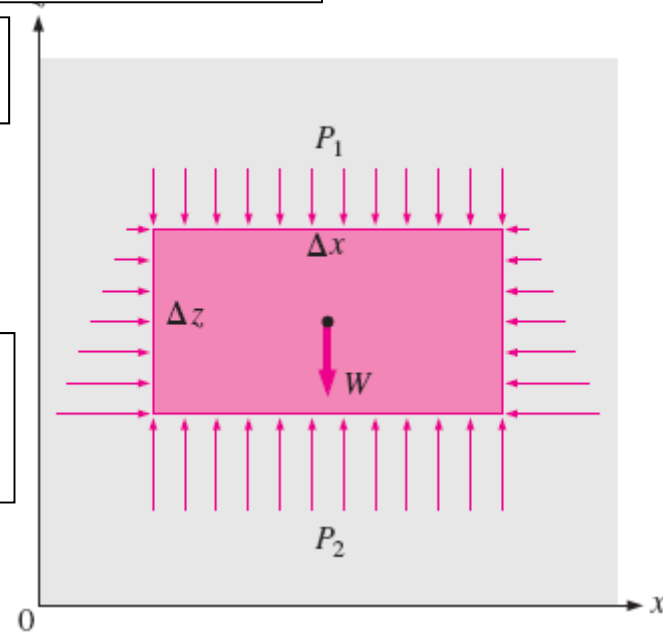
$$P = P_{\text{atm}} + \rho gh \quad \text{or} \quad P_{\text{gage}} = \rho gh$$

$$\frac{dP}{dz} = -\rho g$$

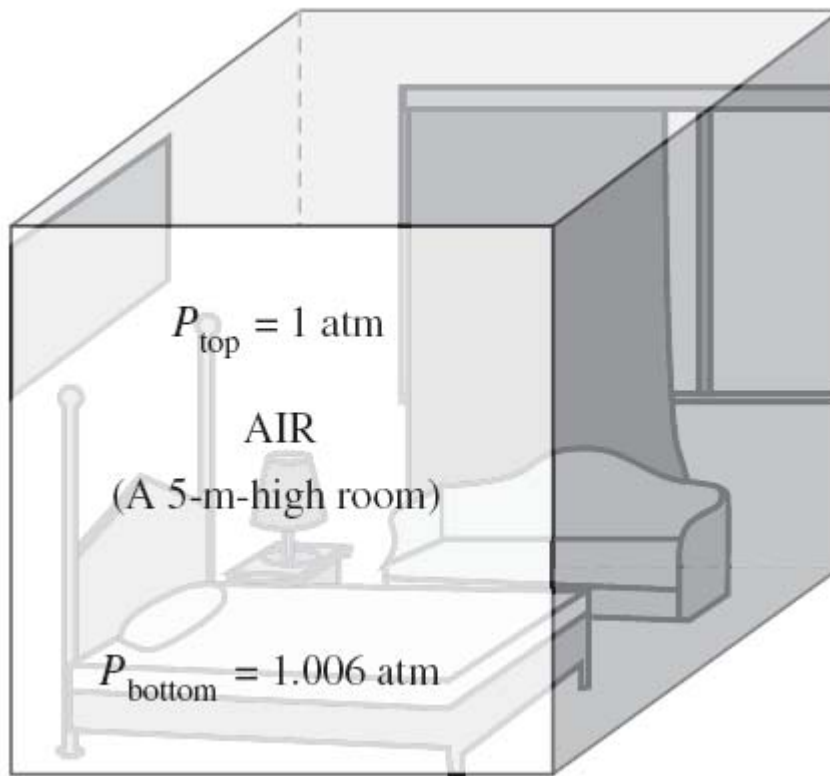
$$\Delta P = P_2 - P_1 = - \int_1^2 \rho g dz$$



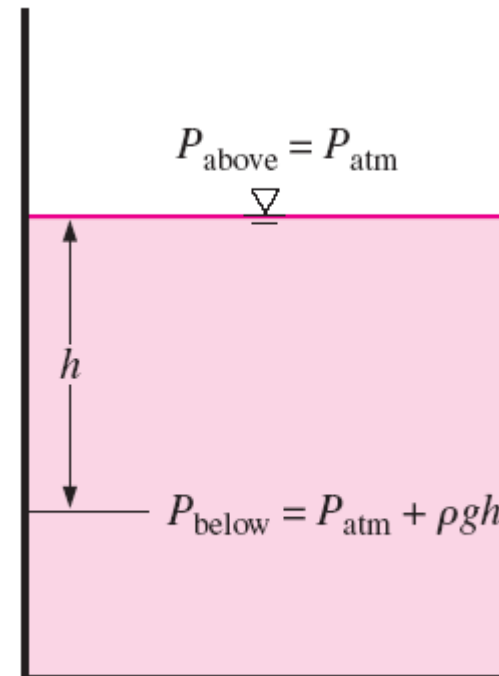
The pressure of a fluid at rest increases with depth (as a result of added weight).



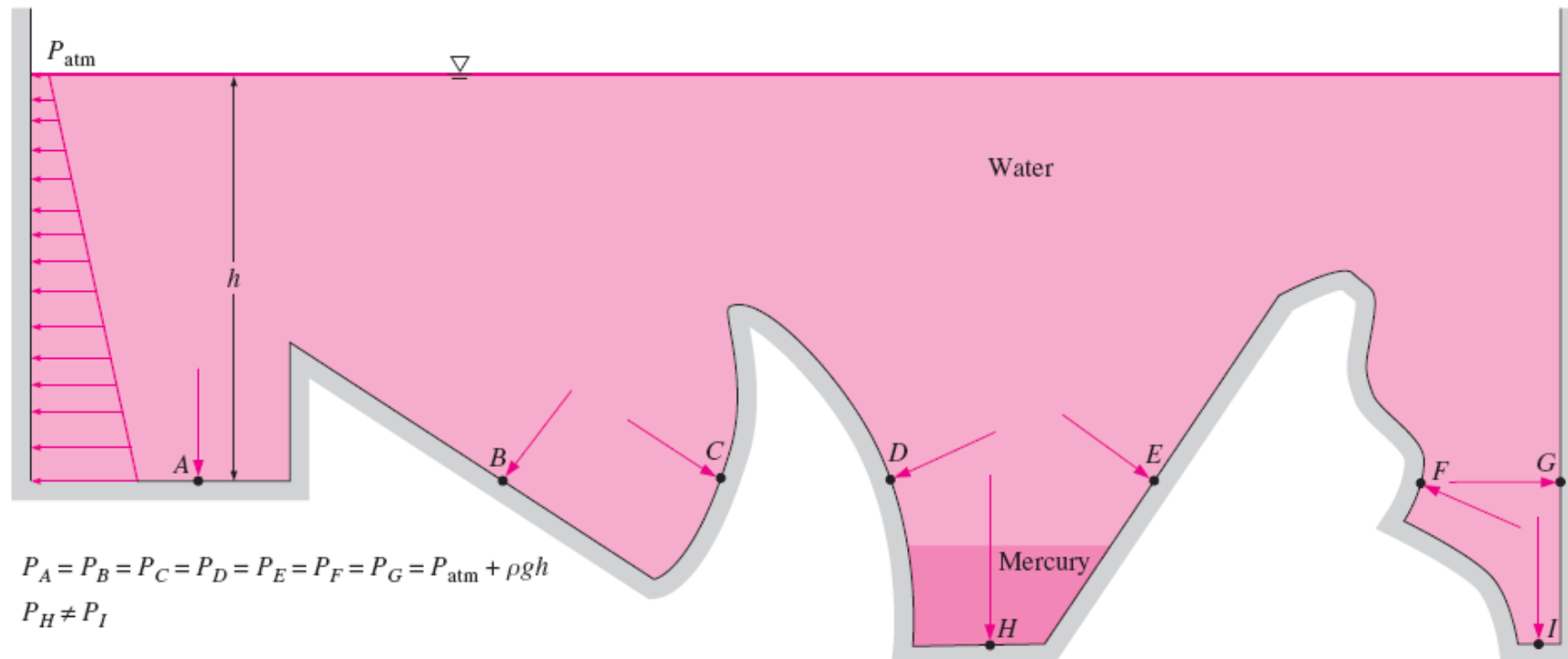
Free-body diagram of a rectangular fluid element in equilibrium.



In a room filled with a gas, the variation of pressure with height is negligible.



Pressure in a liquid at rest increases linearly with distance from the free surface.



The pressure is the same at all points on a horizontal plane in a given fluid regardless of geometry, provided that the points are interconnected by the same fluid.

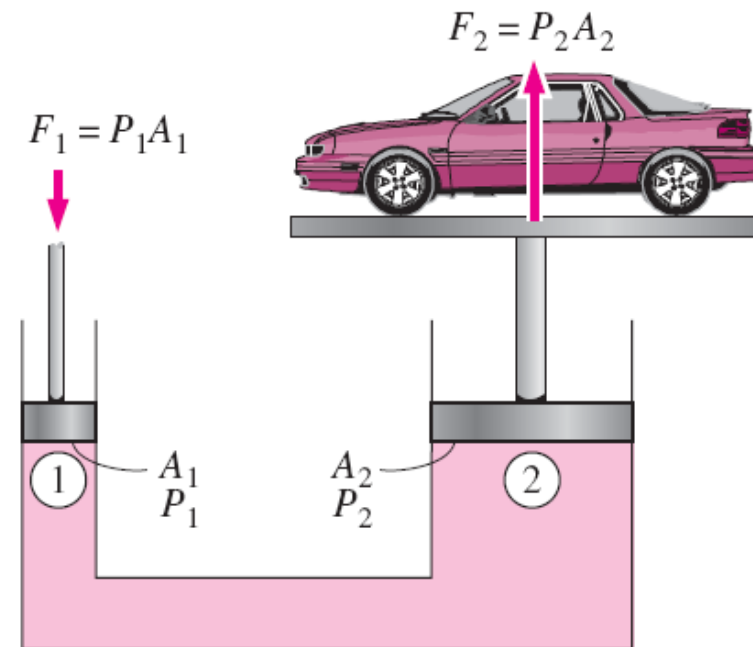
**Pascal's law:** The pressure applied to a confined fluid increases the pressure throughout by the same amount.

$$P_1 = P_2 \quad \rightarrow \quad \frac{F_1}{A_1} = \frac{F_2}{A_2} \quad \rightarrow \quad \frac{F_2}{F_1} = \frac{A_2}{A_1}$$

The area ratio  $A_2/A_1$  is called the *ideal mechanical advantage* of the hydraulic lift.

Using a hydraulic car jack with a piston area ratio of  $A_2/A_1 = 10$ ,

For example, a person can lift a 1000-kg car by applying a force of just 100 kgf ( =908 N)

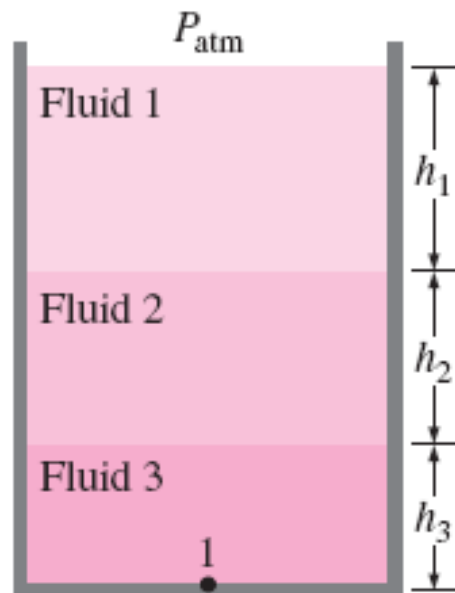


Lifting of a large weight by a small force by the application of Pascal's law.

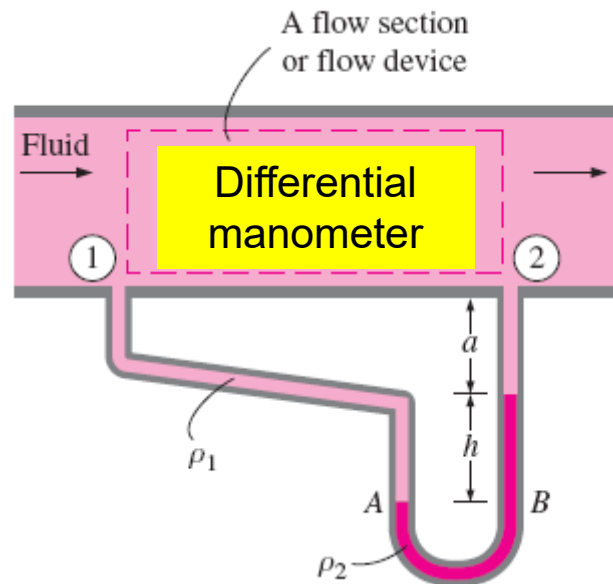
# THE MANOMETER

It is commonly used to measure small and moderate pressure differences. A manometer contains one or more fluids such as mercury, water, alcohol, or oil.

$$P_{\text{atm}} + \rho_1 g h_1 + \rho_2 g h_2 + \rho_3 g h_3 = P_1$$

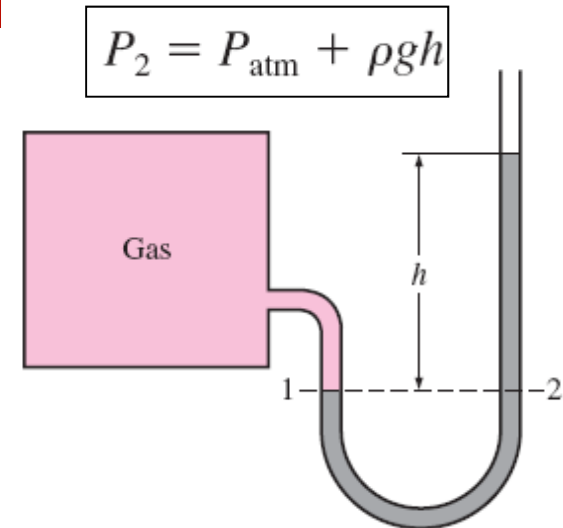


In stacked-up fluid layers, the pressure change across a fluid layer of density  $\rho$  and height  $h$  is  $\rho g h$ .



$$P_1 + \rho_1 g(a + h) - \rho_2 g h - \rho_1 g a = P_2$$

$$P_1 - P_2 = (\rho_2 - \rho_1) g h$$



The basic manometer.

Measuring the pressure drop across a flow section or a flow device

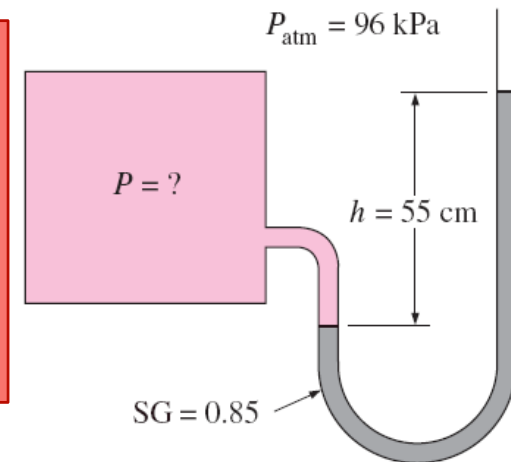
## EXAMPLE 1-6

A manometer is used to measure the pressure in a tank. The fluid used has a specific gravity of 0.85, and the manometer column height is 55 cm. If the local atmospheric pressure is 96 kPa, determine the absolute pressure within the tank.

**Solution** The reading of a manometer attached to a tank and the atmospheric pressure are given. The absolute pressure in the tank is to be determined.

**Assumptions** The fluid in the tank is a gas whose density is much lower than the density of manometer fluid.

**Properties** The specific gravity of the manometer fluid is given to be 0.85. We take the standard density of water to be  $1000 \text{ kg/m}^3$ .



$$\rho = SG (\rho_{\text{H}_2\text{O}}) = (0.85)(1000 \text{ kg/m}^3) = 850 \text{ kg/m}^3$$

$$P = P_{\text{atm}} + \rho gh$$

$$= 96 \text{ kPa} + (850 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(0.55 \text{ m}) \left( \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right) \left( \frac{1 \text{ kPa}}{1000 \text{ N/m}^2} \right)$$

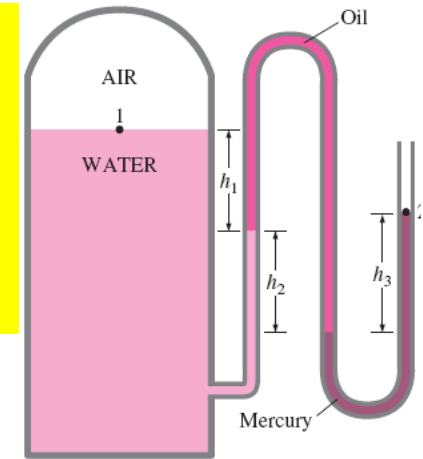
$$= \mathbf{100.6 \text{ kPa}}$$

**Discussion** Note that the gage pressure in the tank is 4.6 kPa.



### EXAMPLE 1-7

The water in a tank is pressurized by air, and the pressure is measured by a multifluid manometer. The tank is located on a mountain at an altitude of 1400 m where the atmospheric pressure is 85.6 kPa. Determine the air pressure in the tank if  $h_1=0.1$  m,  $h_2=0.2$  m, and  $h_3=0.35$  m. Take the densities  $\rho_{\text{water}}=1000$  kg/m<sup>3</sup>,  $\rho_{\text{oil}}=850$  kg/m<sup>3</sup>, and  $\rho_{\text{mercury}}=13,600$  kg/m<sup>3</sup>, respectively.



**Solution** The pressure in a pressurized water tank is measured by a multifluid manometer. The air pressure in the tank is to be determined.

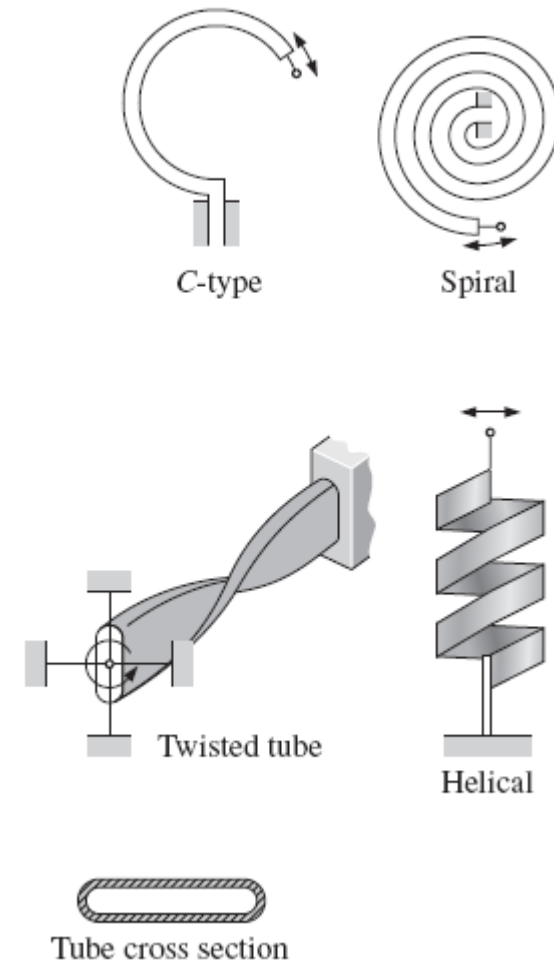
**Assumption** The air pressure in the tank is uniform (i.e., its variation with elevation is negligible due to its low density), and thus we can determine the pressure at the air–water interface.

$$P_1 + \rho_{\text{water}}gh_1 + \rho_{\text{oil}}gh_2 - \rho_{\text{mercury}}gh_3 = P_{\text{atm}}$$

$$\begin{aligned} P_1 &= P_{\text{atm}} - \rho_{\text{water}}gh_1 - \rho_{\text{oil}}gh_2 + \rho_{\text{mercury}}gh_3 \\ &= P_{\text{atm}} + g(\rho_{\text{mercury}}h_3 - \rho_{\text{water}}h_1 - \rho_{\text{oil}}h_2) \\ &= 85.6 \text{ kPa} + (9.81 \text{ m/s}^2)[(13,600 \text{ kg/m}^3)(0.35\text{m}) - 1000 \text{ kg/m}^3)(0.1 \text{ m}) \\ &\quad - (850 \text{ kg/m}^3)(0.2 \text{ m})]\left(\frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2}\right)\left(\frac{1 \text{ kPa}}{1000 \text{ N/M}^2}\right) \\ &= \mathbf{130 \text{ kPa}} \end{aligned}$$

## OTHER PRESSURE MEASUREMENT DEVICES

- **Bourdon tube:** Consists of a hollow metal tube bent like a hook whose end is closed and connected to a dial indicator needle.
- **Pressure transducers:** Use various techniques to convert the pressure effect to an electrical effect such as a change in voltage, resistance, or capacitance.
- Pressure transducers are smaller and faster, and they can be more sensitive, reliable, and precise than their mechanical counterparts.
- **Strain-gage pressure transducers:** Work by having a diaphragm deflect between two chambers open to the pressure inputs.
- **Piezoelectric transducers:** Also called **solid-state pressure transducers**, work on the principle that an electric potential is generated in a crystalline substance when it is subjected to mechanical pressure.

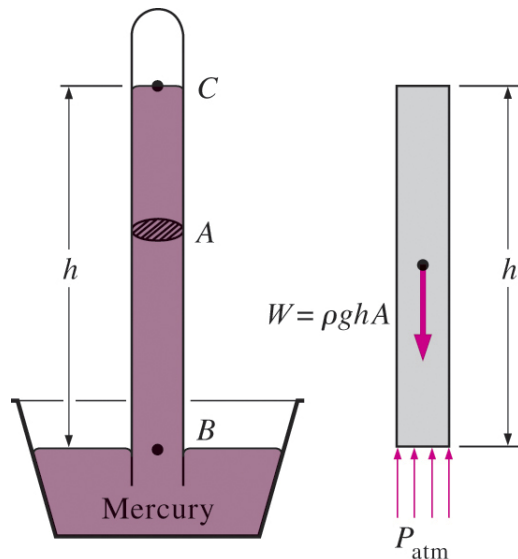


Various types of Bourdon tubes used to measure pressure.

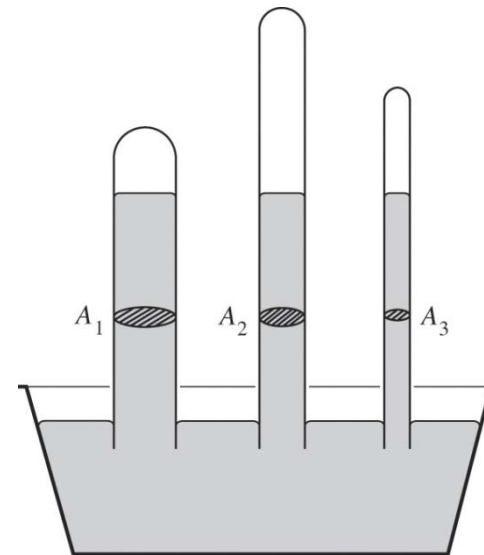
# THE BAROMETER AND ATMOSPHERIC PRESSURE

- Atmospheric pressure is measured by a device called a **barometer**; thus, the atmospheric pressure is often referred to as the **barometric pressure**.
- A frequently used pressure unit is the **standard atmosphere**, which is defined as the pressure produced by a column of mercury 760 mm in height at 0°C ( $\rho_{\text{Hg}} = 13,595 \text{ kg/m}^3$ ) under standard gravitational acceleration ( $g = 9.807 \text{ m/s}^2$ ).

$$P_{\text{atm}} = \rho gh$$



The basic barometer.



The length or the cross-sectional area of the tube has no effect on the height of the fluid column of a barometer, provided that the tube diameter is large enough to avoid surface tension (capillary) effects.

### EXAMPLE 1-8

Determine the atmospheric pressure at a location where the barometric reading is 740 mm Hg and the gravitational acceleration is  $g=9.81 \text{ m/s}^2$ . Assume the temperature of mercury to be  $10^\circ\text{C}$ , at which its density is  $13,570 \text{ kg/m}^3$ .

**Solution** The barometric reading at a location in height of mercury column is given. The atmospheric pressure is to be determined.

**Assumptions** The temperature of mercury is assumed to be  $10^\circ\text{C}$ .

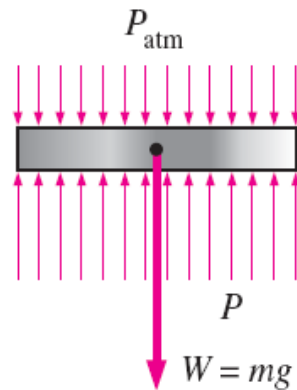
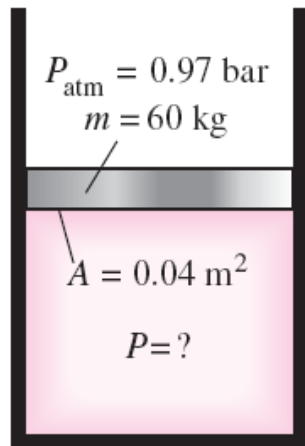
**Properties** The density of mercury is given to be  $13,570 \text{ kg/m}^3$ .

$$\begin{aligned} P_{\text{atm}} &= \rho gh \\ &= (13,570 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(0.74 \text{ m}) \left( \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right) \left( \frac{1 \text{ kPa}}{1000 \text{ N/m}^2} \right) \\ &= \mathbf{98.5 \text{ kPa}} \end{aligned}$$

**Discussion** Note that density changes with temperature, and thus this effect should be considered in calculations.

### EXAMPLE 1-9

The piston of a vertical piston–cylinder device containing a gas has a mass of 60 kg and a cross-sectional area of  $0.04 \text{ m}^2$ . The local atmospheric pressure is 0.97 bar, and the gravitational acceleration is  $9.81 \text{ m/s}^2$ . (a) Determine the pressure inside the cylinder. (b) If some heat is transferred to the gas and its volume is doubled, do you expect the pressure inside the cylinder to change?



**Solution** A gas is contained in a vertical cylinder with a heavy piston. The pressure inside the cylinder and the effect of volume change on pressure are to be determined.  
**Assumptions** Friction between the piston and the cylinder is negligible.

(a) Determine the pressure inside the cylinder

$$PA = P_{\text{atm}}A + W$$

$$P = P_{\text{atm}} + \frac{mg}{A}$$

$$= 0.97 \text{ bar} + \frac{(60 \text{ kg})(9.81 \text{ m/s}^2)}{(0.04 \text{ m}^2)} \left( \frac{1 \text{ N}}{1 \text{ kg} \cdot \text{m/s}^2} \right) \left( \frac{1 \text{ kPa}}{10^5 \text{ N/m}^2} \right) = \mathbf{1.12 \text{ bars}}$$

(b) The volume change will have no effect on the free-body diagram drawn in part (a), and therefore the pressure inside the cylinder will remain the same.

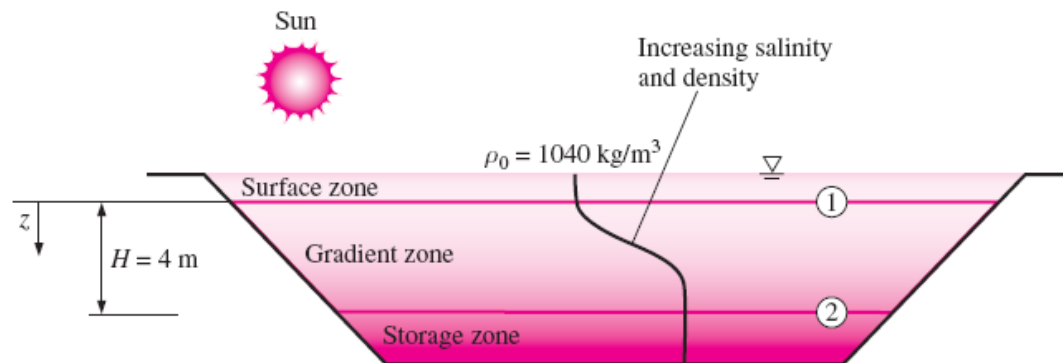
**Discussion** If the gas behaves as an ideal gas, the absolute temperature doubles when the volume is doubled at constant pressure.

## EXAMPLE 1-10

Solar ponds are small artificial lakes of a few meters deep that are used to store solar energy. The rise of heated water to the surface is prevented by adding salt at the pond bottom. In a typical salt gradient solar pond, the density of water increases in the gradient zone and the density can be expressed as;

$$\rho = \rho_0 \sqrt{1 + \tan^2 \left( \frac{\pi}{4} \frac{z}{H} \right)}$$

where  $\rho_0$  is the density on the water surface,  $z$  is the vertical distance measured downward from the top of the gradient zone, and  $H$  is the thickness of the gradient zone. For  $H=4$  m,  $\rho_0=1040$  kg/m<sup>3</sup>, and a thickness of 0.8 m for the surface zone, calculate the gage pressure at the bottom of the gradient zone.



**Solution** The variation of density of saline water in the gradient zone of a solar pond with depth is given. The gage pressure at the bottom of the gradient zone is to be determined.

**Assumptions** The density in the surface zone of the pond is constant.

**Properties** The density of brine on the surface is given to be 1040 kg/m<sup>3</sup>.



$$P_1 = \rho g h_1 = (1040 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(0.8 \text{ m}) \left( \frac{1 \text{ kN}}{1000 \text{ kg} \cdot \text{m/s}^2} \right) = 8.16 \text{ kPa}$$

$$dP = \rho g dz$$

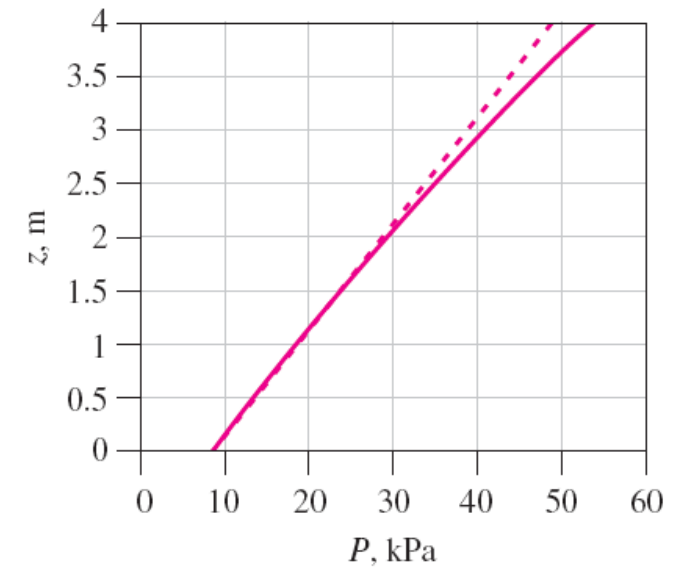
$$P - P_1 = \int_0^z \rho g dz$$

$$P = P_1 + \int_0^z \rho_0 \sqrt{1 + \tan^2 \left( \frac{\pi}{4} \frac{z}{H} \right)} g dz$$

$$P = P_1 + \rho_0 g \frac{4H}{\pi} \sinh^{-1} \left( \tan \frac{\pi}{4} \frac{z}{H} \right)$$

$$P_2 = 8.16 \text{ kPa} + (1040 \text{ kg/m}^3)(9.81 \text{ m/s}^2) \frac{4(4 \text{ m})}{\pi} \sinh^{-1} \left( \tan \frac{\pi}{4} \frac{4}{4} \right) \left( \frac{1 \text{ kN}}{1000 \text{ kg} \cdot \text{m/s}^2} \right)$$

$$= \mathbf{54.0 \text{ kPa (gage)}}$$



The variation of gage pressure with depth in the gradient zone of the solar pond.

**Discussion** the variation of pressure with depth is not linear when density varies with depth.

# PROBLEM-SOLVING TECHNIQUE

- Step 1: Problem Statement
- Step 2: Schematic
- Step 3: Assumptions and Approximations
- Step 4: Physical Laws
- Step 5: Properties
- Step 6: Calculations
- Step 7: Reasoning, Verification, and Discussion

**EES (Engineering Equation Solver)** (Pronounced as ease): EES is a program that solves systems of linear or nonlinear algebraic or differential equations numerically. It has a large library of built-in thermodynamic property functions as well as mathematical functions. Unlike some software packages, EES does not solve engineering problems; it only solves the equations supplied by the user.

# SUMMARY

- Thermodynamics and energy
  - Application areas of thermodynamics
- Importance of dimensions and units
  - Some SI and English units, Dimensional homogeneity, Unity conversion ratios
- Systems and control volumes
- Properties of a system
- Density and specific gravity
- State and equilibrium
  - The state postulate
- Processes and cycles
  - The steady-flow process
- Temperature and the zeroth law of thermodynamics
  - Temperature scales
- Pressure
  - Variation of pressure with depth
- The manometer and the atmospheric pressure
- Problem solving technique

Thermodynamics: An Engineering Approach, 5<sup>th</sup> Edition  
Yunus A. Cengel, Michael A. Boles  
McGraw-Hill, 2008

# Chapter 2

## ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

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# ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

## 2-1 Introduction

## 2-2 Forms of Energy

Some Physical Insight to Internal Energy

More on Nuclear Energy

Mechanical Energy

## 2-3 Energy Transfer by Heat

Historical Background on Heat

## 2-4 Energy Transfer by Work

Electrical Work

## 2-5 Mechanical Forms of Work

Shaft Work, Spring Work

Work Done on Elastic Solid Bars

Work Associated with the Stretching of a Liquid Film

Work Done to Raise or to Accelerate a Body

Nonmechanical Forms of Work

## 2-6 The First Law of Thermodynamics

Energy Balance

Energy Change of a System,  $\Delta E_{\text{system}}$

Mechanisms of Energy Transfer,  $\Delta E_{\text{in}}$  and  $\Delta E_{\text{out}}$

## 2-7 Energy Conversion Efficiencies

Efficiencies of Mechanical and Electrical Devices

## 2-8 Energy and Environment

Ozone and Smog, Acid Rain

The Greenhouse Effect: Global Warming and Climate Change

# Objectives

- Introduce the concept of energy and define its various forms.
- Discuss the nature of internal energy.
- Define the concept of heat and the terminology associated with energy transfer by heat.
- Discuss the three mechanisms of heat transfer: conduction, convection, and radiation.
- Define the concept of work, including electrical work and several forms of mechanical work.
- Introduce the first law of thermodynamics, energy balances, and mechanisms of energy transfer to or from a system.
- Determine that a fluid flowing across a control surface of a control volume carries energy across the control surface in addition to any energy transfer across the control surface that may be in the form of heat and/or work.
- Define energy conversion efficiencies.
- Discuss the implications of energy conversion on the environment.



# INTRODUCTION

- If we take the entire room—including the air and the refrigerator (or fan)—as the system, which is an adiabatic closed system since the room is well-sealed and well-insulated, the only energy interaction involved is the electrical energy crossing the system boundary and entering the room.
- As a result of the conversion of electric energy consumed by the device to heat, **the room temperature will rise.**



A refrigerator operating with its door open in a well-sealed and well-insulated room



A fan running in a well-sealed and well-insulated room will raise the temperature of air in the room.

# FORMS OF ENERGY

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy,  $E$**  of a system.
  - Thermodynamics deals only with the **change** of the total energy.
  - **Macroscopic forms of energy:** Those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.
  - **Microscopic forms of energy:** Those related to the molecular structure of a system and the degree of the molecular activity.
  - **Internal energy,  $U$ :** The sum of all the microscopic forms of energy.
- **Kinetic energy, KE:** The energy that a system possesses as a result of its motion relative to some reference frame.
  - **Potential energy, PE:** The energy that a system possesses as a result of its elevation in a gravitational field.



The macroscopic energy of an object changes with velocity and elevation.

$$KE = m \frac{V^2}{2} \quad (\text{kJ})$$

Kinetic energy

$$ke = \frac{V^2}{2} \quad (\text{kJ/kg})$$

Kinetic energy per unit mass

$$PE = mgz \quad (\text{kJ})$$

Potential energy

$$pe = gz \quad (\text{kJ/kg})$$

Potential energy per unit mass

Total energy of a system

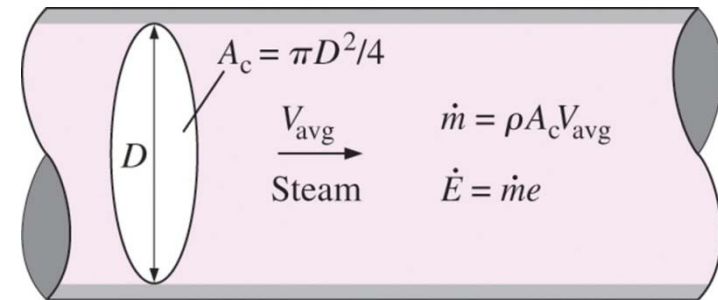
$$E = U + KE + PE = U + m \frac{V^2}{2} + mgz \quad (\text{kJ})$$

Energy of a system per unit mass

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \quad (\text{kJ/kg})$$

Total energy per unit mass

$$e = \frac{E}{m} \quad (\text{kJ/kg})$$



Mass flow rate

$$\dot{m} = \rho \dot{V} = \rho A_c V_{avg} \quad (\text{kg/s})$$

Energy flow rate

$$\dot{E} = \dot{m}e \quad (\text{kJ/s or kW})$$

## EXAMPLE 2-1

A site evaluated for a wind farm is observed to have steady winds at a speed of 8.5 m/s. Determine the wind energy (a) per units mass, (b) for a mass of 10 kg, and (c) for a flow rate of 1154 kg/s for air.

**Solution** A site with a specified wind speed is considered. Wind energy per unit mass, for a specified mass, and for a given mass flow rate of air are to be determined.

**Assumptions** Wind flows steadily at the specified speed.

(a) Wind energy per unit mass of air is

$$e = ke = \frac{V^2}{2} = \frac{(8.5 \text{ m/s})^2}{2} \left( \frac{1 \text{ J/kg}}{1 \text{ m}^2/\text{s}^2} \right) = \mathbf{36.1 \text{ J/kg}}$$

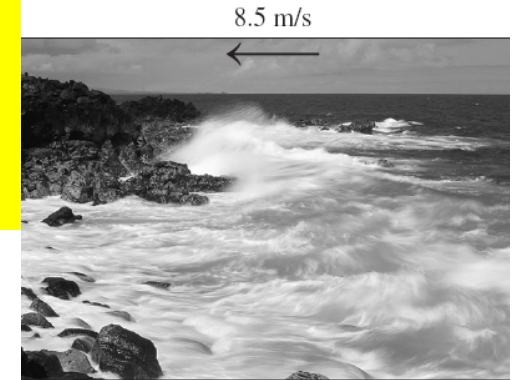
(b) Wind energy for an air mass of 10 kg is

$$E = me = (10 \text{ kg})(36.1 \text{ J/kg}) = \mathbf{361 \text{ J}}$$

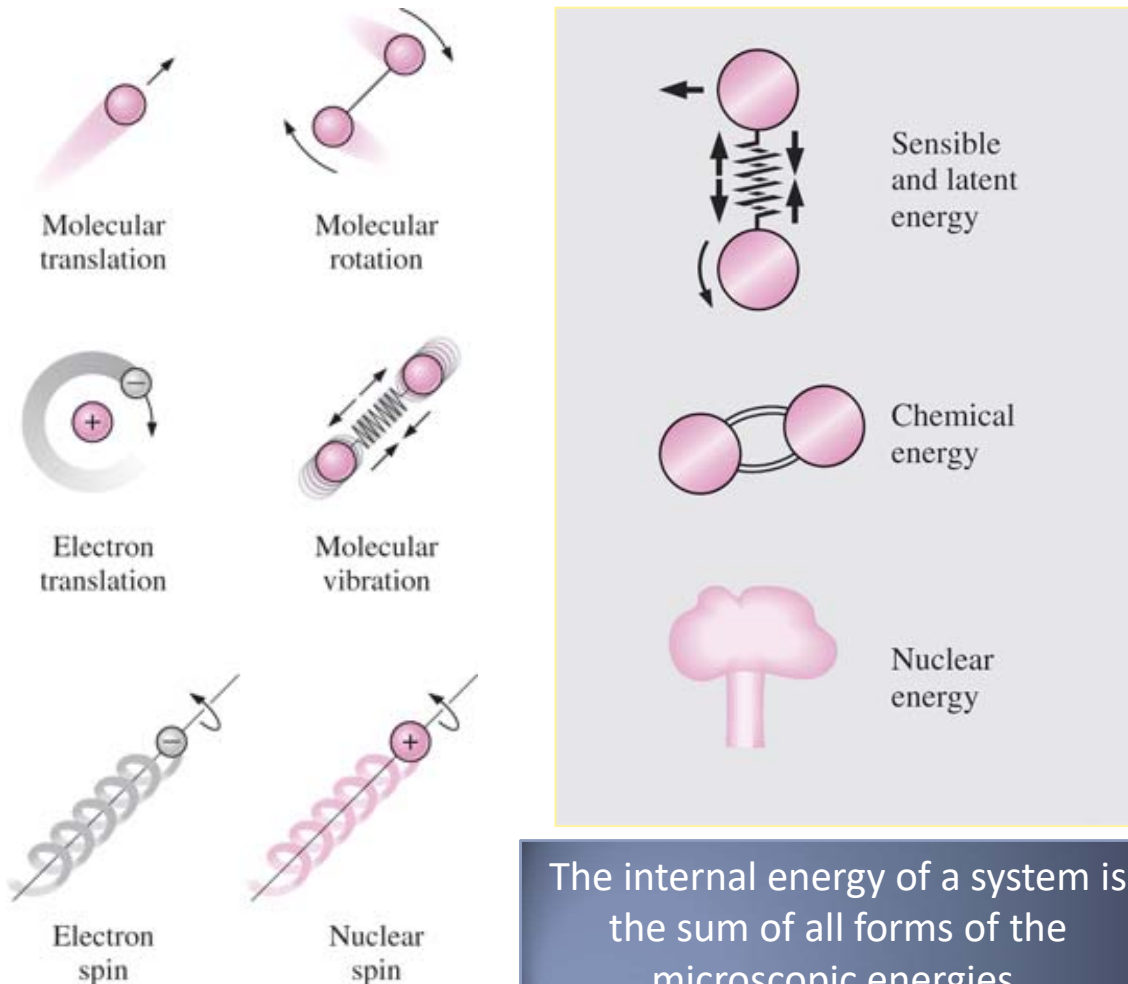
(c) Wind energy for a mass flow rate of 1154 kg/s is

$$\dot{E} = \dot{m}e = (1154 \text{ kg/s})(36.1 \text{ J/kg}) \left( \frac{1 \text{ kW}}{1000 \text{ J/s}} \right) = \mathbf{41.7 \text{ kW}}$$

**Discussion** It can be shown that the specified mass flow rate corresponds to a 12-m diameter flow section when the air density is 1.2 kg/m<sup>3</sup>. Therefore, a wind turbine with a wind span diameter of 12 m has a power generation potential of 41.7 kW. Real wind turbines convert about one-third of this potential to electric power.



# SOME PHYSICAL INSIGHT TO INTERNAL ENERGY



The various forms of microscopic energies that make up *sensible* energy.

The internal energy of a system is the sum of all forms of the microscopic energies.

**Sensible energy:** The portion of the internal energy of a system associated with the kinetic energies of the molecules.

**Latent energy:** The internal energy associated with the phase of a system.

**Chemical energy:** The internal energy associated with the atomic bonds in a molecule.

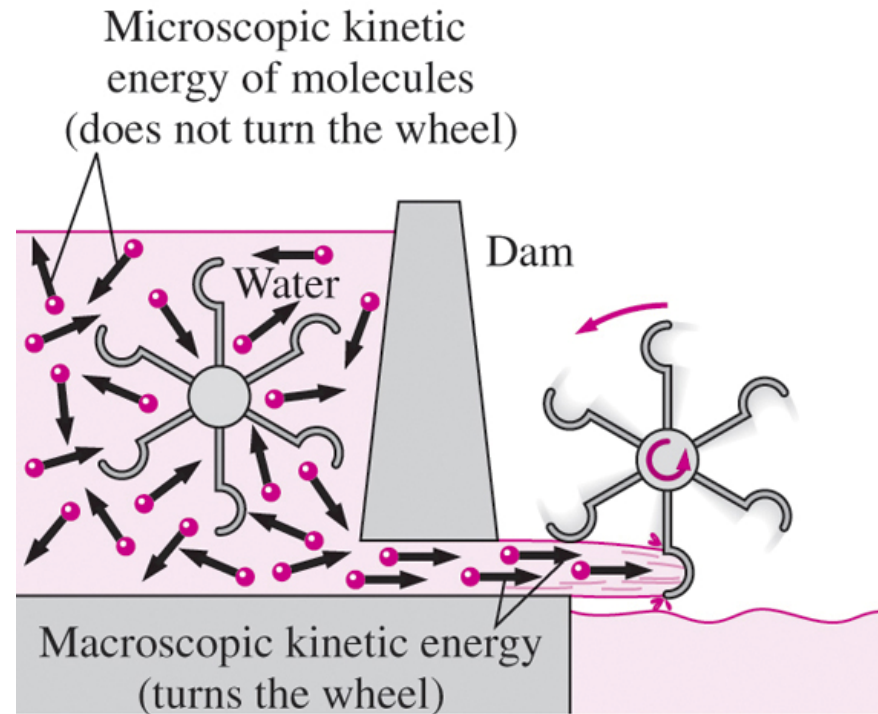
**Nuclear energy:** The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself.

**Thermal = Sensible + Latent**

**Internal = Sensible + Latent + Chemical + Nuclear**



- The total energy of a system, can be *contained* or *stored* in a system, and thus can be viewed as the **static forms of energy**.
- The forms of energy not stored in a system can be viewed as the **dynamic forms of energy** or as **energy interactions**.
- The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process.
- The only two forms of energy interactions associated with a closed system are **heat transfer** and **work**.

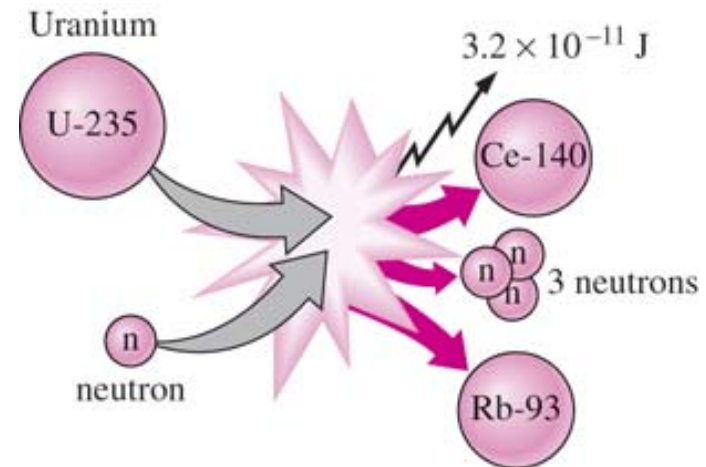


The *macroscopic* kinetic energy is an organized form of energy and is much more useful than the disorganized *microscopic* kinetic energies of the molecules.

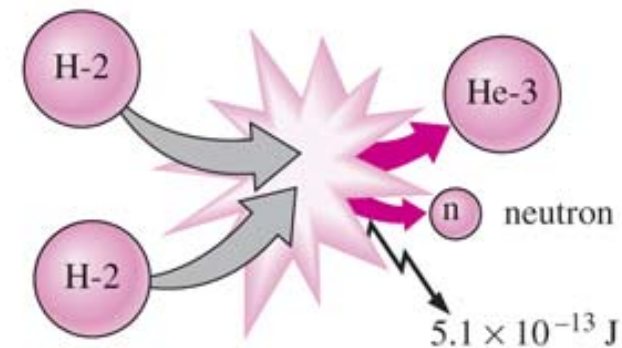
**The difference between heat transfer and work:** An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise it is work.

## MORE ON NUCLEAR ENERGY

- The best known **fission** reaction involves the split of the uranium atom (the U-235 isotope) into other elements and is commonly used to generate electricity in nuclear power plants (440 of them in 2004, generating 363,000 MW worldwide), to power nuclear submarines and aircraft carriers, and even to power spacecraft as well as building nuclear bombs.
- Nuclear energy by **fusion** is released when two small nuclei combine into a larger one.
- The uncontrolled fusion reaction was achieved in the early 1950s, but all the efforts since then to achieve controlled fusion by massive lasers, powerful magnetic fields, and electric currents to generate power have failed.



(a) Fission of uranium



(b) Fusion of hydrogen

The fission of uranium and the fusion of hydrogen during nuclear reactions, and the release of nuclear energy.



## EXAMPLE 2-2

An average car consumes about 5 L of gasoline a day, and the capacity of the fuel tank of a car is about 50 L. Therefore, a car needs to be refueled once every 10 days. Also, the density of gasoline ranges from 0.68 to 0.78 kg/L, and its lower heating value is about 44,000 kJ/kg (that is, 44,000 kJ of heat is released when 1 kg of gasoline is completely burned). Suppose all the problems associated with the radioactivity and waste disposal of nuclear fuels are resolved, and a car is to be powered by U-235. If a new car comes equipped with 0.1-kg of the nuclear fuel U-235, determine if this car will ever need refueling under average driving conditions.

Nuclear  
fuel



**Solution** A car powered by nuclear energy comes equipped with nuclear fuel. It is to be determined if this car will ever need refueling.

**Assumptions** 1 Gasoline is an incompressible substance with an average density of 0.75 kg/L. 2 Nuclear fuel is completely converted to thermal energy

$$m_{\text{gasoline}} = (\rho V)_{\text{gasoline}} = (0.75 \text{ kg/L})(5 \text{ L/day}) = 3.75 \text{ kg/day}$$

$$E = (m_{\text{gasoline}})(\text{Heating value}) = (3.75 \text{ kg/day})(44,000 \text{ kJ/kg}) = 165,000 \text{ kJ/day}$$

$$(6.73 \times 10^{10} \text{ kJ/kg})(0.1 \text{ kg}) = 6.73 \times 10^9 \text{ kJ}$$

$$\text{No. of days} = \frac{\text{Energy content of fuel}}{\text{Daily energy use}} = \frac{6.73 \times 10^9 \text{ kJ}}{165,000 \text{ kJ/day}} = \mathbf{40,790 \text{ days}}$$

**Discussion** The necessary critical mass cannot be achieved with such a small amount of fuel. Further, all of the uranium cannot be converted in fission, again because of the critical mass problems after partial conversion.

# MECHANICAL ENERGY

**Mechanical energy:** The form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.

**Kinetic and potential energies:** The familiar forms of mechanical energy.

Mechanical energy of a flowing fluid per unit mass

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

Rate of mechanical energy of a flowing fluid

$$\dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Mechanical energy change of a fluid during incompressible flow per unit mass

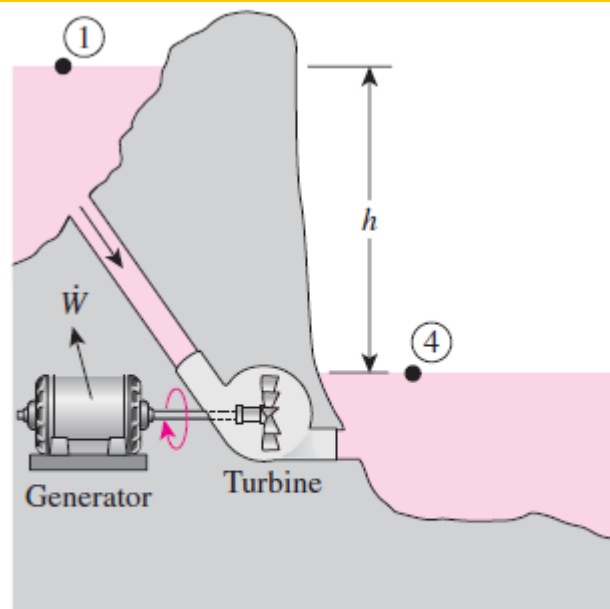
$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \quad (\text{kJ/kg})$$

Rate of mechanical energy change of a fluid during incompressible flow

$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right)$$

Mechanical energy is illustrated by an ideal hydraulic turbine coupled with an ideal generator. In the absence of irreversible losses, the maximum produced power is proportional to

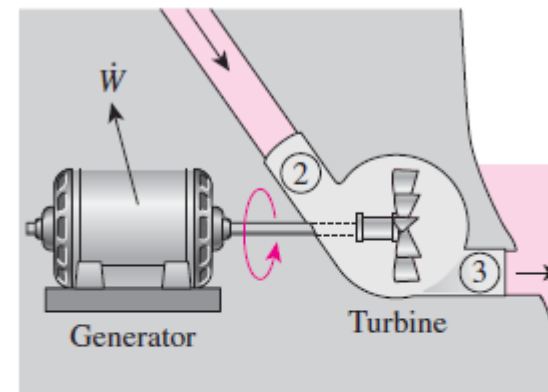
- (a) the change in water surface elevation from the upstream to the downstream reservoir
- (b) the drop in water pressure from just upstream to just downstream of the turbine.



$$\dot{W}_{\max} = \dot{m} \Delta e_{\text{mech}} = \dot{m} g (z_1 - z_4) = \dot{m} g h$$

since  $P_1 \approx P_4 = P_{\text{atm}}$  and  $V_1 = V_4 \approx 0$

(a)



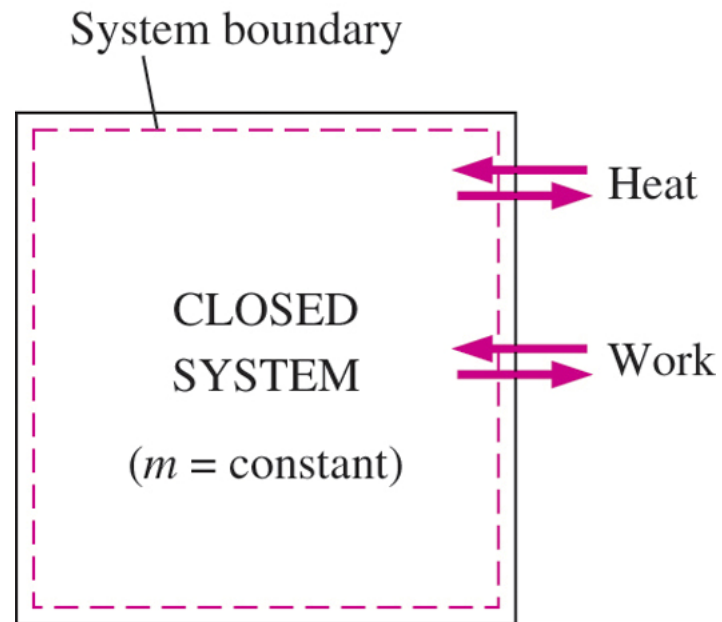
$$\dot{W}_{\max} = \dot{m} \Delta e_{\text{mech}} = \dot{m} \frac{(P_2 - P_3)}{\rho} = \dot{m} \frac{\Delta P}{\rho}$$

since  $V_2 \approx V_3$  and  $z_2 = z_3$

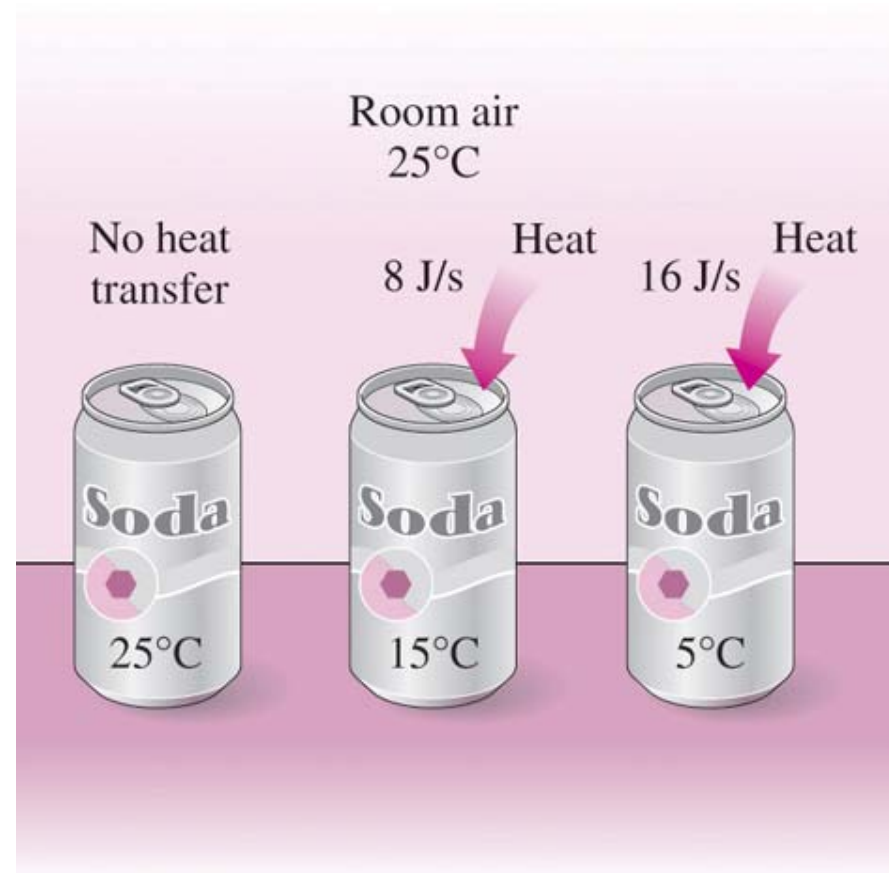
(b)

# ENERGY TRANSFER BY HEAT

**Heat:** The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.



Energy can cross the boundaries of a closed system in the form of heat and work.



Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

Heat transfer per unit mass

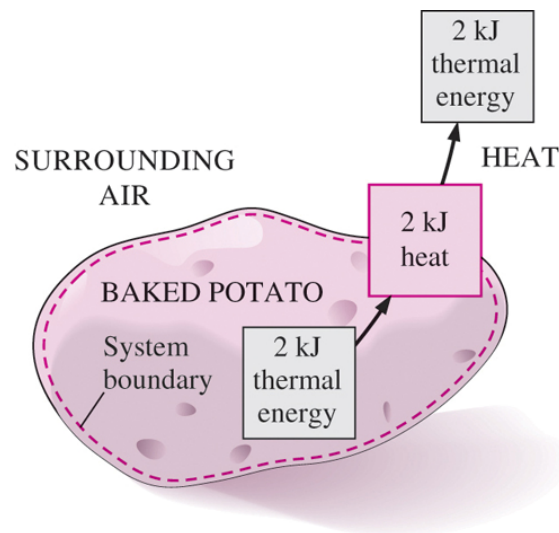
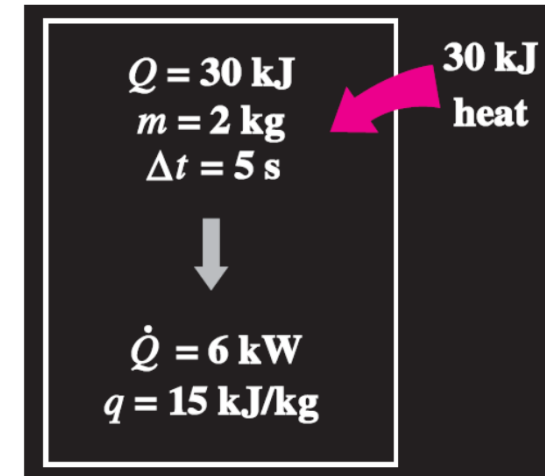
$$q = \frac{Q}{m} \quad (\text{kJ/kg})$$

Amount of heat transfer when heat transfer rate is constant

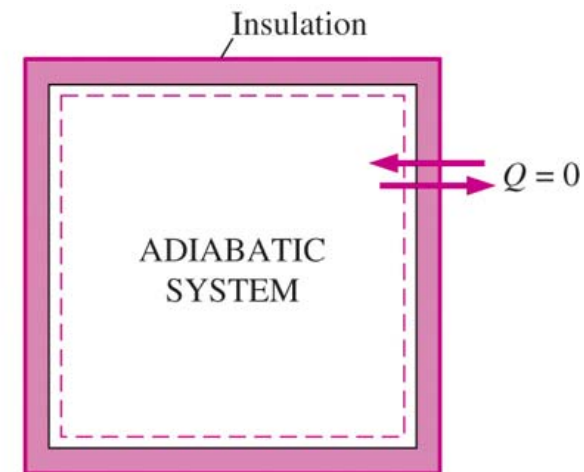
$$Q = \dot{Q} \Delta t \quad (\text{kJ})$$

Amount of heat transfer when heat transfer rate changes with time

$$Q = \int_{t_1}^{t_2} \dot{Q} dt$$



Energy is recognized as heat transfer only as it crosses the system boundary.



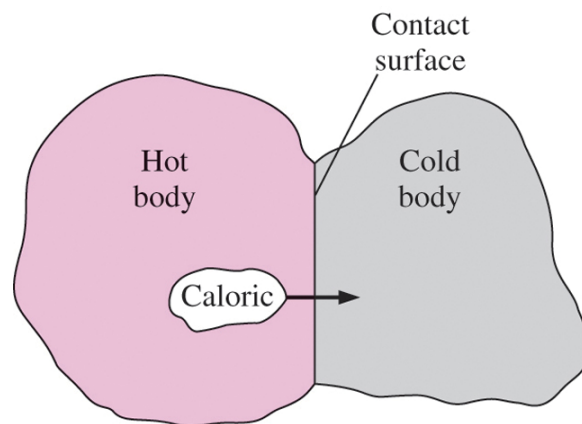
During an adiabatic process, a system exchanges no heat with its surroundings.

# HISTORICAL BACKGROUND ON HEAT

- **Kinetic theory:** Treats molecules as tiny balls that are in motion and thus possess kinetic energy.
- **Heat:** The energy associated with the random motion of atoms and molecules.

## Heat transfer mechanisms:

- **Conduction:** The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between particles.
- **Convection:** The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.
- **Radiation:** The transfer of energy due to the emission of electromagnetic waves (or photons).



In the early nineteenth century, heat was thought to be an invisible fluid called the *caloric* that flowed from warmer bodies to the cooler ones.

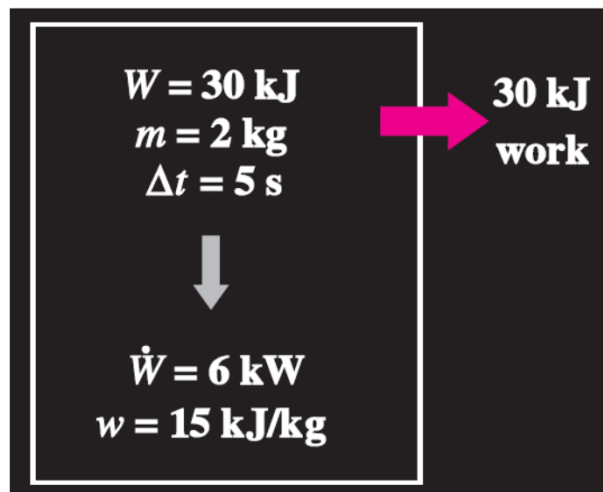


# ENERGY TRANSFER BY WORK

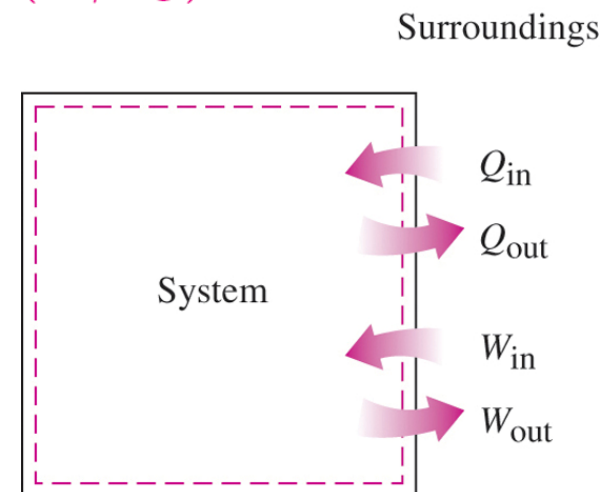
- **Work:** The energy transfer associated with a force acting through a distance.
  - **A rising piston, a rotating shaft, and an electric wire crossing the system boundaries** are all associated with work interactions
- **Formal sign convention:** *Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative.*
- Alternative to sign convention is to use the subscripts **in** and **out** to indicate direction. This is the primary approach in this text.

Work done per unit mass

$$w = \frac{W}{m} \quad (\text{kJ/kg})$$



Power is the work done per unit time (kW)



Specifying the directions of heat and work.



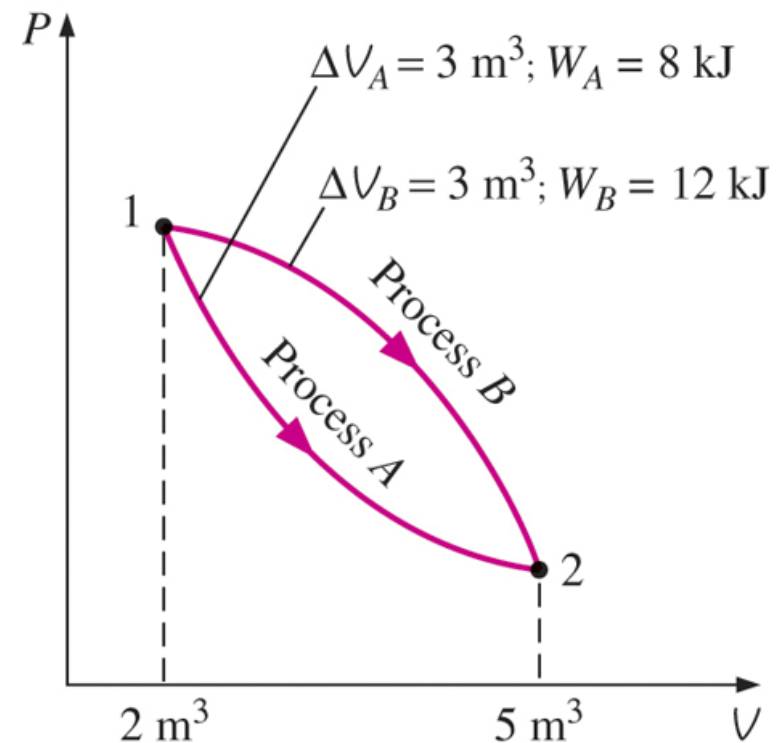
# Heat versus Work

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are **boundary** phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a **process**, not a state.
- Unlike properties, heat or work has no meaning at a state.
- Both are **path functions** (i.e., their magnitudes depend on the path followed during a process as well as the end states).

Properties are point functions have exact differentials ( $d$ ).

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

Path functions have inexact differentials ( $\delta$ )



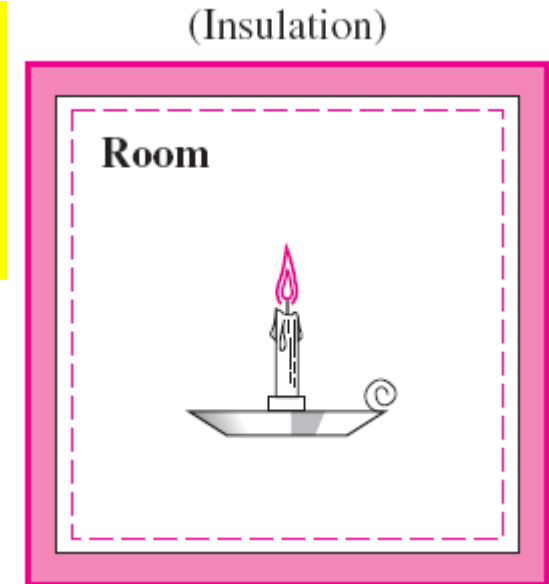
Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

$$\int_1^2 \delta W = W_{12} \quad (\text{not } \Delta W)$$

### EXAMPLE 2-3

A candle is burning in a well-insulated room. Taking the room (the air plus the candle) as the system, determine (a) if there is any heat transfer during this burning process and (b) if there is any change in the internal energy of the system.

**Solution** A candle burning in a well-insulated room is considered. It is to be determined whether there is any heat transfer and any change in internal energy.



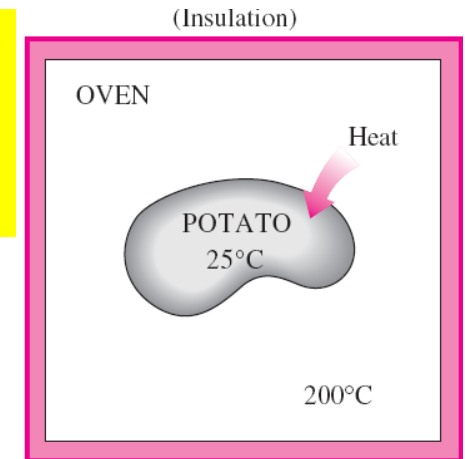
**Analysis** (a) The interior surfaces of the room form the system boundary, as indicated by the dashed lines in Figure. As pointed out earlier, heat is recognized as it crosses the boundaries. Since the room is well insulated, we have an adiabatic system and no heat will pass through the boundaries. Therefore,  $Q = 0$  for this process.

(b) The internal energy involves energies that exist in various forms (sensible, latent, chemical, nuclear). During the process just described, part of the chemical energy is converted to sensible energy. Since there is no increase or decrease in the total internal energy of the system,  $\Delta U = 0$  for this process.

### EXAMPLE 2-4

A potato initially at room temperature ( $25^{\circ}\text{C}$ ) is being baked in an oven that is maintained at  $200^{\circ}\text{C}$ , as shown in Figure. Is there any heat transfer during this baking process?

**Solution** A potato is being baked in an oven. It is to be determined whether there is any heat transfer during this process.

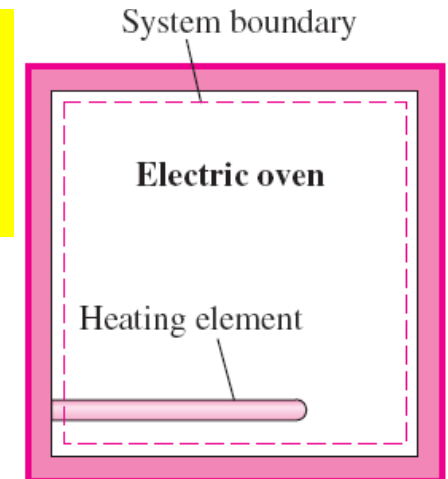


**Analysis** This is not a well-defined problem since the system is not specified. Let us assume that we are observing the potato, which will be our system. Then the skin of the potato can be viewed as the system boundary. Part of the energy in the oven will pass through the skin to the potato. Since the driving force for this energy transfer is a temperature difference, this is a heat transfer process.

### EXAMPLE 2-5

A well-insulated electric oven is being heated through its heating element. If the entire oven, including the heating element, is taken to be the system, determine whether this is a heat or work interaction.

**Solution** A well-insulated electric oven is being heated by its heating element. It is to be determined whether this is a heat or work interaction.

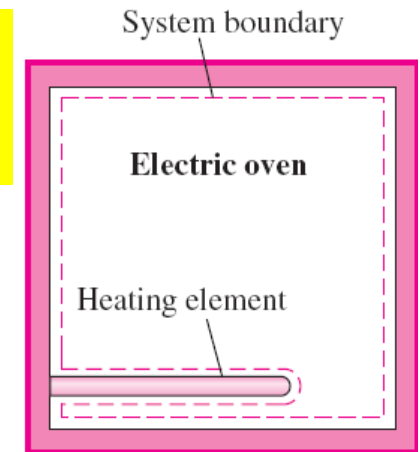


**Analysis** For this problem, the interior surfaces of the oven form the system boundary, as shown in Figure. The energy content of the oven obviously increases during this process, as evidenced by a rise in temperature. This energy transfer to the oven is not caused by a temperature difference between the oven and the surrounding air. Instead, it is caused by *electrons* crossing the system boundary and thus doing work. Therefore, this is a work interaction.

### EXAMPLE 2-6

Answer the question in Example 2–5 if the system is taken as only the air in the oven without the heating element.

**Solution** The question in Example 2–5 is to be reconsidered by taking the system to be the air in the oven only.



**Analysis** This time, the system boundary will include the outer surface of the heating element and will not cut through it, as shown in Figure. Therefore, no electrons will be crossing the system boundary at any point. Instead, the energy generated in the interior of the heating element will be transferred to the air around it as a result of the temperature difference between the heating element and the air in the oven. Therefore, this is a heat transfer process.

**Discussion** For both cases, the amount of energy transfer to the air is the same. These two examples show that the same interaction can be heat or work, depending on how the system is selected.

# ELECTRICAL WORK

Electrical work

$$W_e = \mathbf{V}N$$

Electrical power

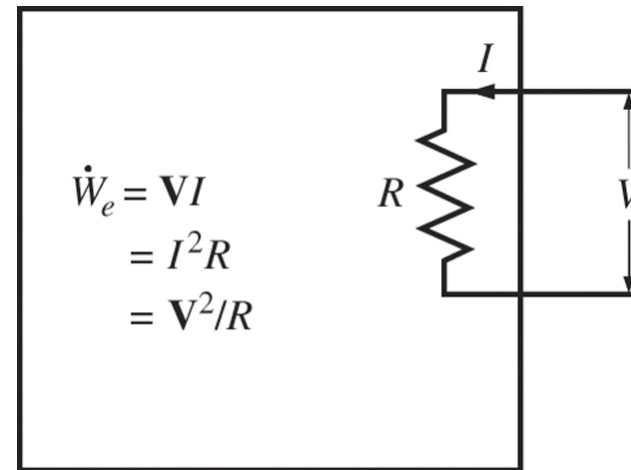
$$\dot{W}_e = \mathbf{V}I \quad (\text{W})$$

When potential difference and current change with time

$$W_e = \int_1^2 \mathbf{V}I \, dt \quad (\text{kJ})$$

When potential difference and current remain constant

$$W_e = \mathbf{V}I \, \Delta t \quad (\text{kJ})$$



Electrical power in terms of resistance  $R$ , current  $I$ , and potential difference  $\mathbf{V}$ .

# MECHANICAL FORMS OF WORK

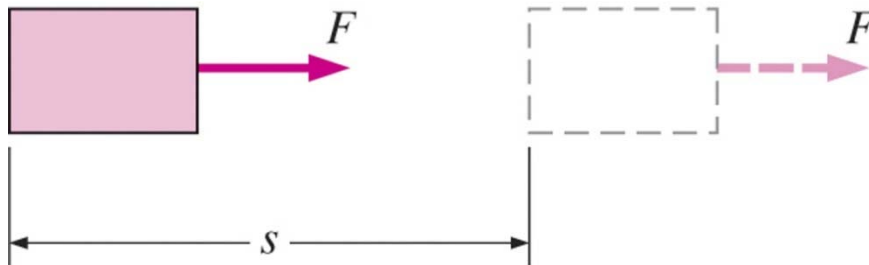
- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a **force** acting on the boundary.
  - the boundary must **move**.

Work = Force  $\times$  Distance

$$W = Fs \quad (\text{kJ})$$

When force is not constant

$$W = \int_1^2 F ds \quad (\text{kJ})$$



The work done is proportional to the force applied ( $F$ ) and the distance traveled ( $s$ ).



If there is no movement, no work is done.



# SHAFT WORK

A force  $F$  acting through a moment arm  $r$  generates a torque  $T$

$$T = Fr \rightarrow F = \frac{T}{r}$$

This force acts through a distance  $s$

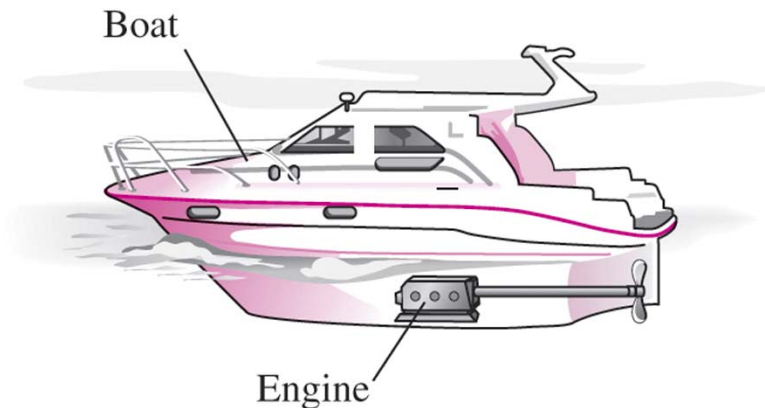
$$s = (2\pi r)n$$

## Shaft work

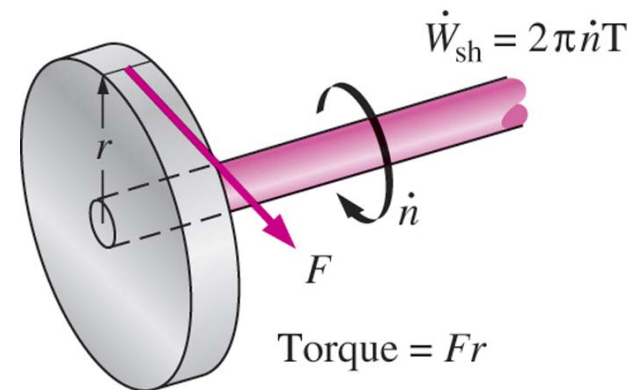
$$W_{\text{sh}} = Fs = \left(\frac{T}{r}\right)(2\pi rn) = 2\pi nT \quad (\text{kJ})$$

The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{\text{sh}} = 2\pi \dot{n}T \quad (\text{kW})$$



Energy transmission through rotating shafts is commonly encountered in practice.

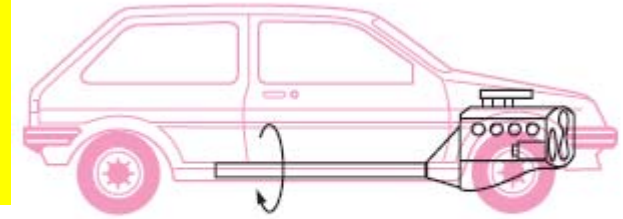


Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

### EXAMPLE 2-7

Determine the power transmitted through the shaft of a car when the torque applied is  $200 \text{ N} \cdot \text{m}$  and the shaft rotates at a rate of 4000 revolutions per minute (rpm).

**Solution** The torque and the rpm for a car engine are given. The power transmitted is to be determined.



$$n = 4000 \text{ rpm}$$

$$\tau = 200 \text{ Nm}$$

$$\begin{aligned}\dot{W}_{\text{sh}} &= 2\pi nT = (2\pi) \left( 4000 \frac{1}{\text{min}} \right) (200 \text{ N} \cdot \text{m}) \left( \frac{1 \text{ min}}{60 \text{ s}} \right) \left( \frac{1 \text{ kJ}}{1000 \text{ N} \cdot \text{m}} \right) \\ &= \mathbf{83.8 \text{ kW}} \quad (\text{or } 112 \text{ hp})\end{aligned}$$

**Discussion** Note that power transmitted by a shaft is proportional to torque and the rotational speed.

# SPRING WORK

When the length of the spring changes by a differential amount  $dx$  under the influence of a force  $F$ , the work done is

$$\delta W_{\text{spring}} = F dx$$

Substituting and integrating yield

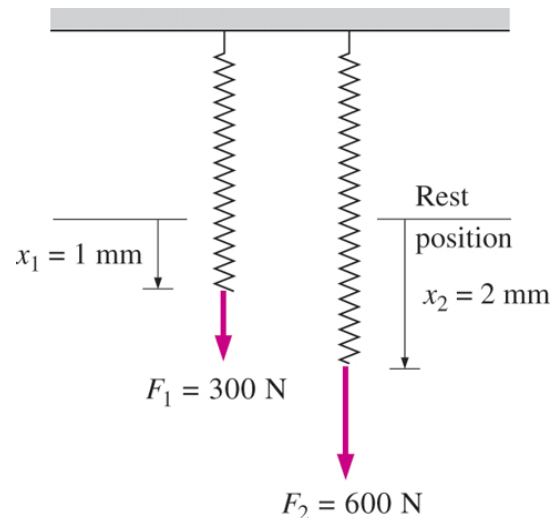
$$W_{\text{spring}} = \frac{1}{2}k(x_2^2 - x_1^2) \quad (\text{kJ})$$

$x_1$  and  $x_2$ : the initial and the final displacements

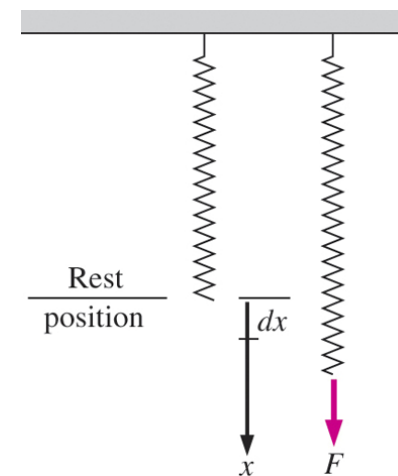
For linear elastic springs, the displacement  $x$  is proportional to the force applied

$$F = kx \quad (\text{kN})$$

$k$ : spring constant (kN/m)



The displacement of a linear spring doubles when the force is doubled.



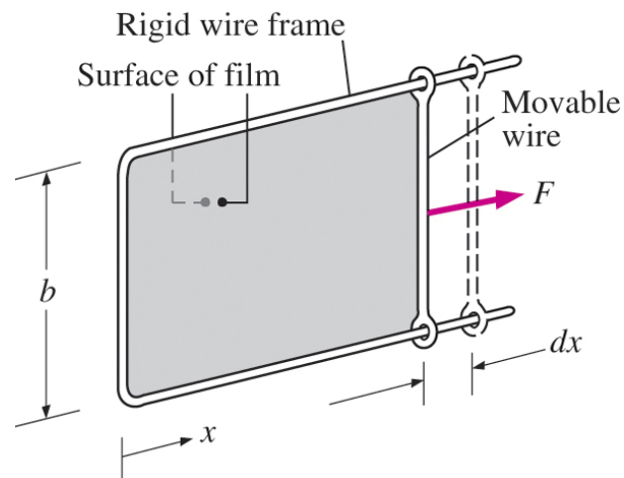
Elongation of a spring under the influence of a force.

# WORK DONE ON ELASTIC SOLID BARS

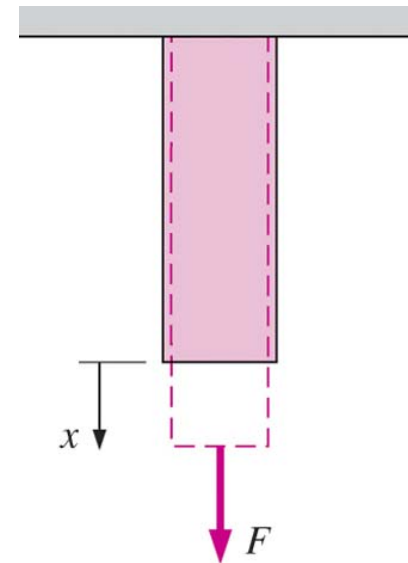
$$W_{\text{elastic}} = \int_1^2 F dx = \int_1^2 \sigma_n A dx \quad (\text{kJ})$$

## Work Associated with the Stretching of a Liquid Film

$$W_{\text{surface}} = \int_1^2 \sigma_s dA \quad (\text{kJ})$$



Stretching a liquid film with a movable wire.



Solid bars behave as springs under the influence of a force.

# WORK DONE TO RAISE OR TO ACCELERATE A BODY

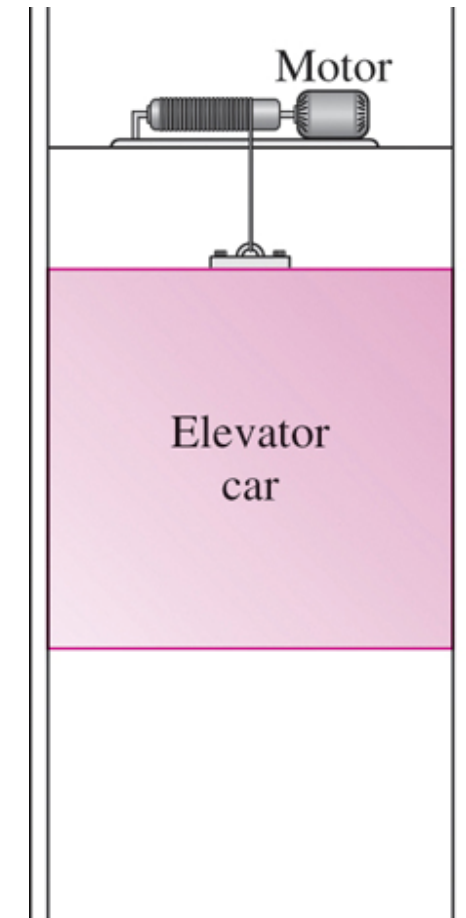
1. The work transfer needed to raise a body is equal to the change in the potential energy of the body.
2. The work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body.

## Non-mechanical Forms of Work

**Electrical work:** The generalized force is the *voltage* (the electrical potential) and the generalized displacement is the *electrical charge*.

**Magnetic work:** The generalized force is the *magnetic field strength* and the generalized displacement is the total *magnetic dipole moment*.

**Electrical polarization work:** The generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium*.



The energy transferred to a body while being raised is equal to the change in its potential energy.

### EXAMPLE 2-8

Consider a 1200-kg car cruising steadily on a level road at 90 km/h. Now the car starts climbing a hill that is sloped 30° from the horizontal. If the velocity of the car is to remain constant during climbing, determine the additional power that must be delivered by the engine.

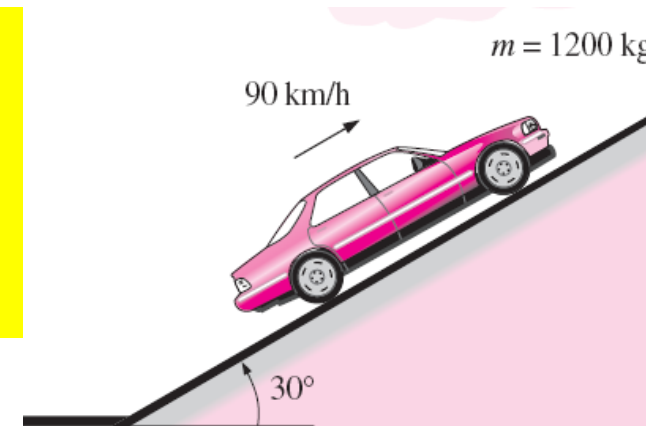
**Solution** A car is to climb a hill while maintaining a constant velocity. The additional power needed is to be determined.

**Analysis** The additional power required is simply the work that needs to be done per unit time to raise the elevation of the car, which is equal to the change in the potential energy of the car per unit time:

$$\dot{W}_g = mg \Delta z / \Delta t = mgV_{\text{vertical}}$$

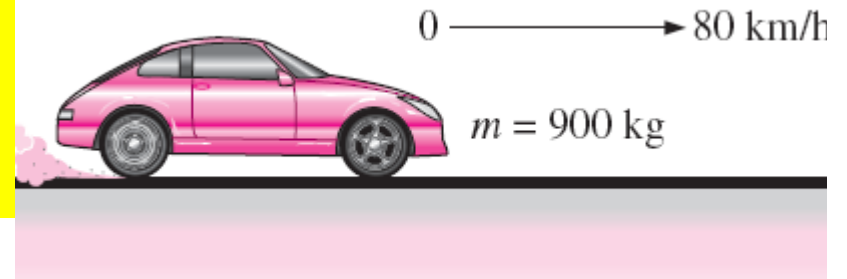
$$\begin{aligned} &= (1200 \text{ kg})(9.81 \text{ m/s}^2)(90 \text{ km/h})(\sin 30^\circ) \left( \frac{1 \text{ m/s}}{3.6 \text{ km/h}} \right) \left( \frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) \\ &= 147 \text{ kJ/s} = \mathbf{147 \text{ kW}} \quad (\text{or } 197 \text{ hp}) \end{aligned}$$

**Discussion** Note that the car engine will have to produce almost 200 hp of additional power while climbing the hill if the car is to maintain its velocity.



### EXAMPLE 2-9

Determine the power required to accelerate a 900-kg car shown in Figure from rest to a velocity of 80 km/h in 20 s on a level road.



**Solution** The power required to accelerate a car to a specified velocity is to be determined.

$$W_a = \frac{1}{2}m(V_2^2 - V_1^2) = \frac{1}{2}(900 \text{ kg}) \left[ \left( \frac{80,000 \text{ m}}{3600 \text{ s}} \right)^2 - 0^2 \right] \left( \frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right)$$
$$= 222 \text{ kJ}$$

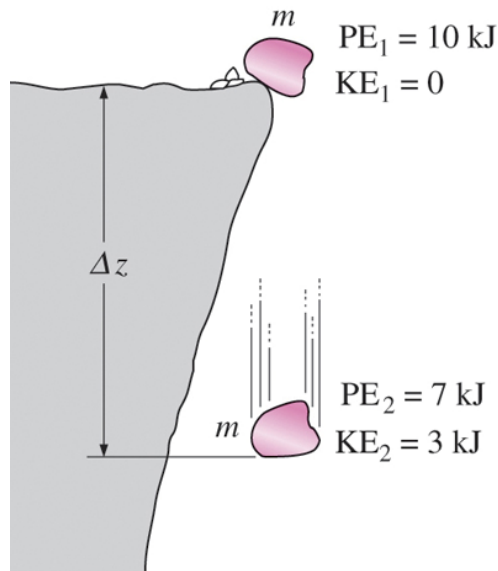
$$\dot{W}_a = \frac{W_a}{\Delta t} = \frac{222 \text{ kJ}}{20 \text{ s}} = \mathbf{11.1 \text{ kW}} \quad (\text{or } 14.9 \text{ hp})$$

**Discussion** This is in addition to the power required to overcome friction, rolling resistance, and other imperfections.

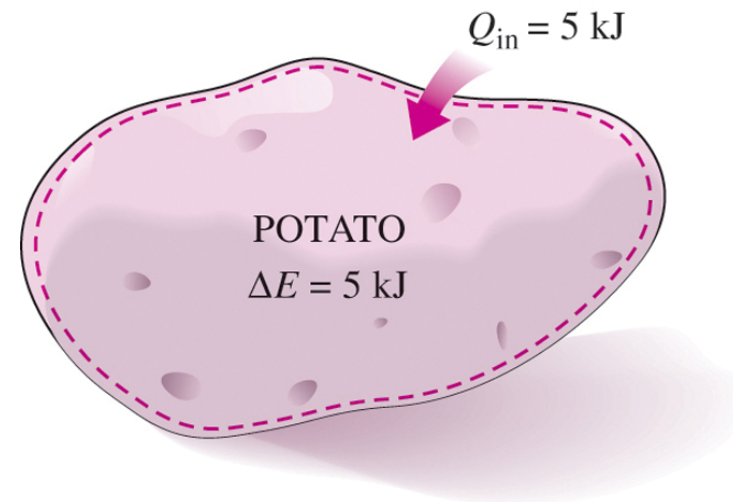


# THE FIRST LAW OF THERMODYNAMICS

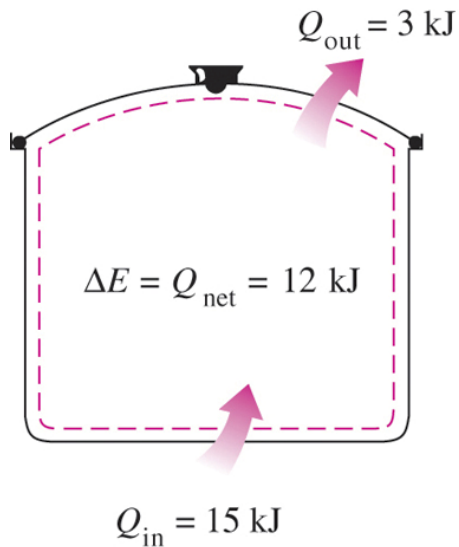
- **The first law of thermodynamics (the conservation of energy principle)** provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- The first law states that **energy can be neither created nor destroyed during a process; it can only change forms.**
- **The First Law:** For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.



Energy cannot be created or destroyed; it can only change forms.

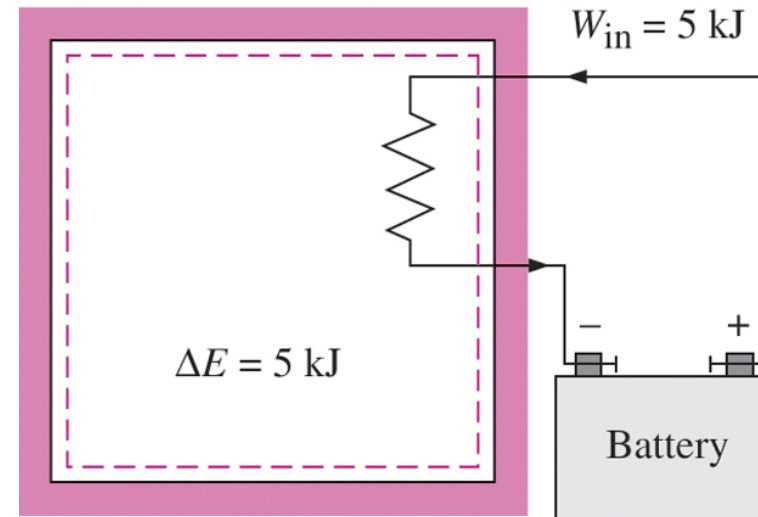


The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.



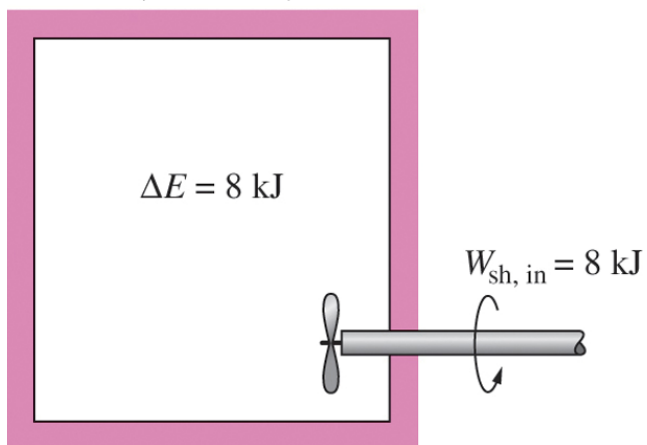
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.

(Adiabatic)



The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.

(Adiabatic)



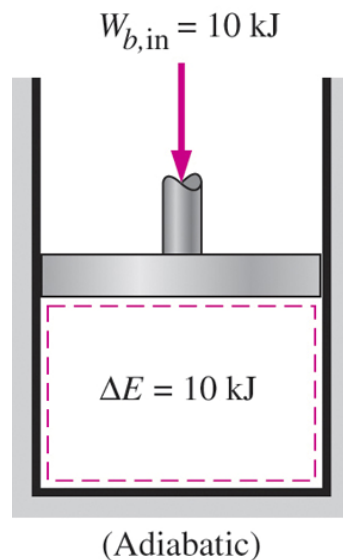
The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

# ENERGY BALANCE

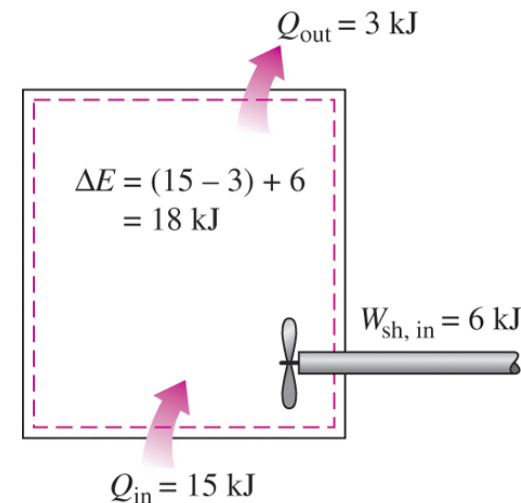
*The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.*

$$\left( \begin{array}{c} \text{Total energy} \\ \text{entering the system} \end{array} \right) - \left( \begin{array}{c} \text{Total energy} \\ \text{leaving the system} \end{array} \right) = \left( \begin{array}{c} \text{Change in the total} \\ \text{energy of the system} \end{array} \right)$$

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



The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.



The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

## ENERGY CHANGE OF A SYSTEM, $\Delta E_{\text{SYSTEM}}$

Energy change = Energy at final state – Energy at initial state

$$\Delta E_{\text{system}} = E_{\text{final}} - E_{\text{initial}} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

Internal, kinetic, and potential energy changes

$$\Delta U = m(u_2 - u_1)$$

$$\Delta \text{KE} = \frac{1}{2}m(V_2^2 - V_1^2)$$

$$\Delta \text{PE} = mg(z_2 - z_1)$$

Stationary Systems

$$z_1 = z_2 \rightarrow \Delta \text{PE} = 0$$

$$V_1 = V_2 \rightarrow \Delta \text{KE} = 0$$

$$\Delta E = \Delta U$$

# MECHANISMS OF ENERGY TRANSFER, $E_{in}$ AND $E_{out}$

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass, in} - E_{mass, out}) = \Delta E_{system}$$

Heat transfer    Work transfer    Mass flow

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

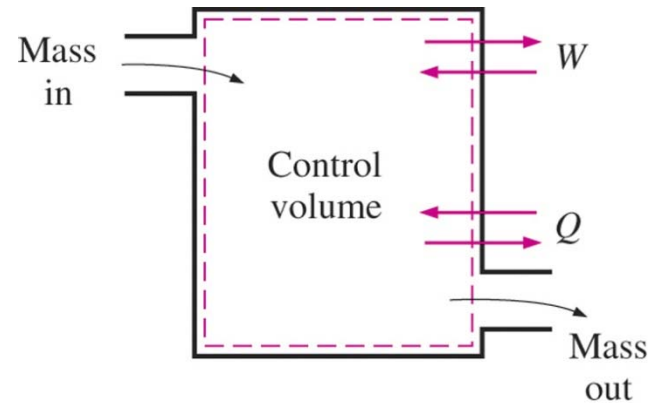
$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad (\text{kW})$$

A closed mass involves only *heat transfer* and *work*.

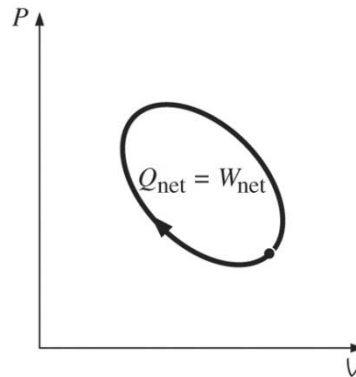
$$Q = \dot{Q} \Delta t, \quad W = \dot{W} \Delta t, \quad \text{and} \quad \Delta E = (dE/dt) \Delta t \quad (\text{kJ})$$

$$e_{in} - e_{out} = \Delta e_{system} \quad (\text{kJ/kg})$$

$$\delta E_{in} - \delta E_{out} = dE_{system} \quad \text{or} \quad \delta e_{in} - \delta e_{out} = de_{system}$$



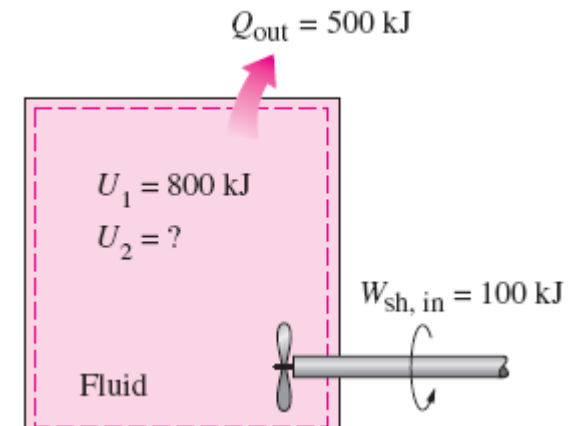
The energy content of a control volume can be changed by mass flow as well as heat and work interactions.



For a cycle  $\Delta E = 0$ , thus  $Q = W$ .

### EXAMPLE 2-10

A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.



**Solution** A fluid in a rigid tank loses heat while being stirred. The final internal energy of the fluid is to be determined.

**Assumptions** **1** The tank is stationary and the kinetic and potential energy changes are zero  $KE=PE=0$ . Therefore  $\Delta E=\Delta U$  and internal energy is the only form of the system's energy that may change during this process. **2** Energy stored in the paddle wheel is negligible.

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}}$$
$$W_{\text{sh, in}} - Q_{\text{out}} = \Delta U = U_2 - U_1$$
$$100 \text{ kJ} - 500 \text{ kJ} = U_2 - 800 \text{ kJ}$$
$$U_2 = \mathbf{400 \text{ kJ}}$$

Therefore, the final internal energy of the system is 400 kJ.

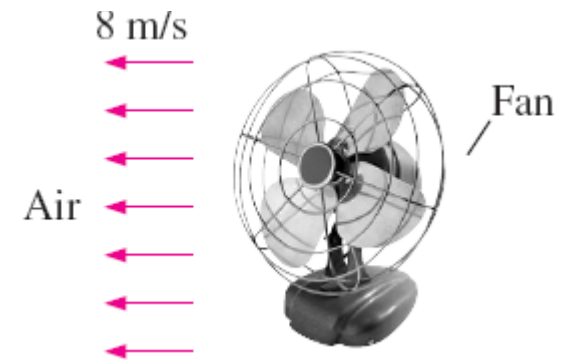


### EXAMPLE 2-11

A fan that consumes 20 W of electric power when operating is claimed to discharge air from a ventilated room at a rate of 1 kg/s at a discharge velocity of 8 m/s. Determine if this claim is reasonable.

**Solution** A fan is claimed to increase the velocity of air to a specified value while consuming electric power at a specified rate. The validity of this claim is to be investigated.

**Assumptions** The ventilating room is relatively calm, and air velocity in it is negligible.



$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\frac{dE_{\text{system}}}{dt}}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \xrightarrow{0 \text{ (steady)}} 0 \rightarrow \dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{W}_{\text{elect, in}} = \dot{m}_{\text{air}} ke_{\text{out}} = \dot{m}_{\text{air}} \frac{V_{\text{out}}^2}{2}$$

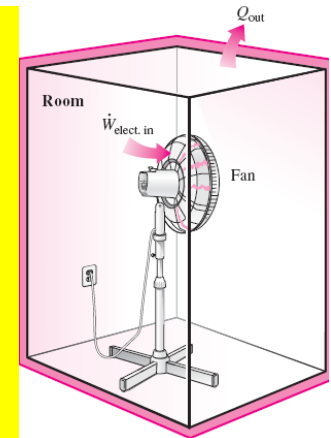
$$V_{\text{out}} = \sqrt{\frac{2\dot{W}_{\text{elect, in}}}{\dot{m}_{\text{air}}}} = \sqrt{\frac{2(20 \text{ J/s})}{1.0 \text{ kg/s}} \left( \frac{1 \text{ m}^2/\text{s}^2}{1 \text{ J/kg}} \right)} = 6.3 \text{ m/s}$$

which is less than 8 m/s. Therefore, the claim is **false**.

**Discussion** There is nothing wrong with the conversion of the entire electrical energy into kinetic energy. Therefore, the first law has no objection to air velocity reaching 6.3 m/s but this is the upper limit. Any claim of higher velocity is in violation of the first law, and thus impossible. In reality, the air velocity will be considerably lower than 6.3 m/s because of the losses associated with the conversion of electrical energy to mechanical shaft energy, and the conversion of mechanical shaft energy to kinetic energy of air.

## EXAMPLE 2-12

A room is initially at the outdoor temperature of 25°C. Now a large fan that consumes 200 W of electricity when running is turned on. The heat transfer rate between the room and the outdoor air is given as  $\dot{Q} = UA(T_i - T_o)$  where  $U = 6$  W/m<sup>2</sup> °C is the overall heat transfer coefficient,  $A = 30$  m<sup>2</sup> is the exposed surface area of the room, and  $T_i$  and  $T_o$  are the indoor and outdoor air temperatures, respectively. Determine the indoor air temperature when steady operating conditions are established.



**Solution** A large fan is turned on and kept on in a room that loses heat to the outdoors. The indoor air temperature is to be determined when steady operation is reached.

**Assumptions** 1 Heat transfer through the floor is negligible.

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}} / dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \xrightarrow{0 \text{ (steady)}} 0 \rightarrow \dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{W}_{\text{elect, in}} = \dot{Q}_{\text{out}} = UA(T_i - T_o) \quad 200 \text{ W} = (6 \text{ W/m}^2 \cdot ^\circ\text{C})(30 \text{ m}^2)(T_i - 25^\circ\text{C})$$

$$T_i = 26.1^\circ\text{C}$$

**Discussion** The motor converts part of the electric energy it draws to mechanical energy in the form of a rotating shaft while the remaining part is dissipated as heat to the room air because of the motor inefficiency. Part of the mechanical energy of the shaft is converted to kinetic energy of air through the blades, which is then converted to thermal energy as air molecules slow down because of friction. The entire electric energy drawn by the fan motor is converted to thermal energy of air, which manifests itself as a rise in temperature.

## EXAMPLE 2-13

The lighting needs of a classroom are met by 30 fluorescent lamps, each consuming 80 W of electricity (Fig. 2–50). The lights in the classroom are kept on for 12 hours a day and 250 days a year. For a unit electricity cost of 7 cents per kWh, determine annual energy cost of lighting for this classroom. Also, discuss the effect of lighting on the heating and air-conditioning requirements of the room.



**Solution** The lighting of a classroom by fluorescent lamps is considered. The annual electricity cost of lighting for this classroom is to be determined, and the lighting's effect on the heating and air-conditioning requirements is to be discussed.

**Assumptions** The effect of voltage fluctuations is negligible so that each fluorescent lamp consumes its rated power.

$$\begin{aligned}\text{Lighting power} &= (\text{Power consumed per lamp}) \times (\text{No. of lamps}) \\ &= (80 \text{ W/lamp})(30 \text{ lamps}) \\ &= 2400 \text{ W} = 2.4 \text{ kW}\end{aligned}$$

$$\text{Operating hours} = (12 \text{ h/day})(250 \text{ days/year}) = 3000 \text{ h/year}$$

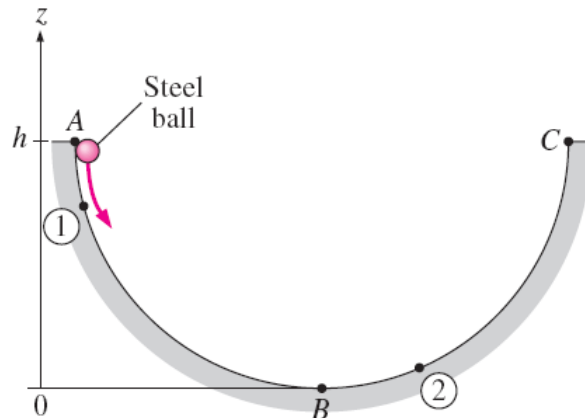
$$\begin{aligned}\text{Lighting energy} &= (\text{Lighting power})(\text{Operating hours}) \\ &= (2.4 \text{ kW})(3000 \text{ h/year}) = 7200 \text{ kWh/year}\end{aligned}$$

$$\begin{aligned}\text{Lighting cost} &= (\text{Lighting energy})(\text{Unit cost}) \\ &= (7200 \text{ kWh/year})(\$0.07/\text{kWh}) = \text{\textcolor{violet}{\$504/year}}\end{aligned}$$

**Discussion** Note that the annual lighting cost of this classroom alone is over \$500. This shows the importance of energy conservation measures. If incandescent light bulbs were used instead of fluorescent tubes, the lighting costs would be four times as much since incandescent lamps use four times as much power for the same amount of light produced.

## EXAMPLE 2-14

The motion of a steel ball in a hemispherical bowl of radius  $h$  is to be analyzed. The ball is initially held at the highest location at point  $A$ , and then it is released. Obtain relations for the conservation of energy of the ball for the cases of frictionless and actual motions.



**Solution** A steel ball is released in a bowl. Relations for the energy balance are to be obtained.

**Assumptions** The motion is frictionless, and thus friction between the ball, the bowl, and the air is negligible.

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

$$-w_{\text{friction}} = (ke_2 + pe_2) - (ke_1 + pe_1)$$

$$\frac{V_1^2}{2} + gz_1 = \frac{V_2^2}{2} + gz_2 + w_{\text{friction}}$$

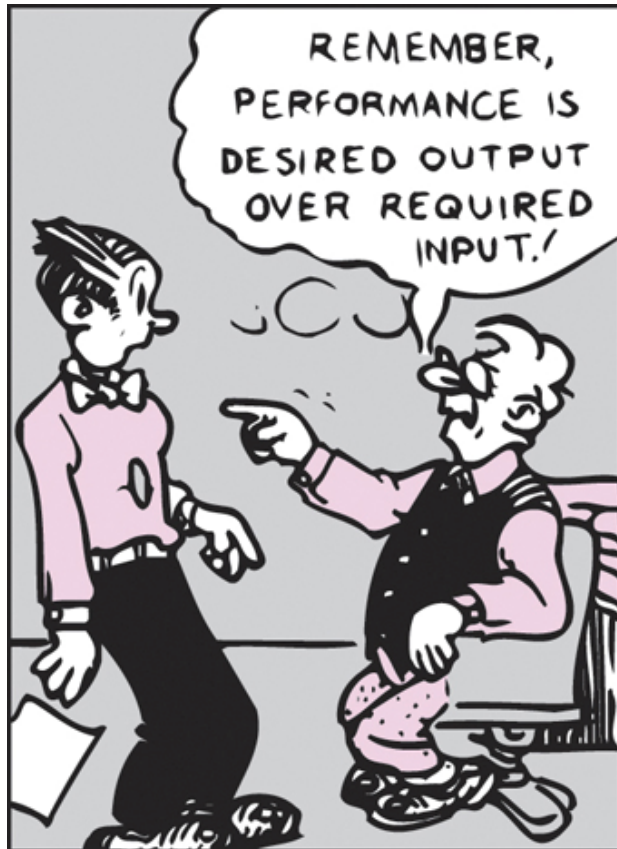
For the idealized case of frictionless motion

$$\frac{V_1^2}{2} + gz_1 = \frac{V_2^2}{2} + gz_2 \quad \text{or} \quad \frac{V^2}{2} + gz = C = \text{constant}$$

**Discussion** This is certainly a more intuitive and convenient form of the conservation of energy equation for this and other similar processes such as the swinging motion of the pendulum of a wall clock.

# ENERGY CONVERSION EFFICIENCIES

**Efficiency** is one of the most frequently used terms in thermodynamics, and it indicates how well an energy conversion or transfer process is accomplished.



The definition of performance is not limited to thermodynamics only.

$$\text{Performance} = \frac{\text{Desired output}}{\text{Required input}}$$

**Efficiency of a water heater:** The ratio of the energy delivered to the house by hot water to the energy supplied to the water heater.

| Type                      | Efficiency |
|---------------------------|------------|
| Gas, conventional         | 55%        |
| Gas, high-efficiency      | 62%        |
| Electric, conventional    | 90%        |
| Electric, high-efficiency | 94%        |



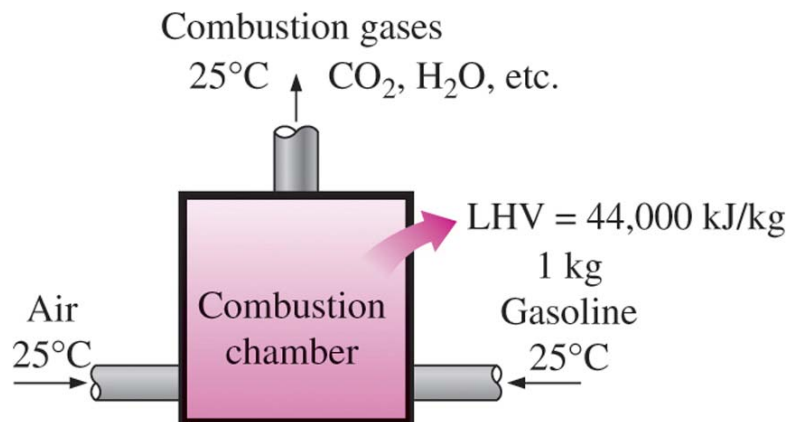


$$\eta_{\text{combustion}} = \frac{Q}{\text{HV}} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

**Heating value of the fuel:** The amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to the room temperature.

**Lower heating value (LHV):** When the water leaves as a vapor.

**Higher heating value (HHV):** When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.



The definition of the heating value of gasoline.

The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the **annual fuel utilization efficiency (AFUE)**, which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cooldown losses.

- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:** The ratio of the net electrical power output to the rate of fuel energy input.

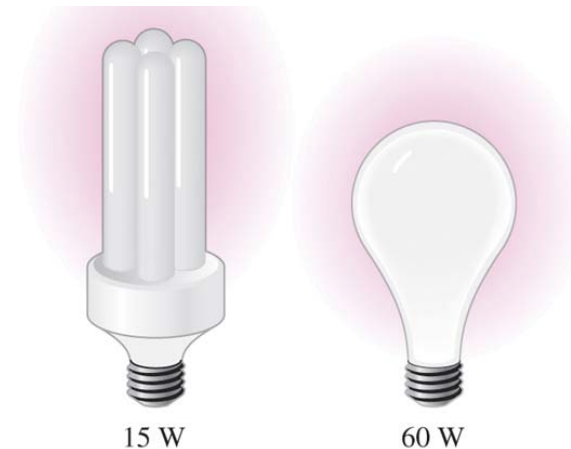
### Overall efficiency of a power plant

$$\eta_{\text{overall}} = \eta_{\text{combustion}} \eta_{\text{thermal}} \eta_{\text{generator}} = \frac{\dot{W}_{\text{net, electric}}}{\text{HHV} \times \dot{m}_{\text{net}}}$$

The efficacy of different lighting systems

| Type of lighting                | Efficacy, lumens/W |
|---------------------------------|--------------------|
| <i>Combustion</i>               |                    |
| Candle                          | 0.2                |
| <i>Incandescent</i>             |                    |
| Ordinary                        | 6–20               |
| Halogen                         | 16–25              |
| <i>Fluorescent</i>              |                    |
| Ordinary                        | 40–60              |
| High output                     | 70–90              |
| Compact                         | 50–80              |
| <i>High-intensity discharge</i> |                    |
| Mercury vapor                   | 50–60              |
| Metal halide                    | 56–125             |
| High-pressure sodium            | 100–150            |
| Low-pressure sodium             | up to 200          |

**Lighting efficacy:**  
The amount of light output in lumens per W of electricity consumed.



A 15-W compact fluorescent lamp provides as much light as a 60-W incandescent lamp.

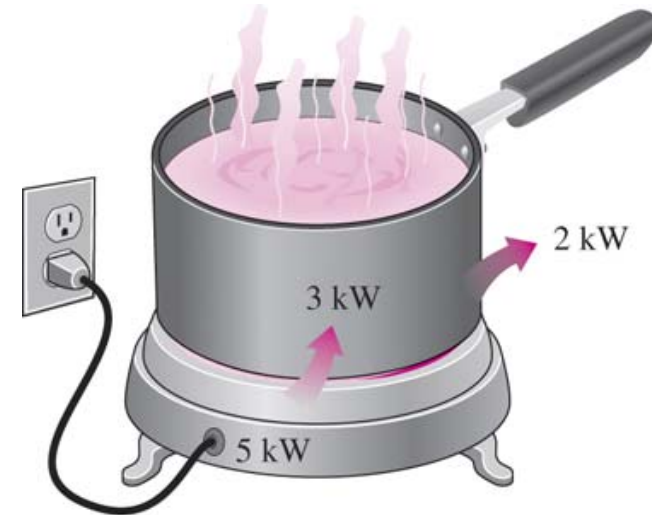


### Energy costs of cooking a casserole with different appliances\*

[From A. Wilson and J. Morril, *Consumer Guide to Home Energy Savings*, Washington, DC: American Council for an Energy-Efficient Economy, 1996, p. 192.]

| Cooking appliance        | Cooking temperature | Cooking time | Energy used | Cost of energy |
|--------------------------|---------------------|--------------|-------------|----------------|
| Electric oven            | 350°F (177°C)       | 1 h          | 2.0 kWh     | \$0.16         |
| Convection oven (elect.) | 325°F (163°C)       | 45 min       | 1.39 kWh    | \$0.11         |
| Gas oven                 | 350°F (177°C)       | 1 h          | 0.112 therm | \$0.07         |
| Frying pan               | 420°F (216°C)       | 1 h          | 0.9 kWh     | \$0.07         |
| Toaster oven             | 425°F (218°C)       | 50 min       | 0.95 kWh    | \$0.08         |
| Crockpot                 | 200°F (93°C)        | 7 h          | 0.7 kWh     | \$0.06         |
| Microwave oven           | "High"              | 15 min       | 0.36 kWh    | \$0.03         |

- Using energy-efficient appliances **conserve energy**.
- It helps the **environment** by reducing the amount of pollutants emitted to the atmosphere during the combustion of fuel.
- The combustion of fuel produces
  - **carbon dioxide**, causes global warming
  - **nitrogen oxides** and **hydrocarbons**, cause smog
  - **carbon monoxide**, toxic
  - **sulfur dioxide**, causes acid rain.



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}}$$

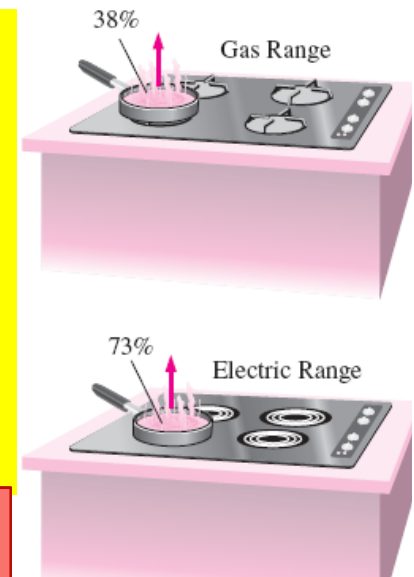
$$= \frac{3 \text{ kWh}}{5 \text{ kWh}} = 0.60$$

The efficiency of a cooking appliance represents the fraction of the energy supplied to the appliance that is transferred to the food.

## EXAMPLE 2-15

The efficiency of cooking appliances affects the internal heat gain from them since an inefficient appliance consumes a greater amount of energy for the same task, and the excess energy consumed shows up as heat in the living space. The efficiency of open burners is determined to be 73 % for electric units and 38 % for gas units. Consider a 2-kW electric burner at a location where the unit costs of electricity and natural gas are \$0.09/kWh and \$0.55/therm, respectively. Determine the rate of energy consumption by the burner and the unit cost of utilized energy for both electric and gas burners.

**Solution** The operation of electric and gas ranges is considered. The rate of energy consumption and the unit cost of utilized energy are to be determined.



$$\dot{Q}_{\text{utilized}} = (\text{Energy input}) \times (\text{Efficiency}) = (2 \text{ kW})(0.73) = \mathbf{1.46 \text{ kW}}$$

$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$0.09/\text{kWh}}{0.73} = \mathbf{\$0.123/\text{kWh}}$$

$$\dot{Q}_{\text{input, gas}} = \frac{\dot{Q}_{\text{utilized}}}{\text{Efficiency}} = \frac{1.46 \text{ kW}}{0.38} = \mathbf{3.84 \text{ kW}} \quad (= 13,100 \text{ Btu/h})$$

$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$0.55/29.3 \text{ kWh}}{0.38} = \mathbf{\$0.049/\text{kWh}}$$

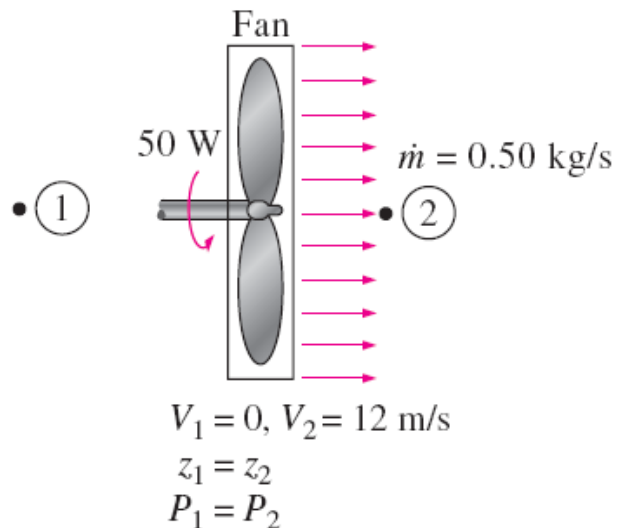
**Discussion** The cost of utilized gas is less than half of the unit cost of utilized electricity. Therefore, despite its higher efficiency, cooking with an electric burner will cost more than twice as much compared to a gas burner in this case.

# EFFICIENCIES OF MECHANICAL AND ELECTRICAL DEVICES

## Mechanical efficiency

$$\eta_{\text{mech}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{\text{mech, out}}}{E_{\text{mech, in}}} = 1 - \frac{E_{\text{mech, loss}}}{E_{\text{mech, in}}}$$

The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the **pump efficiency** and **turbine efficiency**.



$$\eta_{\text{pump}} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{\text{mech, fluid}}}{\dot{W}_{\text{shaft, in}}} = \frac{\dot{W}_{\text{pump, in}}}{\dot{W}_{\text{pump}}}$$

$$\eta_{\text{turbine}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{\text{shaft, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{\dot{W}_{\text{turbine}}}{\dot{W}_{\text{turbine, e}}}$$

$$\begin{aligned} \eta_{\text{mech, fan}} &= \frac{\Delta \dot{E}_{\text{mech, fluid}}}{\dot{W}_{\text{shaft, in}}} = \frac{\dot{m} V_2^2 / 2}{\dot{W}_{\text{shaft, in}}} \\ &= \frac{(0.50 \text{ kg/s})(12 \text{ m/s})^2 / 2}{50 \text{ W}} \\ &= 0.72 \end{aligned}$$

The mechanical efficiency of a fan is the ratio of the kinetic energy of air at the fan exit to the mechanical power input.

Pump efficiency

*Motor:*

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft, out}}}{\dot{W}_{\text{elect, in}}}$$

Generator efficiency

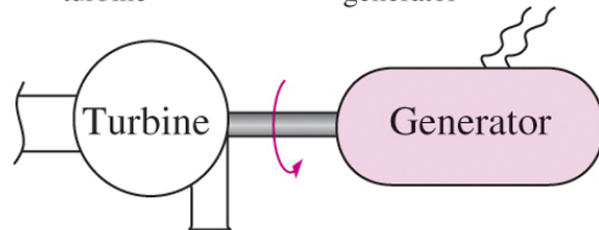
*Generator:*

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect, out}}}{\dot{W}_{\text{shaft, in}}}$$

Pump-Motor overall efficiency

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump, u}}}{\dot{W}_{\text{elect, in}}} = \frac{\Delta \dot{E}_{\text{mech, fluid}}}{\dot{W}_{\text{elect, in}}}$$

$$\eta_{\text{turbine}} = 0.75 \quad \eta_{\text{generator}} = 0.97$$



Turbine-Generator overall efficiency

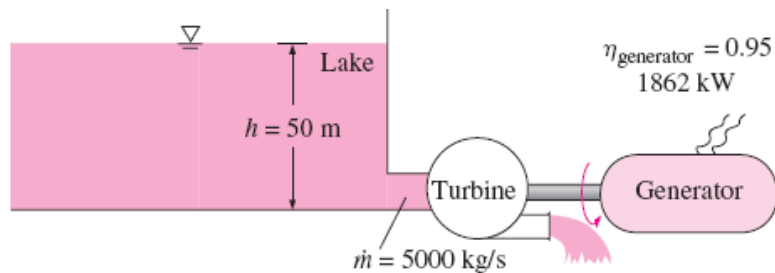
$$\begin{aligned}\eta_{\text{turbine-gen}} &= \eta_{\text{turbine}}\eta_{\text{generator}} \\ &= 0.75 \times 0.97 \\ &= 0.73\end{aligned}$$

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect, out}}}{\dot{W}_{\text{turbine, e}}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|}$$

The overall efficiency of a turbine-generator is the product of the efficiency of the turbine and the efficiency of the generator, and represents the fraction of the mechanical energy of the fluid converted to electric energy.

## EXAMPLE 2-16

The water in a large lake is to be used to generate electricity by the installation of a hydraulic turbine–generator at a location where the depth of the water is 50 m. Water is to be supplied at a rate of 5000 kg/s. If the electric power generated is measured to be 1862 kW and the generator efficiency is 95 %, determine (a) the overall efficiency of the turbine–generator, (b) the mechanical efficiency of the turbine, and (c) the shaft power supplied by the turbine to the generator.



**Solution** A hydraulic turbine–generator is to generate electricity from the water of a lake. The overall efficiency, the turbine efficiency, and the shaft power are to be determined.

**Assumptions** 1 The elevation of the lake remains constant. 2 The mechanical energy of water at the turbine exit is negligible.

(a) the overall efficiency of the turbine–generator

$$e_{\text{mech, in}} - e_{\text{mech, out}} = \frac{P}{\rho} - 0 = gh = (9.81 \text{ m/s}^2)(50 \text{ m}) \left( \frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) = 0.49 \text{ kJ/kg}$$

$$|\Delta \dot{E}_{\text{mech, fluid}}| = \dot{m}(e_{\text{mech, in}} - e_{\text{mech, out}}) = (5000 \text{ kg/s})(0.491 \text{ kJ/kg}) = 2455 \text{ kW}$$

$$\eta_{\text{overall}} = \eta_{\text{turbine-gen}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|} = \frac{1862 \text{ kW}}{2455 \text{ kW}} = \mathbf{0.76}$$

(b) the mechanical efficiency of the turbine

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}} \eta_{\text{generator}} \rightarrow \eta_{\text{turbine}} = \frac{\eta_{\text{turbine-gen}}}{\eta_{\text{generator}}} = \frac{0.76}{0.95} = \mathbf{0.80}$$

(c) the shaft power supplied by the turbine to the generator.

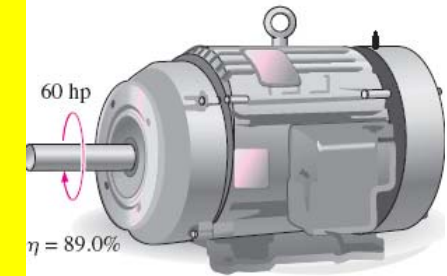
$$\dot{W}_{\text{shaft, out}} = \eta_{\text{turbine}} |\Delta \dot{E}_{\text{mech, fluid}}| = (0.80)(2455 \text{ kW}) = \mathbf{1964 \text{ kW}}$$

**Discussion** Note that the lake supplies 2455 kW of mechanical energy to the turbine, which converts 1964 kW of it to shaft work that drives the generator, which generates 1862 kW of electric power. There are irreversible losses through each component.

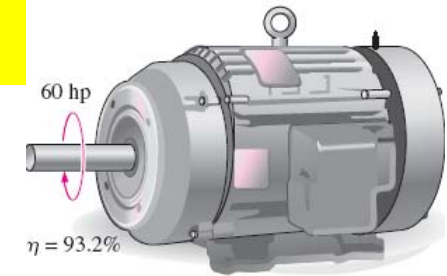


## EXAMPLE 2-16

A 60-hp electric motor (a motor that delivers 60 hp of shaft power at full load) that has an efficiency of 89.0 percent is worn out and is to be replaced by a 93.2 percent efficient high-efficiency motor (Fig. 2–61). The motor operates 3500 hours a year at full load. Taking the unit cost of electricity to be 0.08/kWh, determine the amount of energy and money saved as a result of installing the high-efficiency motor instead of the standard motor. Also, determine the simple payback period if the purchase prices of the standard and high-efficiency motors are \$4520 and \$5160, respectively.



Standard Motor



High-Efficiency Motor

**Solution** A worn out standard motor is to be replaced by a high-efficiency one. The amount of electrical energy and money saved as well as the simple payback period are to be determined.

**Assumptions** The load factor of the motor remains constant at 1 (full load) when operating.

$$\dot{W}_{\text{electric in, standard}} = \dot{W}_{\text{shaft}} / \eta_{\text{standard}} = (\text{Rated power})(\text{Load factor}) / \eta_{\text{standard}}$$

$$\dot{W}_{\text{electric in, efficient}} = \dot{W}_{\text{shaft}} / \eta_{\text{efficient}} = (\text{Rated power})(\text{Load factor}) / \eta_{\text{efficient}}$$

$$\begin{aligned} \text{Power savings} &= \dot{W}_{\text{electric in, standard}} - \dot{W}_{\text{electric in, efficient}} \\ &= (\text{Rated power})(\text{Load factor})[1/\eta_{\text{standard}} - 1/\eta_{\text{efficient}}] \end{aligned}$$



$$\begin{aligned}
 \text{Energy savings} &= (\text{Power savings})(\text{Operating hours}) \\
 &= (\text{Rated power})(\text{Operating hours})(\text{Load factor})(1/\eta_{\text{standard}} - 1/\eta_{\text{efficient}}) \\
 &= (60 \text{ hp})(0.7457 \text{ kW/hp})(3500 \text{ h/year})(1)(1/0.89 - 1/0.932) \\
 &= \mathbf{7929 \text{ kWh/year}}
 \end{aligned}$$

$$\begin{aligned}
 \text{Cost savings} &= (\text{Energy savings})(\text{Unit cost of energy}) \\
 &= (7929 \text{ kWh/year})(\$0.08/\text{kWh}) \\
 &= \mathbf{\$634/\text{year}}
 \end{aligned}$$

$$\text{Excess initial cost} = \text{Purchase price differential} = \$5160 - \$4520 = \$640$$

$$\text{Simple payback period} = \frac{\text{Excess initial cost}}{\text{Annual cost savings}} = \frac{\$640}{\$634/\text{year}} = \mathbf{1.01 \text{ year}}$$

**Discussion** Note that the high-efficiency motor pays for its price differential within about one year from the electrical energy it saves. Considering that the service life of electric motors is several years, the purchase of the higher efficiency motor is definitely indicated in this case.

# ENERGY AND ENVIRONMENT

- The conversion of energy from one form to another often affects the environment and the air we breathe in many ways, and thus the study of energy is not complete without considering its impact on the environment.
- Pollutants emitted during the combustion of fossil fuels are responsible for **smog**, **acid rain**, and **global warming**.
- The environmental pollution has reached such high levels that it became a serious threat to **vegetation**, **wild life**, and **human health**.

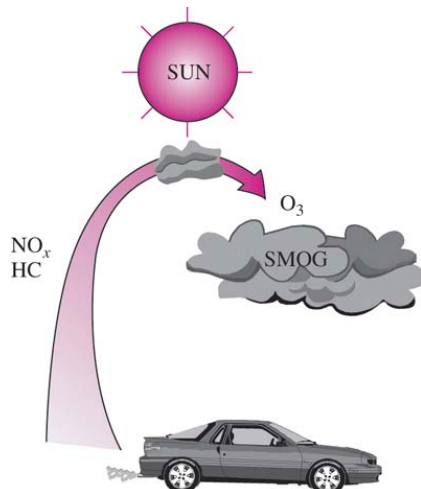


Motor vehicles are the largest source of air pollution.

Energy conversion processes are often accompanied by environmental pollution.

# OZONE AND SMOG

- **Smog**: Made up mostly of ground-level ozone ( $O_3$ ), but it also contains numerous other chemicals, including carbon monoxide (CO), particulate matter such as soot and dust, volatile organic compounds (VOCs) such as benzene, butane, and other hydrocarbons.
- **Hydrocarbons** and **nitrogen oxides** react in the presence of sunlight on hot calm days to form ground-level ozone.
- **Ozone** irritates eyes and damages the air sacs in the lungs where oxygen and carbon dioxide are exchanged, causing eventual hardening of this soft and spongy tissue.
- It also causes shortness of breath, wheezing, fatigue, headaches, and nausea, and aggravates respiratory problems such as asthma.



- The other serious pollutant in smog is **carbon monoxide**, which is a colorless, odorless, poisonous gas.
- It is mostly emitted by motor vehicles.
- It deprives the body's organs from getting enough oxygen by binding with the red blood cells that would otherwise carry oxygen. It is fatal at high levels.
- Suspended **particulate matter** such as **dust** and **soot** are emitted by vehicles and industrial facilities. Such particles irritate the eyes and the lungs.

Ground-level ozone, which is the primary component of smog, forms when HC and  $NO_x$  react in the presence of sunlight in hot calm days.

# ACID RAIN

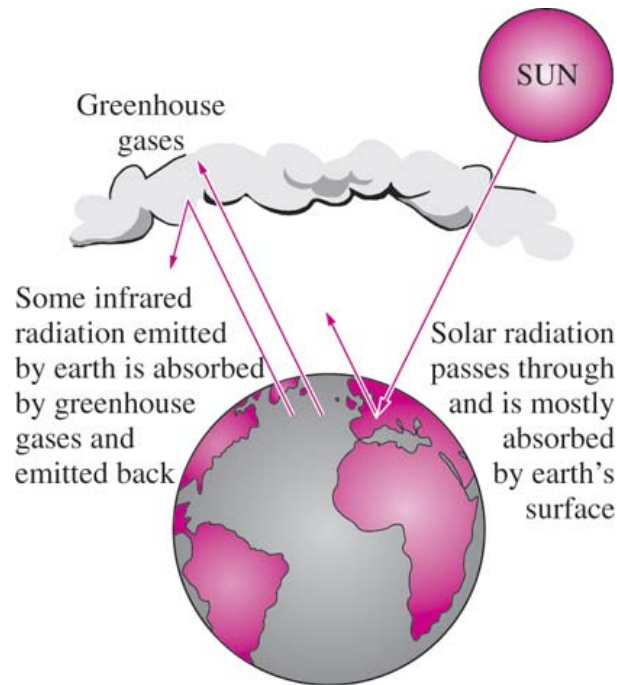
- The sulfur in the fuel reacts with oxygen to form sulfur dioxide ( $\text{SO}_2$ ), which is an air pollutant.
- The main source of  $\text{SO}_2$  is the electric power plants that burn high-sulfur coal.
- Motor vehicles also contribute to  $\text{SO}_2$  emissions since gasoline and diesel fuel also contain small amounts of sulfur.



**Sulfuric acid** and **nitric acid** are formed when sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight.

- The sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight to form sulfuric and nitric acids.
- The acids formed usually dissolve in the suspended water droplets in clouds or fog.
- These acid-laden droplets, which can be as acidic as lemon juice, are washed from the air on to the soil by rain or snow. This is known as **acid rain**.

# THE GREENHOUSE EFFECT: GLOBAL WARMING



The greenhouse effect on earth.

- **Greenhouse effect:** Glass allows the solar radiation to enter freely but blocks the infrared radiation emitted by the interior surfaces. This causes a rise in the interior temperature as a result of the thermal energy buildup in a space (i.e., car).
- The surface of the earth, which warms up during the day as a result of the absorption of solar energy, cools down at night by radiating part of its energy into deep space as infrared radiation.

- **Carbon dioxide (CO<sub>2</sub>)**, water vapor, and trace amounts of some other gases such as methane and nitrogen oxides act like a blanket and keep the earth warm at night by blocking the heat radiated from the earth. The result is **global warming**.
- These gases are called “**greenhouse gases**,” with CO<sub>2</sub> being the primary component.
- CO<sub>2</sub> is produced by the burning of fossil fuels such as **coal, oil, and natural gas**.



- **A 1995 report:** The earth has already warmed about  **$0.5^{\circ}\text{C}$**  during the last century, and they estimate that the earth's temperature will rise another  **$2^{\circ}\text{C}$**  by the year 2100.
- A rise of this magnitude can cause **severe changes in weather patterns** with storms and heavy rains and flooding at some parts and drought in others, major floods due to the melting of ice at the poles, loss of wetlands and coastal areas due to rising sea levels, and other negative results.
- **Improved energy efficiency, energy conservation, and using renewable energy sources** help minimize global warming.



The average car produces several times its weight in  $\text{CO}_2$  every year (it is driven 20,000 km a year, consumes 2300 liters of gasoline, and produces 2.5 kg of  $\text{CO}_2$  per liter).



Renewable energies such as wind are called "green energy" since they emit no pollutants or greenhouse gases.

# SUMMARY

- Forms of energy
  - Macroscopic = kinetic + potential
  - Microscopic = Internal energy (sensible + latent + chemical + nuclear)
- Energy transfer by heat
- Energy transfer by work
- Mechanical forms of work
- The first law of thermodynamics
  - Energy balance
  - Energy change of a system
  - Mechanisms of energy transfer (heat, work, mass flow)
- Energy conversion efficiencies
  - Efficiencies of mechanical and electrical devices (turbines, pumps)
- Energy and environment
  - Ozone and smog
  - Acid rain
  - The Greenhouse effect: Global warming



Thermodynamics: An Engineering Approach, 5<sup>th</sup> Edition  
Yunus A. Cengel, Michael A. Boles  
McGraw-Hill, 2008

# Chapter 3

## PROPERTIES OF PURE SUBSTANCES

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# PROPERTIES OF PURE SUBSTANCES

3-1 Pure Substance

3-2 Phases of a Pure Substance

3-3 Phase-Change Processes of Pure Substances

Compressed Liquid and Saturated Liquid

Saturated Vapor and Superheated Vapor

Saturation Temperature and Saturation Pressure

Some Consequences of  $T_{sat}$  and  $P_{sat}$  Dependence

3-4 Property Diagrams for Phase-Change Processes

1 The  $T$ - $v$  Diagram - 2 The  $P$ - $v$  Diagram - 3 The  $P$ - $T$  Diagram

The  $P$ - $v$ - $T$  Surface

3-5 Property Tables

Enthalpy—A Combination Property

1a Saturated Liquid and Saturated Vapor States

1b Saturated Liquid-Vapor Mixture

2 Superheated Vapor

3 Compressed Liquid

Reference State and Reference Values

3-6 The Ideal-Gas Equation of State

Is Water Vapor an Ideal Gas?

3-7 Compressibility Factor—A Measure of Deviation from Ideal-Gas Behavior

3-8 Other Equations of State

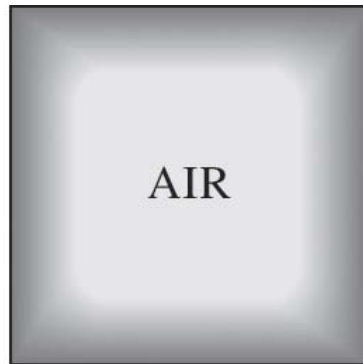
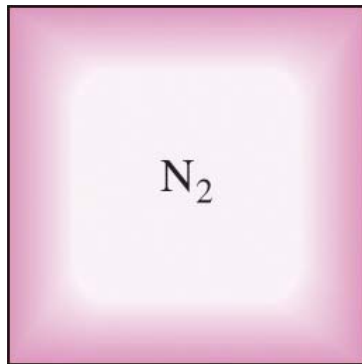
Van der Waals - Beattie-Bridgeman - Benedict-Webb-Rubin and  
Virial Equation of State

# Objectives

- 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.
- Introduce the compressibility factor, which accounts for the deviation of real gases from ideal-gas behavior.
- Present some of the best-known equations of state.

# PURE SUBSTANCE

- **Pure substance:** A substance that has a fixed chemical composition throughout.
- Air is a mixture of several gases, but it is considered to be a pure substance.



Nitrogen and gaseous air are pure substances.



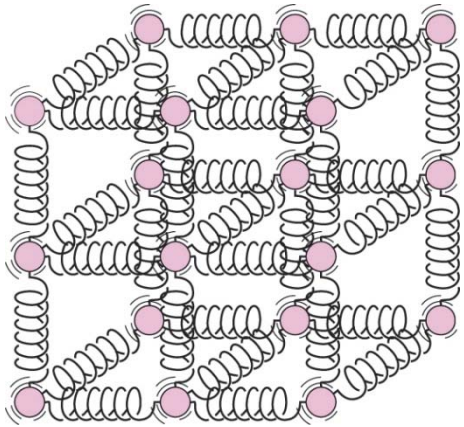
(a)  $H_2O$



(b) AIR

A mixture of liquid and gaseous water is a pure substance, but a mixture of liquid and gaseous air is not.

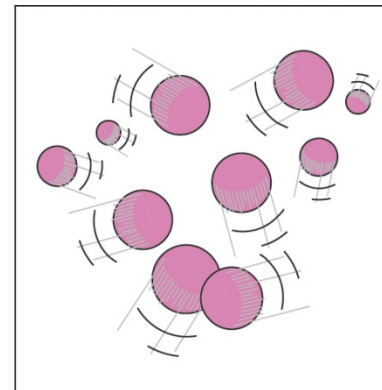
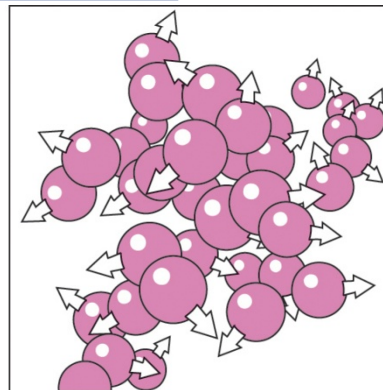
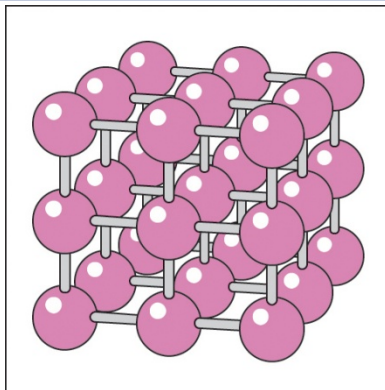
# PHASES OF A PURE SUBSTANCE



The molecules in a solid are kept at their positions by the large spring like inter-molecular forces.



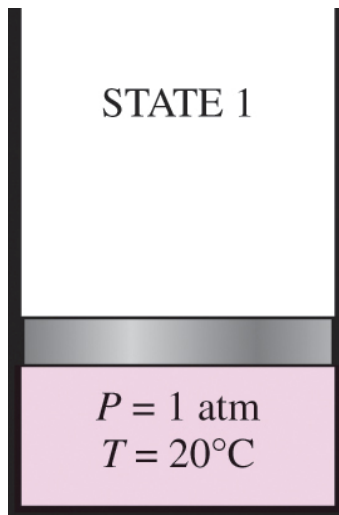
In a solid, the attractive and repulsive forces between the molecules tend to maintain them at relatively constant distances from each other.



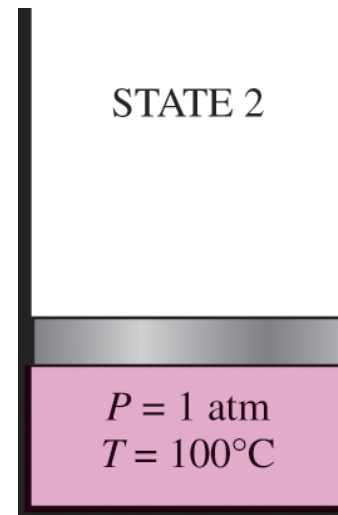
The arrangement of atoms in different phases: (a) molecules are at relatively fixed positions in a solid, (b) groups of molecules move about each other in the liquid phase, and (c) molecules move about at random in the gas phase.

# PHASE-CHANGE PROCESSES OF PURE SUBSTANCES

- **Compressed liquid (subcooled liquid):** A substance that it is *not about to* vaporize.
- **Saturated liquid:** A liquid that is *about to* vaporize.



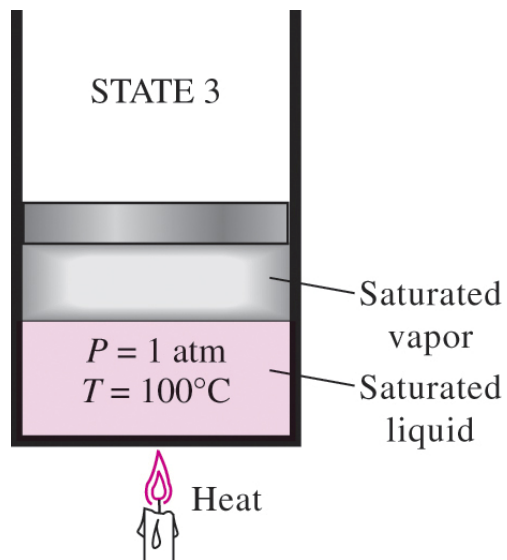
At 1 atm and  $20^\circ\text{C}$ , water exists in the liquid phase (*compressed liquid*).



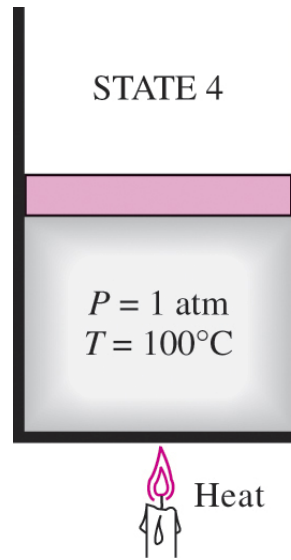
At 1 atm pressure and  $100^\circ\text{C}$ , water exists as a liquid that is ready to vaporize (*saturated liquid*).



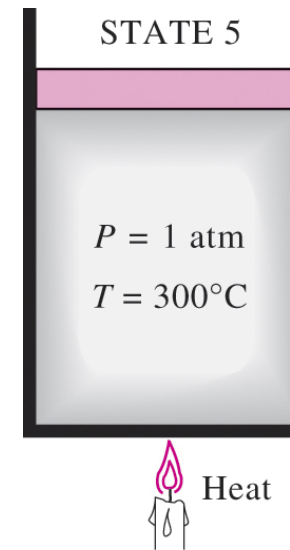
- **Saturated vapor:** A vapor that is *about to condense*.
- **Saturated liquid–vapor mixture:** The state at which the *liquid and vapor phases coexist* in equilibrium.
- **Superheated vapor:** A vapor that is *not about to condense* (i.e., not a saturated vapor).



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

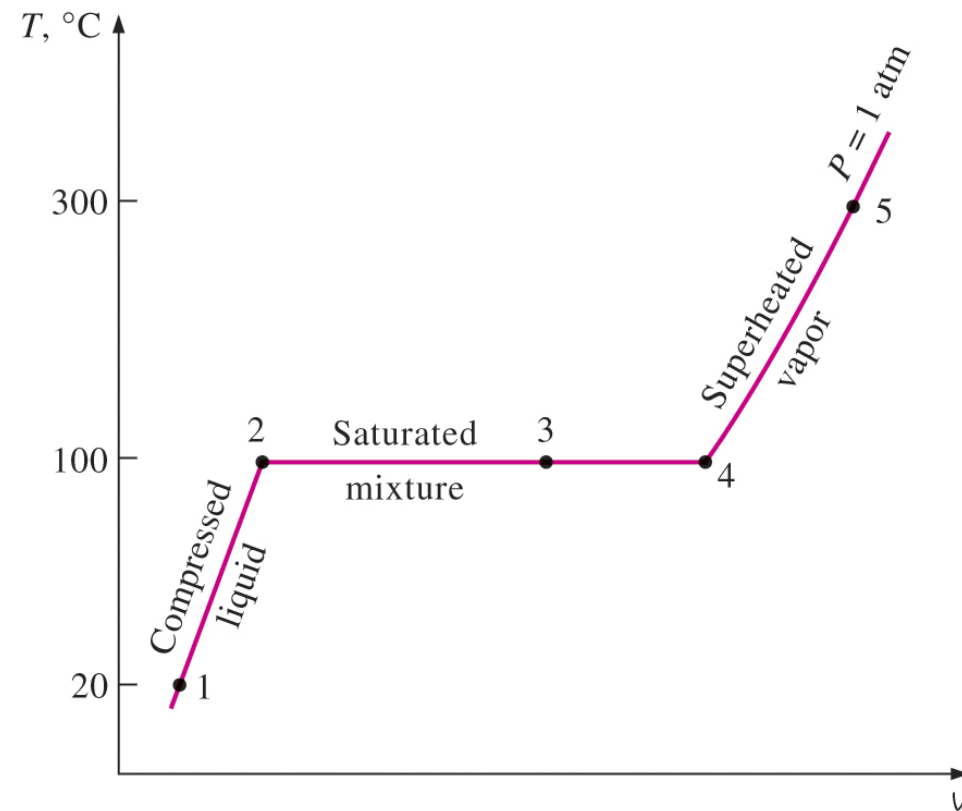


At 1 atm pressure, the temperature remains constant at  $100^\circ\text{C}$  until the last drop of liquid is vaporized (*saturated vapor*).



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

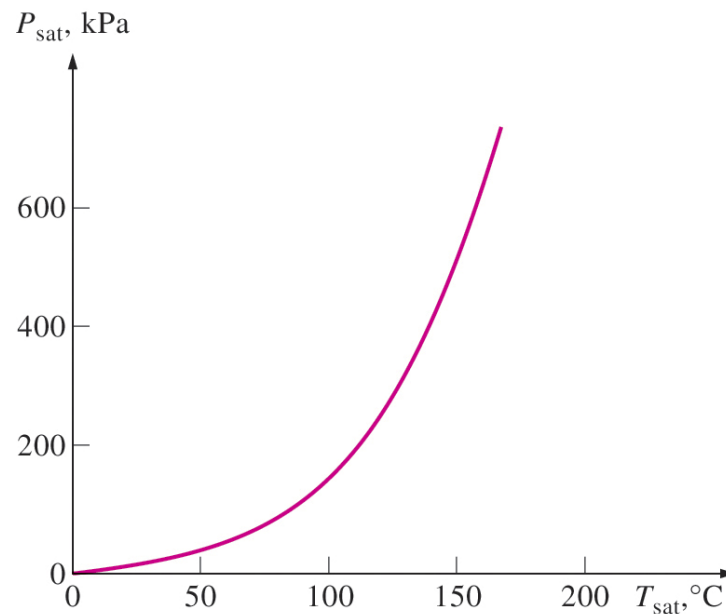
If the entire process between state 1 and 5 described in the figure is reversed by cooling the water while maintaining the pressure at the same value, the water will go back to state 1, retracing the same path, and in so doing, the amount of heat released will exactly match the amount of heat added during the heating process.



T-v diagram for the heating process of water at constant pressure.

# 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 boils at 100°C at 1 atm pressure.
- **Saturation temperature  $T_{\text{sat}}$** : The temperature at which a pure substance changes phase at a given pressure.
- **Saturation pressure  $P_{\text{sat}}$** : The pressure at which a pure substance changes phase at a given temperature.



The liquid–vapor saturation curve of a pure substance (numerical values are for water).

Saturation (boiling) pressure of water at various temperatures

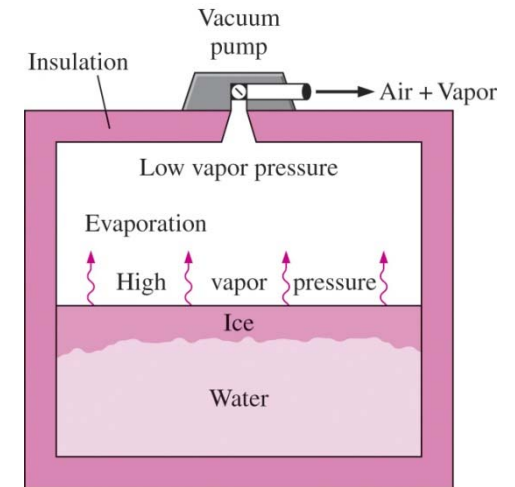
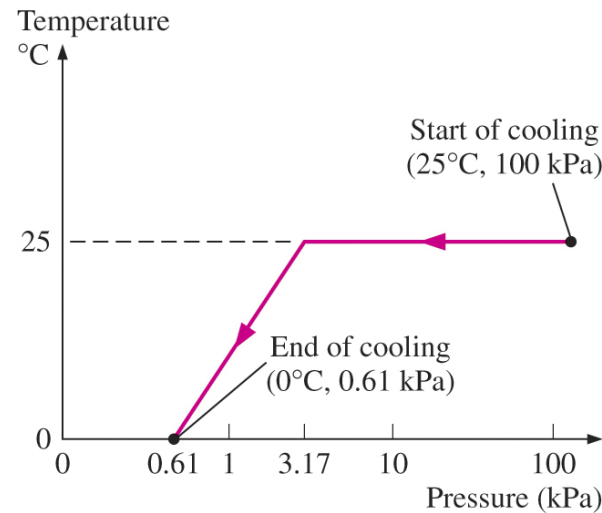
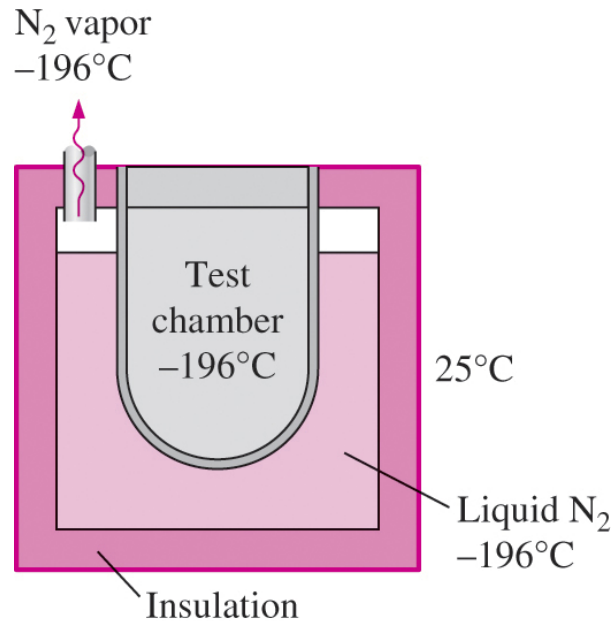
| Temperature,<br>$T, ^\circ\text{C}$ | Saturation<br>pressure,<br>$P_{\text{sat}}, \text{ kPa}$ |
|-------------------------------------|--|
| –10                                 | 0.26   |
| –5                                  | 0.40   |
| 0                                   | 0.61   |
| 5                                   | 0.87   |
| 10                                  | 1.23   |
| 15                                  | 1.71   |
| 20                                  | 2.34   |
| 25                                  | 3.17   |
| 30                                  | 4.25   |
| 40                                  | 7.39   |
| 50                                  | 12.35  |
| 100                                 | 101.4  |
| 150                                 | 476.2  |
| 200                                 | 1555   |
| 250                                 | 3976   |
| 300                                 | 8588   |

- **Latent heat:** The amount of energy absorbed or released during a phase-change process.
- **Latent heat of fusion:** The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.
- **Latent heat of vaporization:** The amount of energy absorbed during vaporization and it is equivalent to the energy released during condensation.
- 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.
- The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

| Elevation, m | Atmospheric pressure, kPa | Boiling temperature, °C |
|--------------|---------------------------|-------------------------|
| 0            | 101.33                    | 100.0                   |
| 1,000        | 89.55                     | 96.5                    |
| 2,000        | 79.50                     | 93.3                    |
| 5,000        | 54.05                     | 83.3                    |
| 10,000       | 26.50                     | 66.3                    |
| 20,000       | 5.53                      | 34.7                    |

# SOME CONSEQUENCES OF $T_{SAT}$ AND $P_{SAT}$ DEPENDENCE



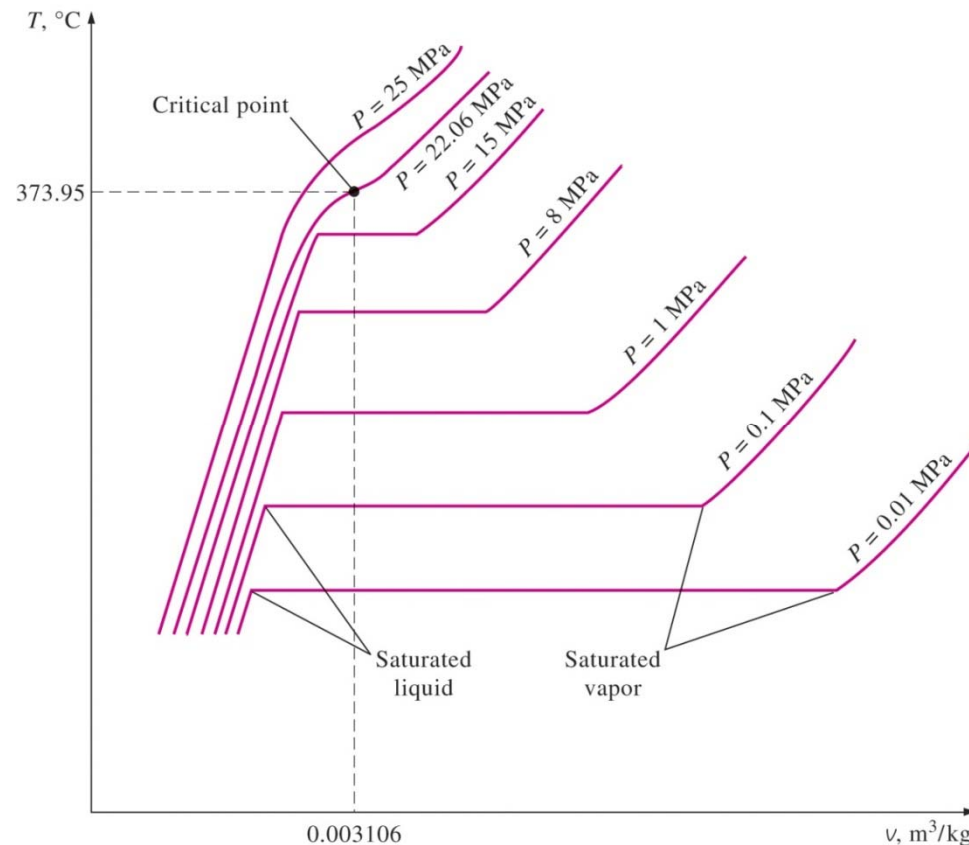
The temperature of liquid nitrogen exposed to the atmosphere remains constant at  $196^{\circ}\text{C}$ , and thus it maintains the test chamber at  $196^{\circ}\text{C}$ .

The variation of the temperature of fruits and vegetables with pressure during vacuum cooling from  $25^{\circ}\text{C}$  to  $0^{\circ}\text{C}$ .

In 1775, ice was made by evacuating the air space in a water tank.

# PROPERTY DIAGRAMS FOR PHASE-CHANGE PROCESSES

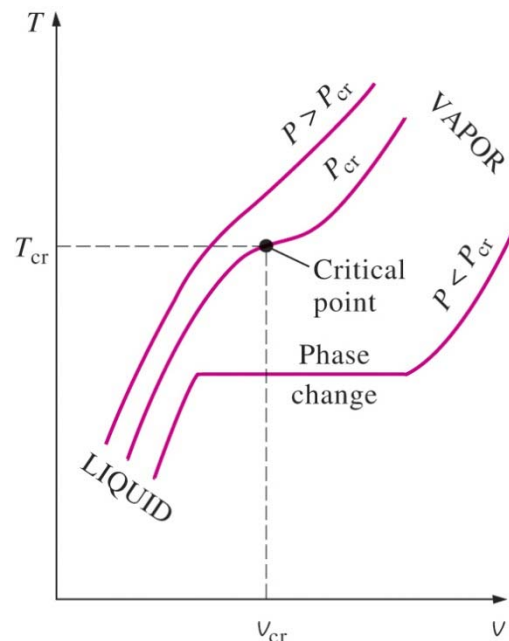
- The variations of properties during phase-change processes are best studied and understood with the help of property diagrams such as the  $T$ - $v$ ,  $P$ - $v$ , and  $P$ - $T$  diagrams for pure substances.



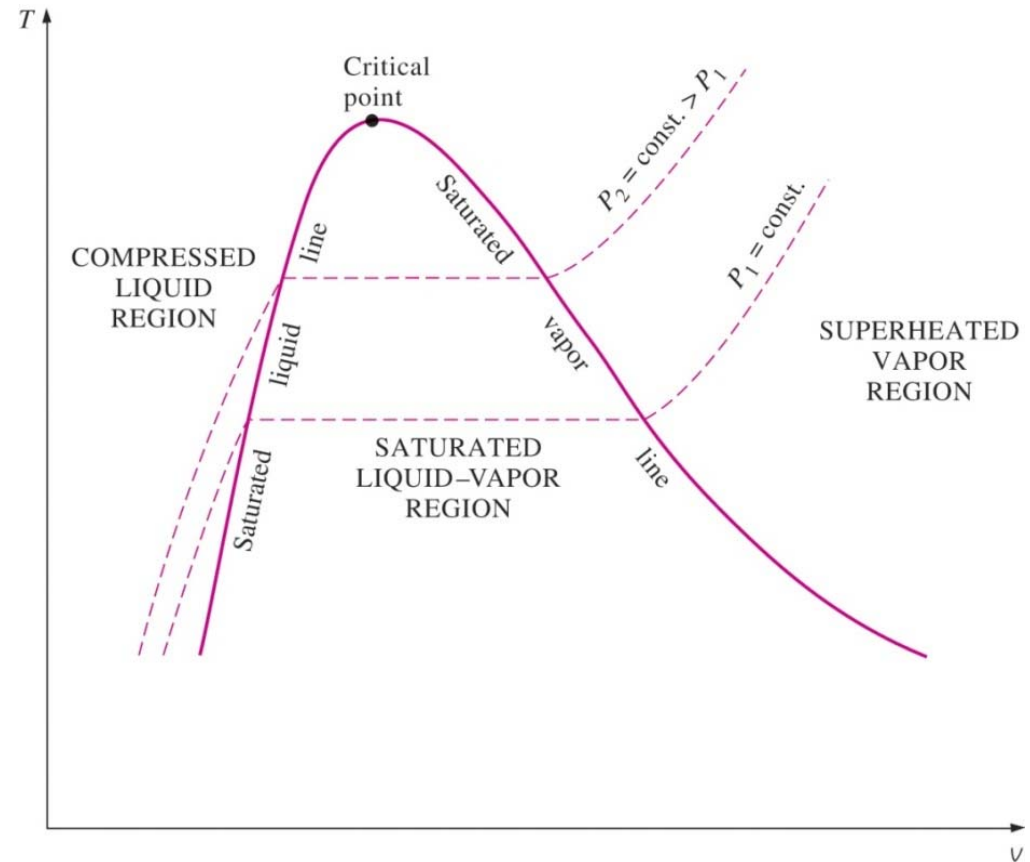
$T$ - $v$  diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).



- saturated liquid line
- saturated vapor line
- compressed liquid region
- superheated vapor region
- saturated liquid–vapor mixture region (wet region)

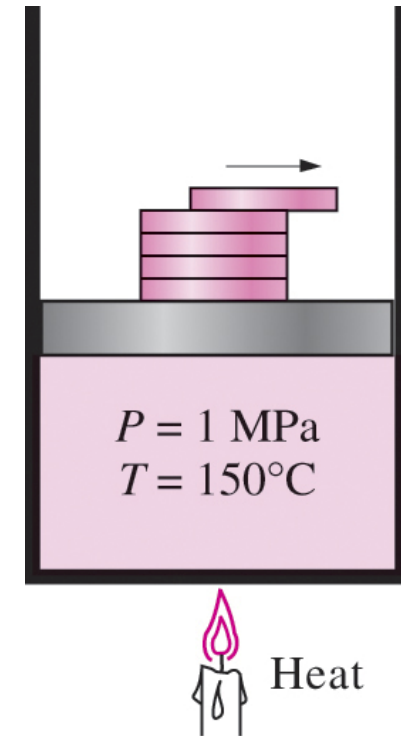
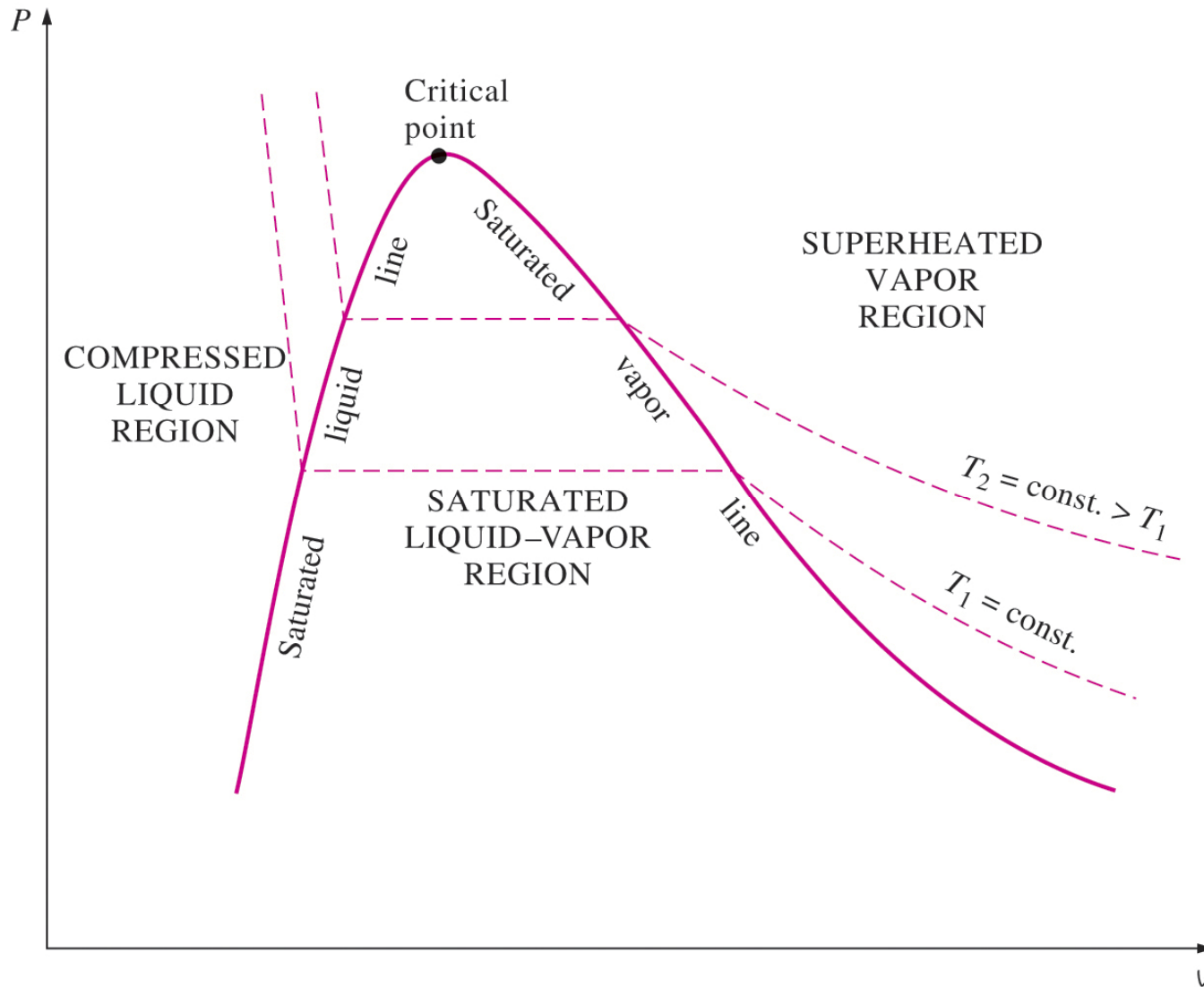


At supercritical pressures ( $P > P_{cr}$ ), there is no distinct phase-change (boiling) process.



T-v diagram of a pure substance.

**Critical point:** The point at which the saturated liquid and saturated vapor states are identical.



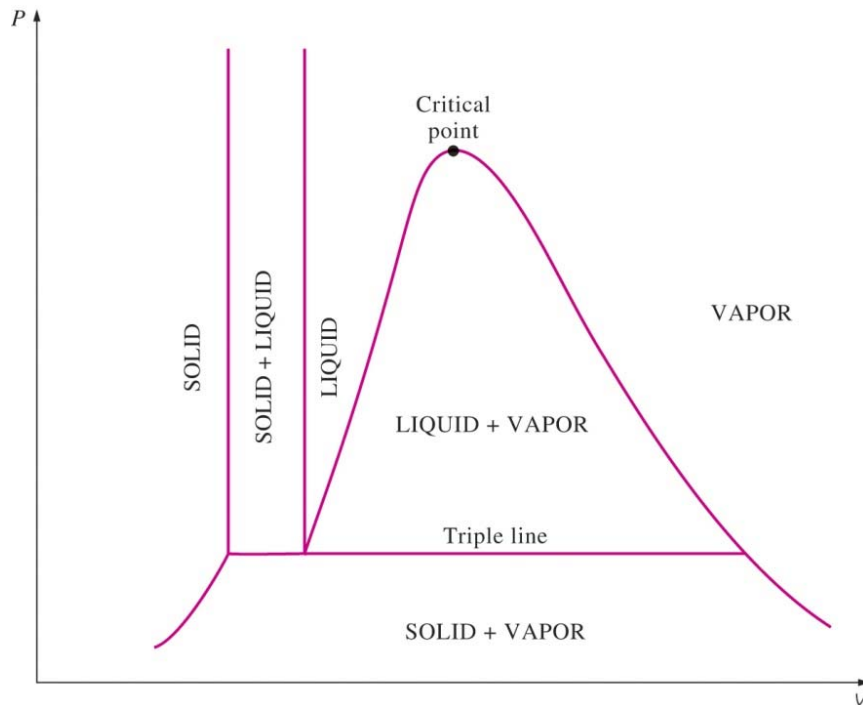
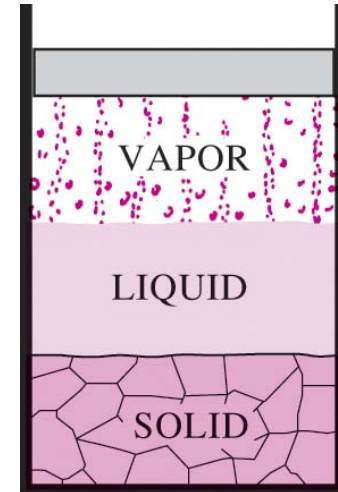
The pressure in a piston-cylinder device can be reduced by reducing the weight of the piston.

$P$ - $v$  diagram of a pure substance.

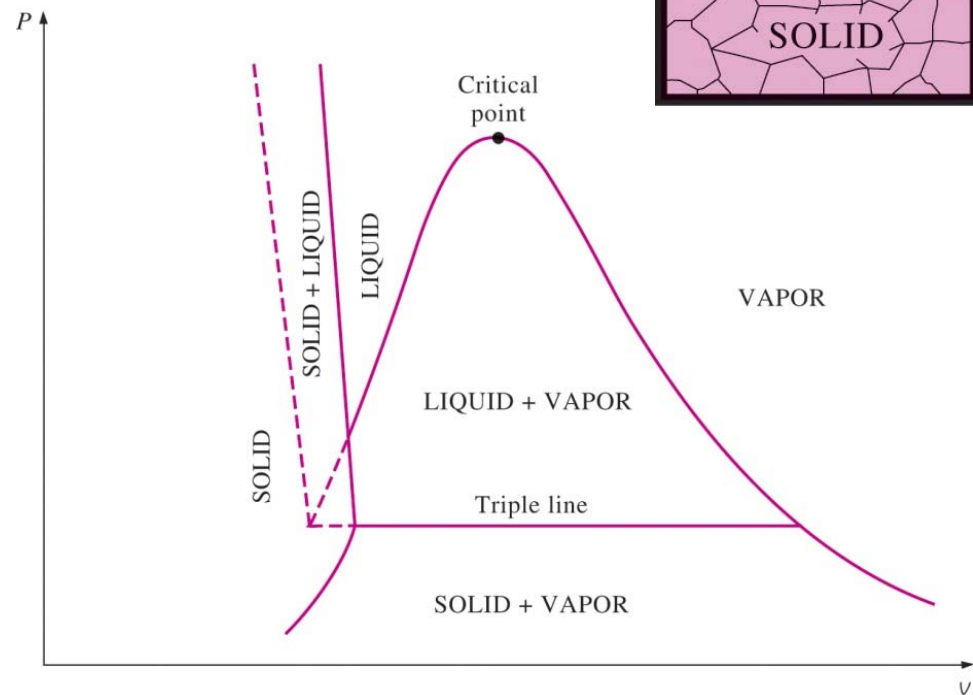
# EXTENDING THE DIAGRAMS TO INCLUDE THE SOLID PHASE

For water,  
 $T_{tp} = 0.01^\circ\text{C}$   
 $P_{tp} = 0.6117 \text{ kPa}$

At triple-point pressure and temperature, a substance exists in three phases in equilibrium.



*P-v diagram of a substance that contracts on freezing.*



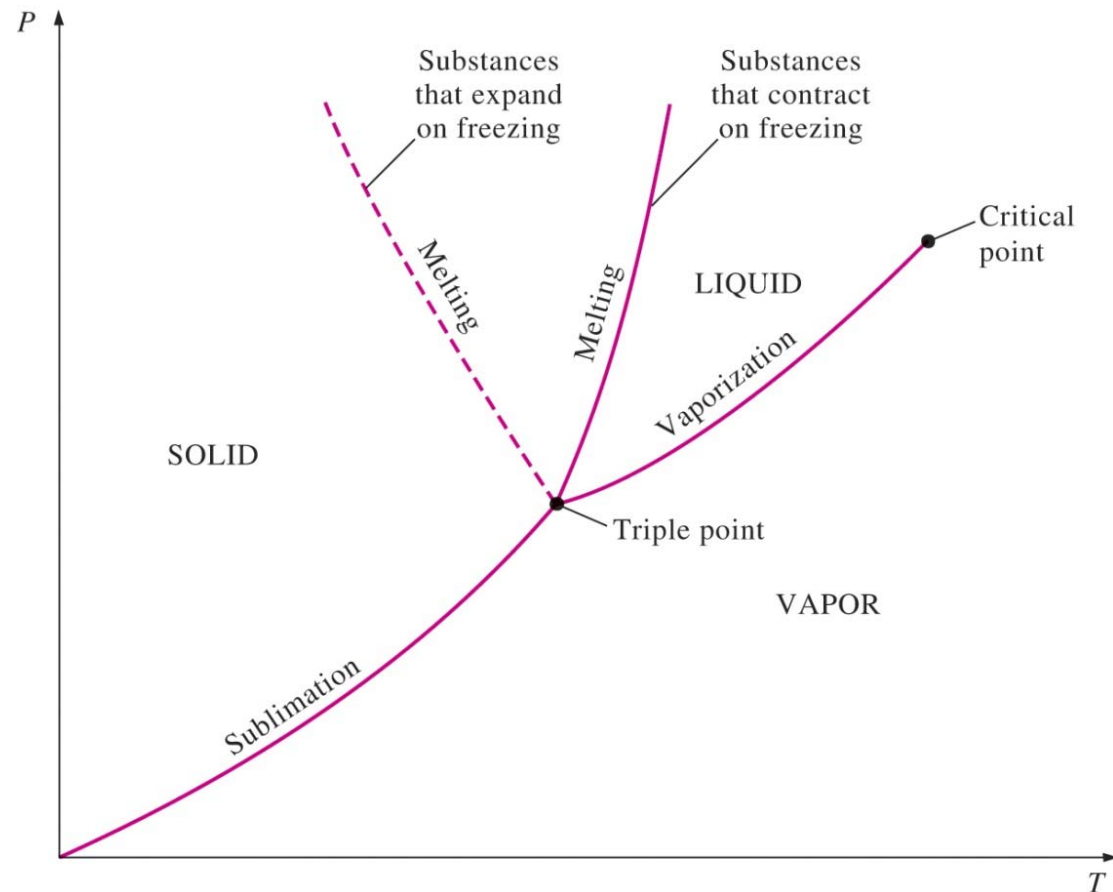
*P-v diagram of a substance that expands on freezing (such as water).*

# Phase Diagram

**Sublimation:** Passing from the solid phase directly into the vapor phase.

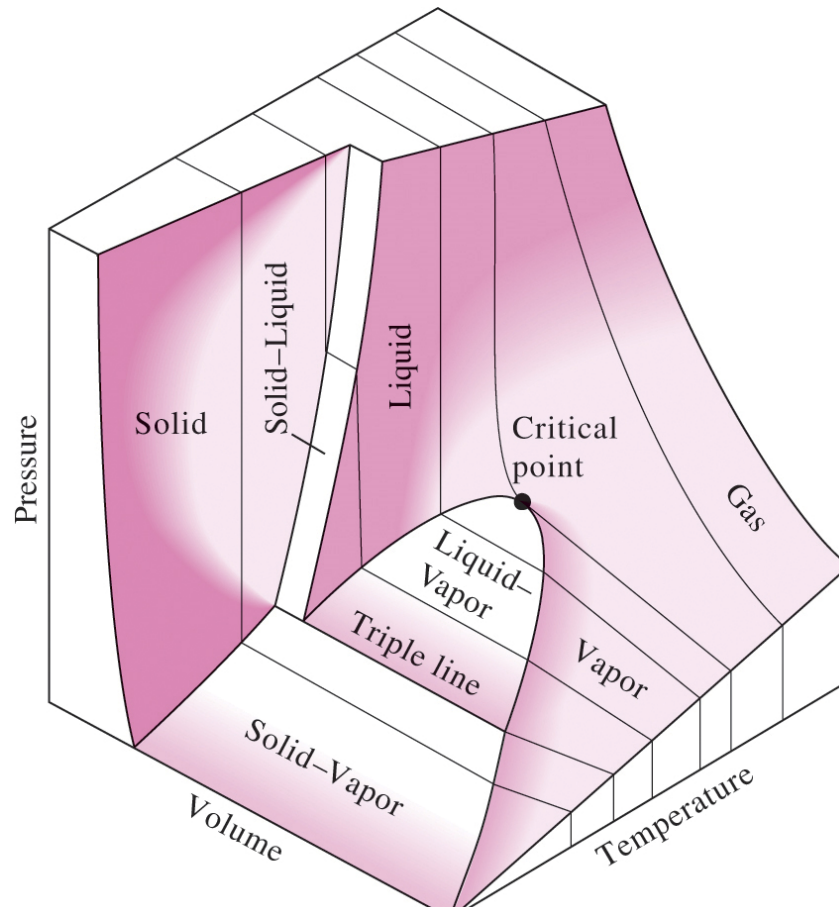


At low pressures (below the triple-point value), solids evaporate without melting first (*sublimation*).

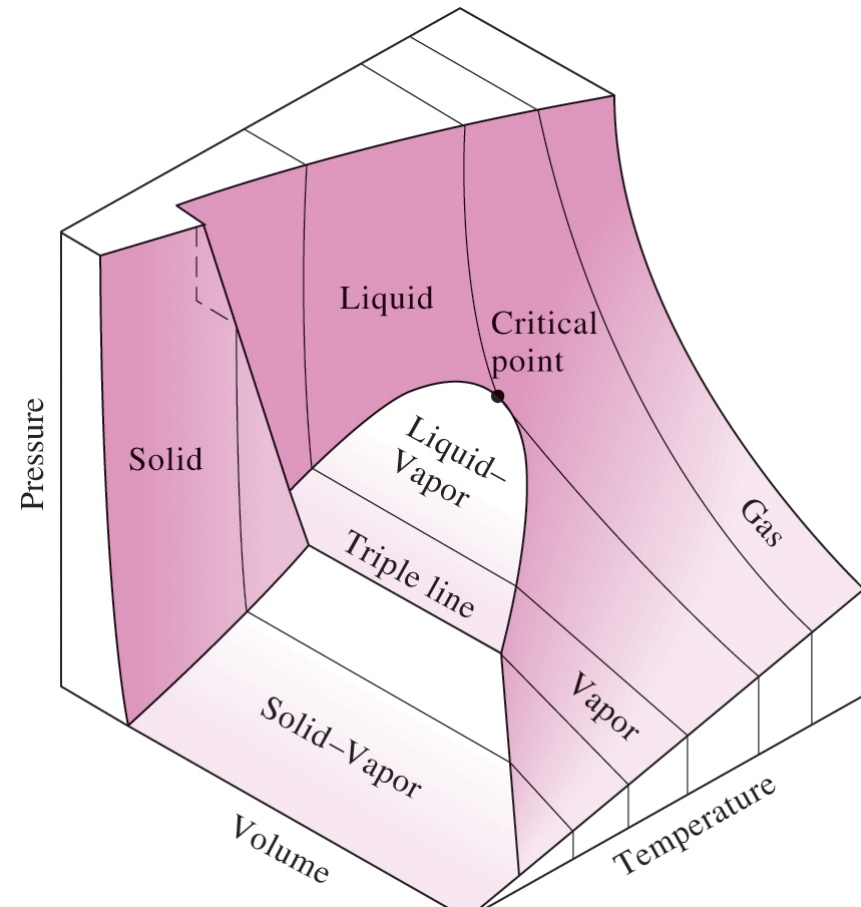


$P$ - $T$  diagram of pure substances.

The  $P$ - $v$ - $T$  surfaces present a great deal of information at once, but in a thermodynamic analysis it is more convenient to work with two-dimensional diagrams, such as the  $P$ - $v$  and  $T$ - $v$  diagrams.



$P$ - $v$ - $T$  surface of a substance that contracts on freezing.



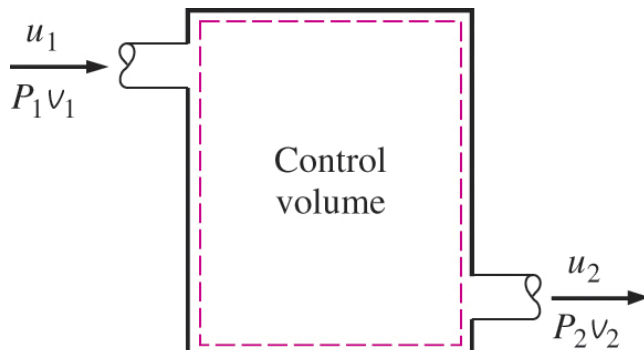
$P$ - $v$ - $T$  surface of a substance that expands on freezing (like water).

# 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.

## Enthalpy—A Combination Property

$$h = u + Pv \quad (\text{kJ/kg}) \quad H = U + PV \quad (\text{kJ})$$



The combination  $u + Pv$  is frequently encountered in the analysis of control volumes.

$$\begin{aligned} \text{kPa} \cdot \text{m}^3 &\equiv \text{kJ} \\ \text{kPa} \cdot \text{m}^3/\text{kg} &\equiv \text{kJ/kg} \\ \text{bar} \cdot \text{m}^3 &\equiv 100 \text{ kJ} \\ \text{MPa} \cdot \text{m}^3 &\equiv 1000 \text{ kJ} \\ \text{psi} \cdot \text{ft}^3 &\equiv 0.18505 \text{ Btu} \end{aligned}$$

The product *pressure*  $\times$  *volume* has energy units.



# SATURATED LIQUID AND SATURATED VAPOR STATES

- Table A–4: Saturation properties of water under temperature.
- Table A–5: Saturation properties of water under pressure.

A partial list of Table A–4.

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

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor

$v_f$  = specific volume of saturated liquid

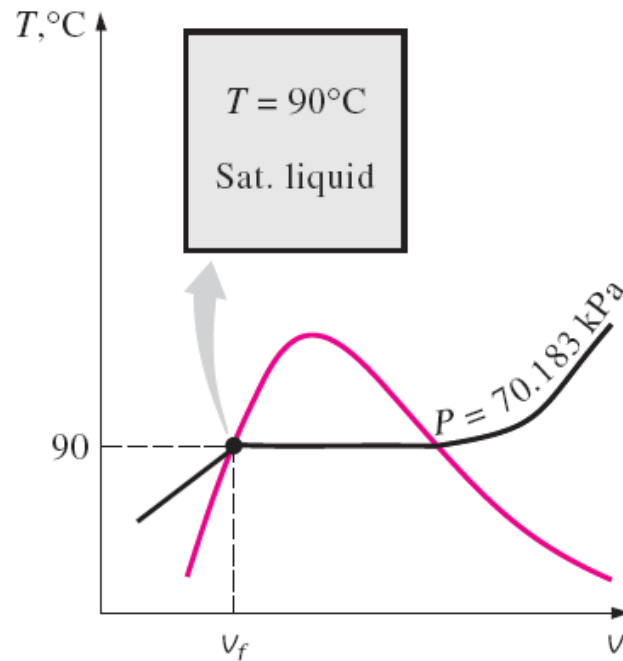
$v_g$  = specific volume of saturated vapor

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

**Enthalpy of vaporization,  $h_{fg}$  (Latent heat of vaporization):** The amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.

### EXAMPLE 3-1

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** A rigid tank contains saturated liquid water. The pressure and volume of the tank are to be determined.

Since saturation conditions exist in the tank, the pressure must be the saturation pressure at 90°C:

$$P = P_{\text{sat @ } 90^\circ\text{C}} = \mathbf{70.183 \text{ kPa}}$$

The specific volume of the saturated liquid at 90°C is

$$v = v_{f @ 90^\circ\text{C}} = 0.001036 \text{ m}^3/\text{kg}$$

The total volume of the tank is

$$V = mv = (50 \text{ kg})(0.001036 \text{ m}^3/\text{kg}) = \mathbf{0.0518 \text{ m}^3}$$

### EXAMPLE 3-2

A piston–cylinder device contains  $0.06 \text{ m}^3$  of saturated water vapor at 350-kPa pressure. Determine the temperature and the mass of the vapor inside the cylinder.

The temperature inside must be the saturation temperature at this pressure:

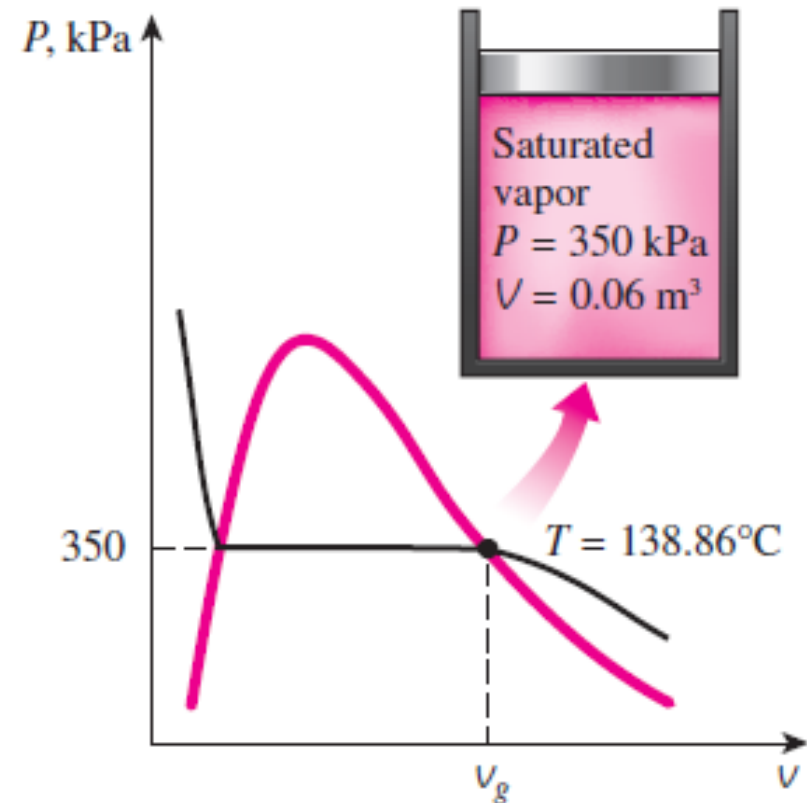
$$T = T_{\text{doy}} @ 350 \text{ kPa} = 138.86^\circ\text{C} \quad (\text{Tablo A-5})$$

The specific volume of the saturated vapor at 350 kPa

$$v = v_g @ 350 \text{ kPa} = 0.52422 \text{ m}^3/\text{kg}$$

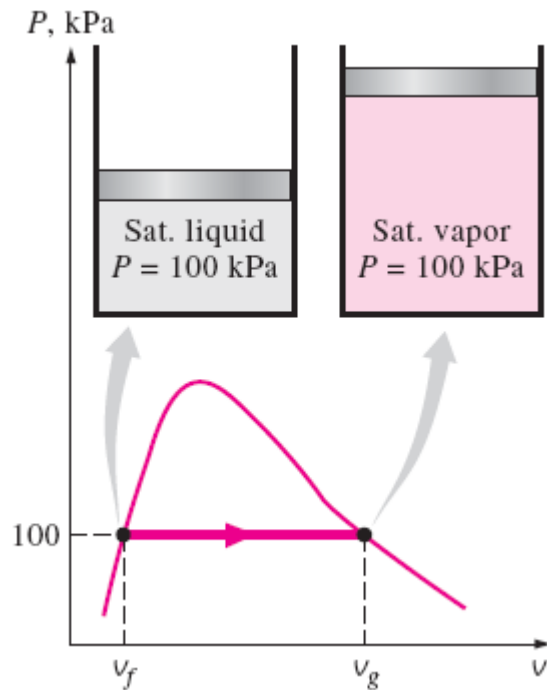
the mass of water vapor inside the cylinder becomes

$$m = \frac{V}{v} = \frac{0.06 \text{ m}^3}{0.52422 \text{ m}^3/\text{kg}} = 0.114 \text{ kg}$$



### EXAMPLE 3-3

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 added to the water.



**Solution** Saturated liquid water is vaporized at constant pressure. The volume change and the energy added are to be determined.

(a) the volume change

$$v_{fg} = v_g - v_f = 1.6941 - 0.001043 = 1.6931 \text{ m}^3/\text{kg}$$

$$\Delta V = m v_{fg} = (0.2 \text{ kg})(1.6931 \text{ m}^3/\text{kg}) = \mathbf{0.3386 \text{ m}^3}$$

(b) the amount of energy added to the water.

$$h_{fg} = 2257.5 \text{ kJ/kg for water at 100 kPa.}$$

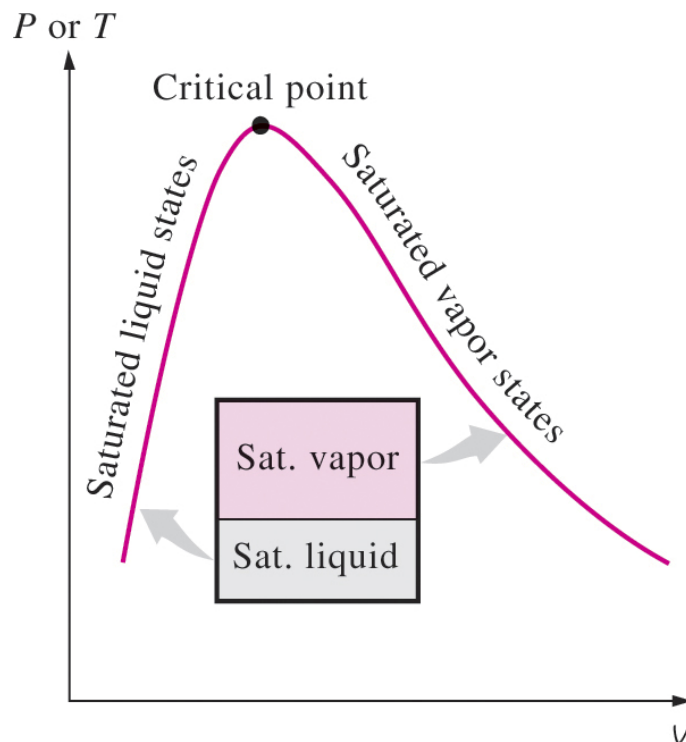
$$m h_{fg} = (0.2 \text{ kg})(2257.5 \text{ kJ/kg}) = \mathbf{451.5 \text{ kJ}}$$

# SATURATED LIQUID-VAPOR MIXTURE

**Quality,  $x$**  : The ratio of the mass of vapor to the total mass of the mixture.

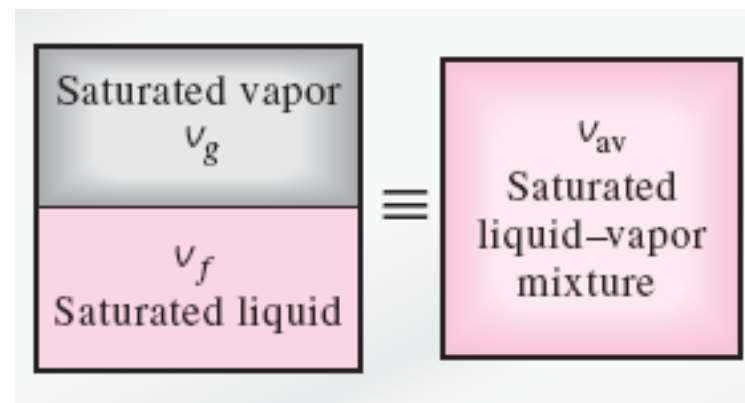
**Quality is between 0 and 1  $\rightarrow$  0: sat. liquid, 1: sat. vapor.**

*The properties of the saturated liquid are the same whether it exists alone or in a mixture with saturated vapor.*



$$x = \frac{m_{\text{vapor}}}{m_{\text{total}}} \quad m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapor}} = m_f + m_g$$

Temperature and pressure are dependent properties for a mixture.



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

A two-phase system can be treated as a homogeneous mixture for convenience.

$$V = V_f + V_g$$

$$V = mV \longrightarrow m_t v_{av} = m_f v_f + m_g v_g$$

$$m_f = m_t - m_g \longrightarrow m_t v_{av} = (m_t - m_g) v_f + m_g v_g$$

$$v_{av} = (1 - x) v_f + x v_g$$

$$v_{av} = v_f + x v_{fg} \quad (\text{m}^3/\text{kg})$$

$$x = \frac{v_{av} - v_f}{v_{fg}}$$

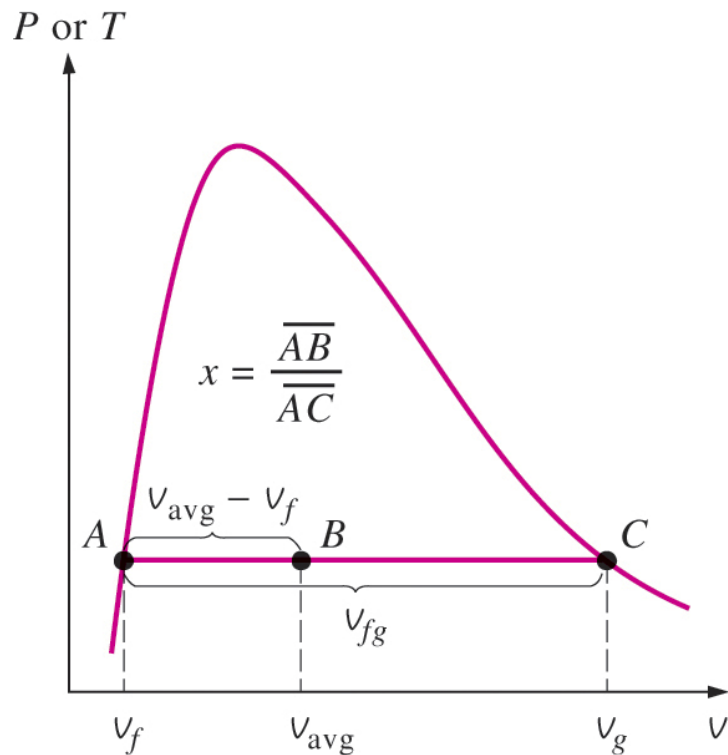
$$u_{av} = u_f + x u_{fg} \quad (\text{kJ/kg})$$

$$h_{av} = h_f + x h_{fg} \quad (\text{kJ/kg})$$

$$y \longrightarrow v, u, \text{ or } h.$$

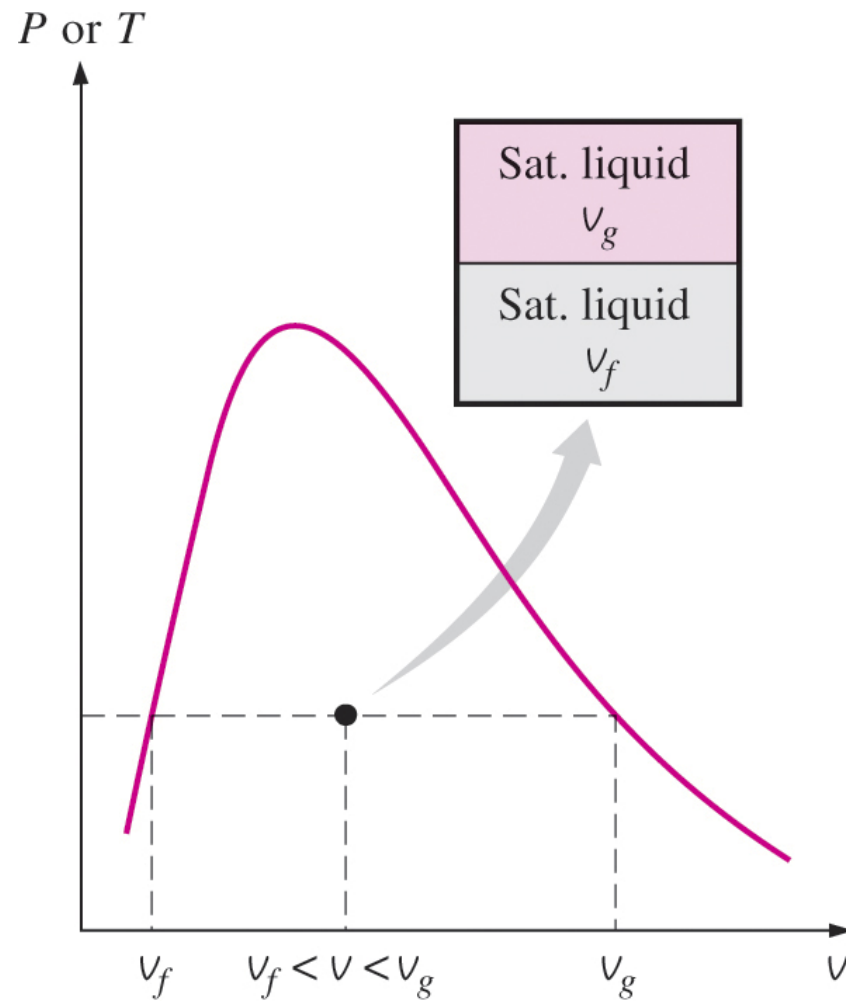
$$y_{av} = y_f + x y_{fg}$$

$$y_f \leq y_{av} \leq y_g$$



The  $v$  value of a saturated liquid–vapor mixture lies between the  $v_f$  and  $v_g$  values at the specified  $T$  or  $P$ .

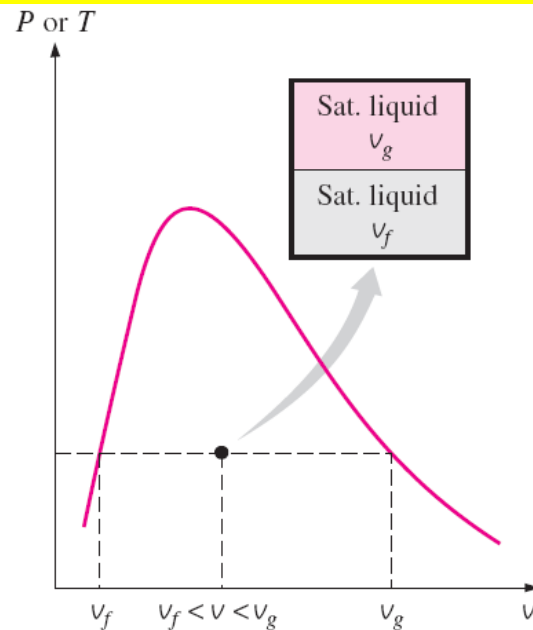




Quality is related to the horizontal distances on  $P$ - $v$  and  $T$ - $v$  diagrams.

### EXAMPLE 3-4

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** A rigid tank contains saturated mixture. The pressure and the volume of the tank are to be determined.

(a) the pressure in the tank

$$P = P_{\text{sat @ } 90^\circ\text{C}} = 70.183 \text{ kPa}$$

(b) the volume of the tank.

At 90°C, we have  $v_f = 0.001036 \text{ m}^3/\text{kg}$ ,  $v_g = 2.3593 \text{ m}^3/\text{kg}$

$$\begin{aligned} V &= V_f + V_g = m_f v_f + m_g v_g \\ &= (8 \text{ kg})(0.001036 \text{ m}^3/\text{kg}) + (2 \text{ kg})(2.3593 \text{ m}^3/\text{kg}) \\ &= 4.73 \text{ m}^3 \end{aligned}$$

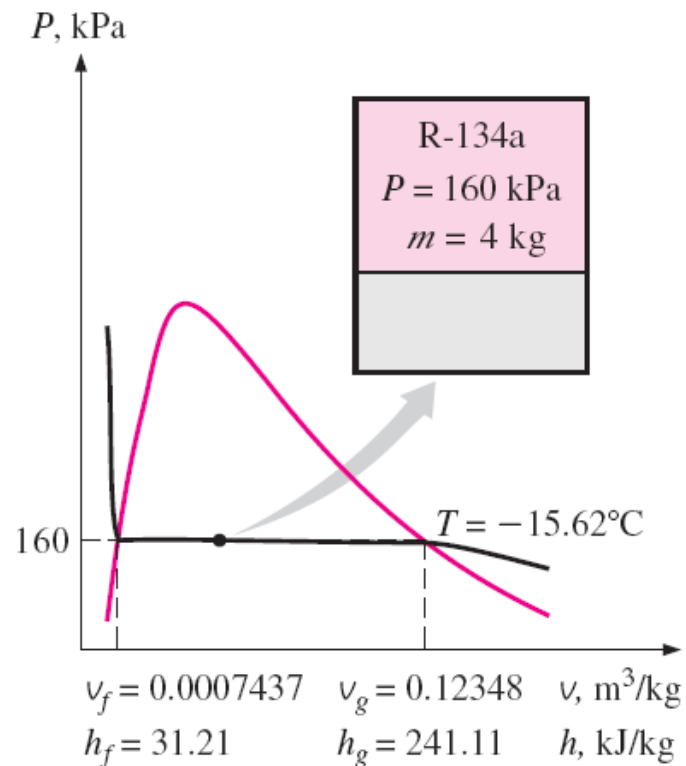
$$x = \frac{m_g}{m_t} = \frac{2 \text{ kg}}{10 \text{ kg}} = 0.2$$

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

$$V = m v = (10 \text{ kg})(0.473 \text{ m}^3/\text{kg}) = 4.73 \text{ m}^3$$

### EXAMPLE 3-5

An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (a) the temperature of the refrigerant, (b) the quality, (c) the enthalpy of the refrigerant, and (d) the volume occupied by the vapor phase.



**Solution** A vessel is filled with refrigerant-134a. Properties of the refrigerant are to be determined.

(a) the temperature of the refrigerant,

$$v = \frac{V}{m} = \frac{0.080 \text{ m}^3}{4 \text{ kg}} = 0.02 \text{ m}^3/\text{kg}$$

$$v_f = 0.0007437 \text{ m}^3/\text{kg}$$

$$v_g = 0.12348 \text{ m}^3/\text{kg}$$

$$v_f < v < v_g$$

(Table A-12)

$$T = T_{\text{sat @ } 160 \text{ kPa}} = -15.60^\circ\text{C}$$

(b) the quality can be determined from

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.02 - 0.0007437}{0.12348 - 0.0007437} = 0.157$$

(c) At 160 kPa, we also read from Table A-12 that  $h_f = 31.21$  kJ/kg and  $h_{fg} = 209.90$  kJ/kg. Then,

$$\begin{aligned} h &= h_f + xh_{fg} \\ &= 31.21 \text{ kJ/kg} + (0.157)(209.90 \text{ kJ/kg}) \\ &= \mathbf{64.2 \text{ kJ/kg}} \end{aligned}$$

(d) the volume occupied by the vapor phase.

The mass of the vapor is

$$m_g = xm_t = (0.157)(4 \text{ kg}) = 0.628 \text{ kg}$$

$$V_g = m_g v_g = (0.628 \text{ kg})(0.12348 \text{ m}^3/\text{kg}) = \mathbf{0.0775 \text{ m}^3} \text{ (or 77.5 L)}$$

The rest of the volume (2.5 L) is occupied by the liquid.

# 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.

In this region, temperature and pressure are independent properties.

| $T, ^\circ\text{C}$                          | $v, \text{m}^3/\text{kg}$ | $u, \text{kJ/kg}$ | $h, \text{kJ/kg}$ |
|--|---------------------------|-------------------|-------------------|
| $P = 0.1 \text{ MPa} (99.61^\circ\text{C})$  |                           |                   |                   |
| Sat.   | 1.6941                    | 2505.6            | 2675.0            |
| 100  | 1.6959                    | 2506.2            | 2675.8            |
| 150  | 1.9367                    | 2582.9            | 2776.6            |
| $\vdots$                                     | $\vdots$                  | $\vdots$          | $\vdots$          |
| 1300   | 7.2605                    | 4687.2            | 5413.3            |
| $P = 0.5 \text{ MPa} (151.86^\circ\text{C})$ |                           |                   |                   |
| Sat.   | 0.37483                   | 2560.7            | 2748.1            |
| 200  | 0.42503                   | 2643.3            | 2855.8            |
| 250  | 0.47443                   | 2723.8            | 2961.0            |

Compared to saturated vapor, superheated vapor is characterized by

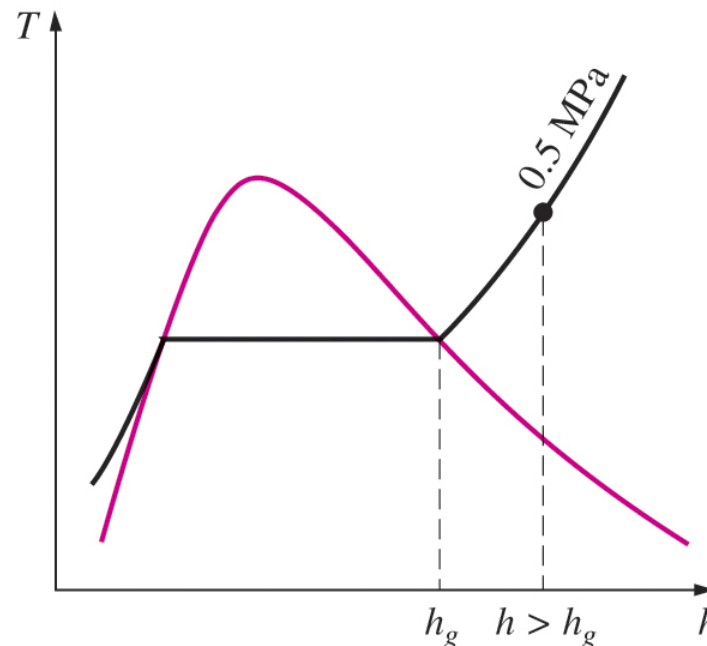
Lower pressures ( $P < P_{\text{sat}}$  at a given  $T$ )

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  $T$ )



At a specified  $P$ , superheated vapor exists at a higher  $h$  than the saturated vapor.

### EXAMPLE 3-6

Determine the internal energy of water at 300 kPa and 200°C

At 300 kPa, the saturation temperature is 120.21°C. Since  $T > T_{\text{sat}}$ , the water is in the superheated vapor region.

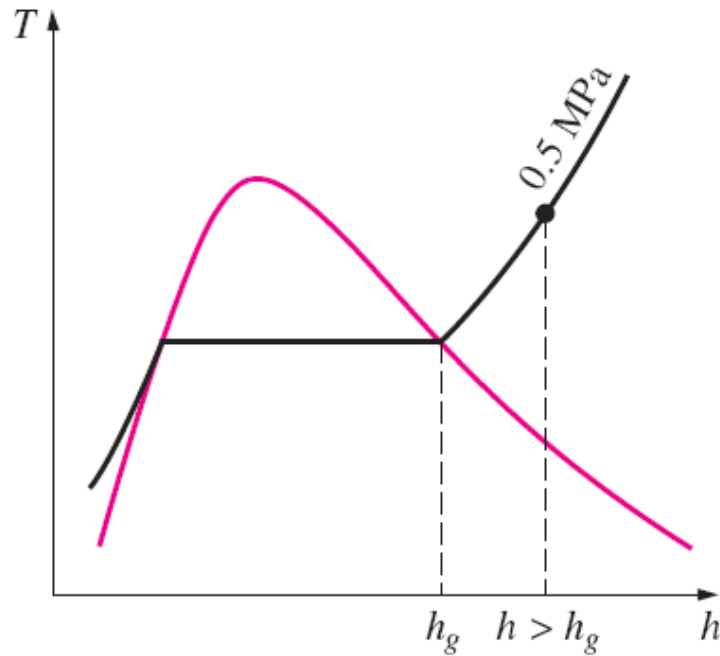
Then the internal energy at the given temperature and pressure is determined from the superheated vapor table.

$$u = 2808.8 \text{ kJ/kg}$$



### EXAMPLE 3-7

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



**Solution** The temperature of water at a specified state is to be determined.

At 0.5 MPa, the enthalpy of saturated water vapor is  $h_g = 2748.1$  kJ/kg. Since  $h > h_g$ , as shown in Figure, we again have superheated vapor. Under 0.5 MPa in Table A-6 we read

| $T, ^\circ\text{C}$ | $h, \text{kJ/kg}$ |
|---------------------|-------------------|
| 200                 | 2855.8            |
| 250                 | 2961.0            |

By linear interpolation it is determined to be

$$T = 216.3^\circ\text{C}$$

# COMPRESSED LIQUID

The compressed liquid properties depend on temperature much more strongly than they do on pressure.

$$y \cong y_{f@T} \quad y \rightarrow v, u, \text{ or } h$$

A more accurate relation for

$$h \cong h_{f@T} + v_{f@T}(P - P_{\text{sat}@T})$$

Given:  $P$  and  $T$

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

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

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

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

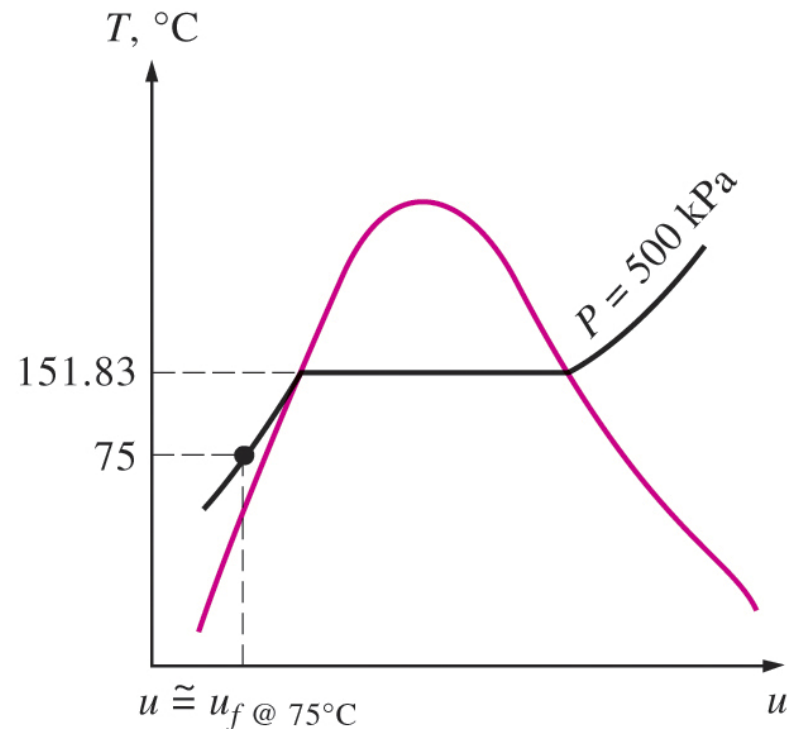
Higher pressures ( $P > P_{\text{sat}}$  at a given  $T$ )

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

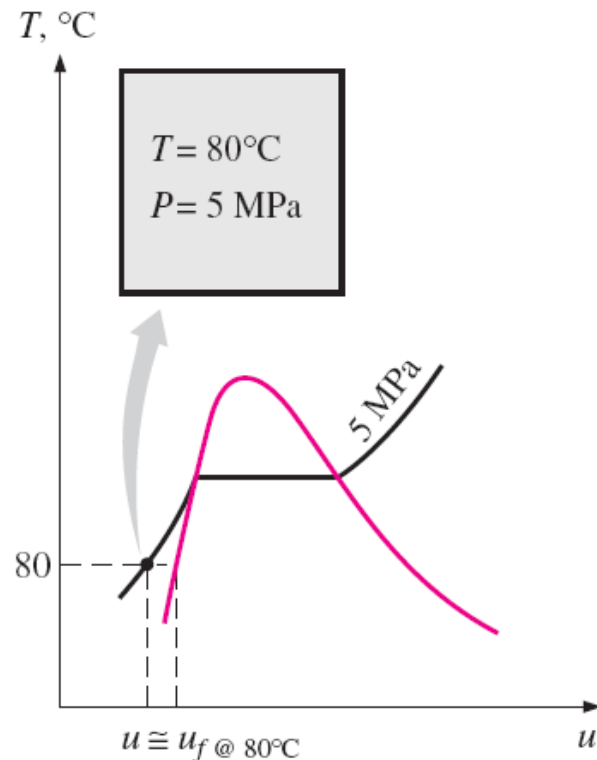
Lower enthalpies ( $h < h_f$  at a given  $P$  or  $T$ )



At a given  $P$  and  $T$ , a pure substance will exist as a compressed liquid if

### EXAMPLE 3-8

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** The exact and approximate values of the internal energy of liquid water are to be determined.

(a) From the compressed liquid table (Table A-7)

$$\left. \begin{array}{l} P = 5 \text{ MPa} \\ T = 80^\circ\text{C} \end{array} \right\} u = 333.82 \text{ kJ/kg}$$

(b) From the saturation table (Table A-4), we read

$$u \cong u_f @ 80^\circ\text{C} = 334.97 \text{ kJ/kg}$$

The error involved is

$$\frac{334.97 - 333.82}{333.82} \times 100 = 0.34\%$$

# REFERENCE STATE AND REFERENCE VALUES

- The values of  $u$ ,  $h$ , and  $s$  cannot be measured directly, and they are calculated from measurable properties using the relations between properties.
- However, those relations give the *changes* in properties, not the values of properties at specified states.
- Therefore, we need to choose a convenient *reference state* and assign a value of *zero* for a convenient property or properties at that state.
- The reference state for water is  $0.01^{\circ}\text{C}$  and for R-134a is  $-40^{\circ}\text{C}$  in tables.
- Some properties may have negative values as a result of the reference state chosen.
- Sometimes different tables list different values for some properties at the same state as a result of using a different reference state.
- However, In thermodynamics we are concerned with the *changes* in properties, and the reference state chosen is of no consequence in calculations.

### EXAMPLE 3-9

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

| $T, ^\circ\text{C}$ | $P, \text{kPa}$ | $u, \text{kJ/kg}$ | $x$ | Phase description |
|---------------------|-----------------|-------------------|-----|-------------------|
| (a)                 | 200             |                   | 0.6 |                   |
| (b) 125             |                 | 1600              |     |                   |
| (c)                 | 1000            | 2950              |     |                   |
| (d) 75              | 500             |                   |     |                   |
| (e)                 | 850             |                   | 0.0 |                   |

(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:

$$T = T_{\text{sat @ 200 kPa}} = \mathbf{120.21^\circ\text{C}} \quad (\text{Table A-5})$$

At 200 kPa, we also read from Table A-5 that  $u_f = 504.50 \text{ kJ/kg}$  and  $u_{fg} = 2024.6 \text{ kJ/kg}$ . Then the average internal energy of the mixture is

$$\begin{aligned} u &= u_f + xu_{fg} \\ &= 504.50 \text{ kJ/kg} + (0.6)(2024.6 \text{ kJ/kg}) \\ &= \mathbf{1719.26 \text{ kJ/kg}} \end{aligned}$$

(b) First go to the saturation table and determine the  $u_f$  and  $u_g$  values at the given temperature. At 125°C, we read  $u_f = 524.83$  kJ/kg and  $u_g = 2534.3$  kJ/kg. Compare the given  $u$  value to these  $u_f$  and  $u_g$  values, keeping in mind that

if  $u < u_f$  we have *compressed liquid*  
 if  $u_f \leq u \leq u_g$  we have *saturated mixture*  
 if  $u > u_g$  we have *superheated vapor*

$$P = P_{\text{sat @ } 125^\circ\text{C}} = \mathbf{232.23 \text{ kPa}} \quad (\text{Table A-4})$$

$$x = \frac{u - u_f}{u_{fg}} = \frac{1600 - 524.83}{2009.5} = \mathbf{0.535}$$

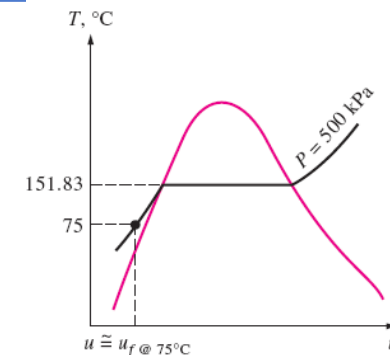
(c) At 1 MPa  $u_f = 761.39$  kJ/kg and  $u_g = 2582.8$  kJ/kg. The specified  $u$  value is 2950 kJ/kg, which is greater than the  $u_g$  value at 1 MPa. Superheated vapor, and the temperature at this state is determined from the superheated vapor table by interpolation to be

$$T = \mathbf{395.2^\circ\text{C}} \quad (\text{Table A-6})$$

(d) The temperature and pressure are given, to determine the region, we go to the saturation table (Table A-5) and determine the saturation temperature value at the given pressure. At 500 kPa, we have  $T_{\text{sat}} = 151.83^\circ\text{C}$ .

if  $T < T_{\text{sat @ given } P}$  we have *compressed liquid*  
 if  $T = T_{\text{sat @ given } P}$  we have *saturated mixture*  
 if  $T > T_{\text{sat @ given } P}$  we have *superheated vapor*

$$u \cong u_f @ 75^\circ\text{C} = \mathbf{313.99 \text{ kJ/kg}} \quad (\text{Table A-4})$$





(e) The quality is given to be  $x = 0$ , and thus we have saturated liquid at the specified pressure of 850 kPa. Then the temperature must be the saturation temperature at the given pressure, and the internal energy must have the saturated liquid value:

$$T = T_{\text{sat @ 850 kPa}} = 172.94^{\circ}\text{C} \quad (\text{Table A-5})$$

$$u = u_f @ 850 \text{ kPa} = 731.00 \text{ kJ/kg} \quad (\text{Table A-5})$$

# THE IDEAL-GAS EQUATION OF STATE

- **Equation of state:** Any equation that relates the pressure, temperature, and specific volume of a substance.
- The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the  $P$ - $v$ - $T$  behavior of a gas quite accurately within some properly selected region.

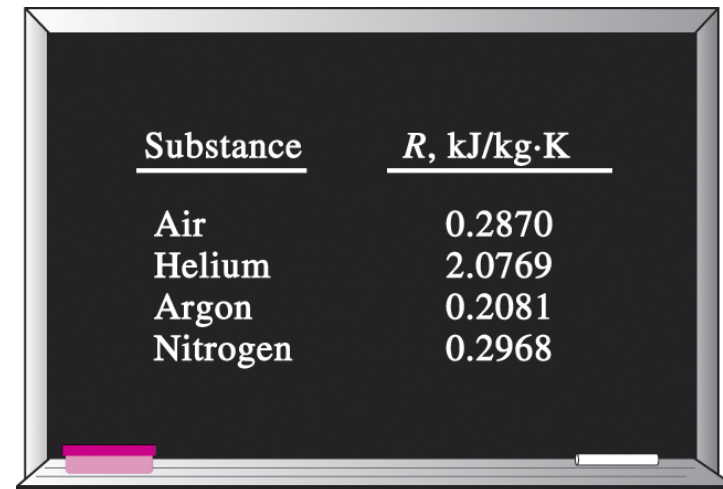
## Ideal gas equation of state

$$P = R \left( \frac{T}{v} \right)$$

$$Pv = RT$$

$$R = \frac{R_u}{M} \quad (\text{kJ/kg} \cdot \text{K} \text{ or } \text{kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})$$

$$R_u = \begin{cases} 8.31447 \text{ kJ/kmol} \cdot \text{K} \\ 8.31447 \text{ kPa} \cdot \text{m}^3/\text{kmol} \cdot \text{K} \\ 0.0831447 \text{ bar} \cdot \text{m}^3/\text{kmol} \cdot \text{K} \\ 1.98588 \text{ Btu/lbmol} \cdot \text{R} \\ 10.7316 \text{ psia} \cdot \text{ft}^3/\text{lbmol} \cdot \text{R} \\ 1545.37 \text{ ft} \cdot \text{lbf/lbmol} \cdot \text{R} \end{cases}$$



| Substance | $R$ , kJ/kg·K |
|-----------|---------------|
| Air       | 0.2870        |
| Helium    | 2.0769        |
| Argon     | 0.2081        |
| Nitrogen  | 0.2968        |

Different substances have different gas constants.

$R$ : gas constant  
 $M$ : molar mass (kg/kmol)  
 $R_u$ : universal gas constant

Mass = Molar mass  $\times$  Mole number

Ideal gas equation at two states for a fixed mass

$$m = MN$$

$$V = m v \longrightarrow PV = mRT$$

$$mR = (MN)R = NR_u \longrightarrow PV = NR_u T$$

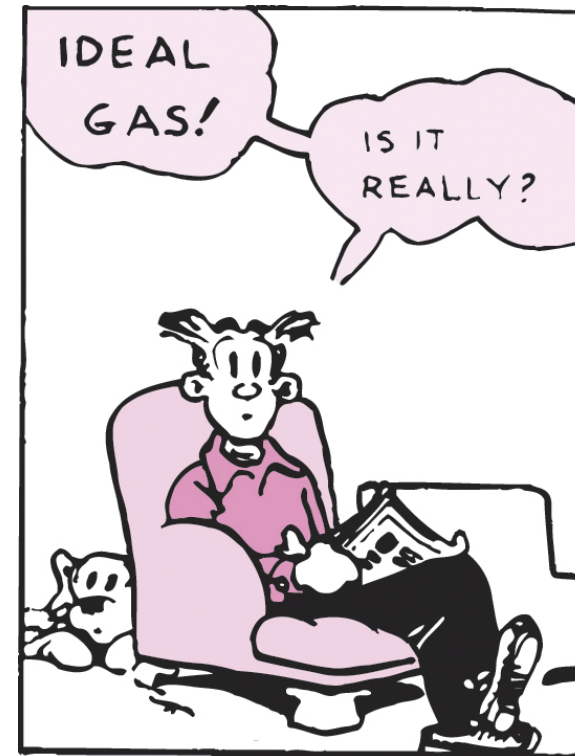
$$V = N\bar{v} \longrightarrow P\bar{v} = R_u T$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Real gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).

| Per unit mass             | Per unit mole                     |
|---------------------------|-----------------------------------|
| $v, \text{m}^3/\text{kg}$ | $\bar{v}, \text{m}^3/\text{kmol}$ |
| $u, \text{kJ/kg}$         | $\bar{u}, \text{kJ/kmol}$         |
| $h, \text{kJ/kg}$         | $\bar{h}, \text{kJ/kmol}$         |

Properties per unit mole are denoted with a bar on the top.

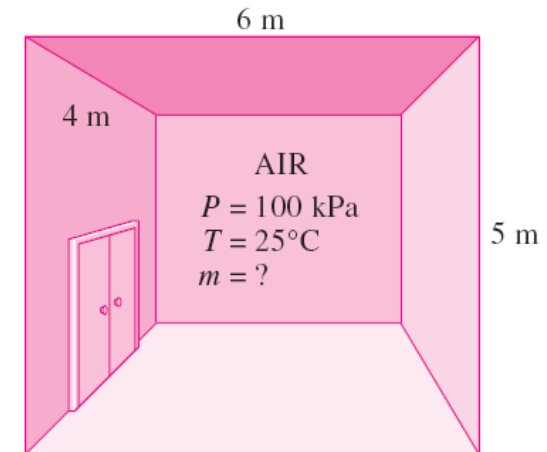


The ideal-gas relation often is not applicable to real gases; thus, care should be exercised when using it.

### EXAMPLE 3-10

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

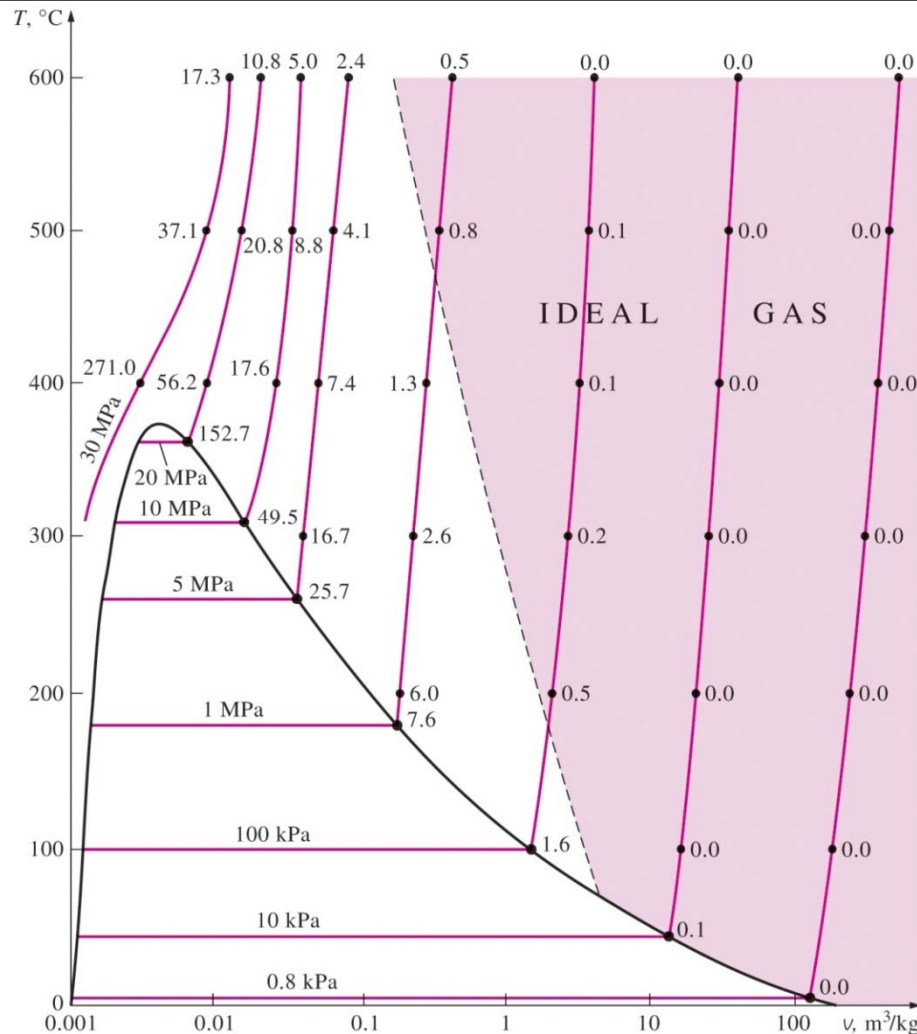
**Solution** The mass of air in a room is to be determined.



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

$$m = \frac{PV}{RT} = \frac{(100 \text{ kPa})(120 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(298 \text{ K})} = \mathbf{140.3 \text{ kg}}$$

# IS WATER VAPOR AN IDEAL GAS?



- At pressures below 10 kPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent).
- At higher pressures, however, the ideal gas assumption yields unacceptable errors, particularly in the vicinity of the critical point and the saturated vapor line.
- In air-conditioning applications, the water vapor in the air can be treated as an ideal gas. Why?
- In steam power plant applications, however, the pressures involved are usually very high; therefore, ideal-gas relations should not be used.

Percentage of error ( $[(v_{\text{table}} - v_{\text{ideal}})/v_{\text{table}}] \times 100$ ) involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.

# COMPRESSIBILITY FACTOR—A MEASURE OF DEVIATION FROM IDEAL-GAS BEHAVIOR

## Compressibility factor $Z$

A factor that accounts for the deviation of real gases from ideal-gas behavior at a given temperature and pressure.

$$Pv = ZRT$$

$$Z = \frac{Pv}{RT} \quad Z = \frac{v_{\text{actual}}}{v_{\text{ideal}}}$$



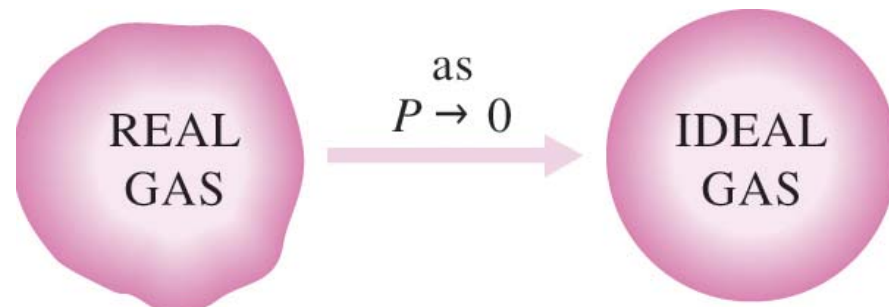
The compressibility factor is unity for ideal gases.

The farther away  $Z$  is from unity, the more the gas deviates from ideal-gas behavior.

*Gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).*

**Question:** What is the criteria for low pressure and high temperature?

**Answer:** The pressure or temperature of a gas is high or low relative to its critical temperature or pressure.



At very low pressures, all gases approach ideal-gas behavior (regardless of their temperature).



Reduced pressure and temperature

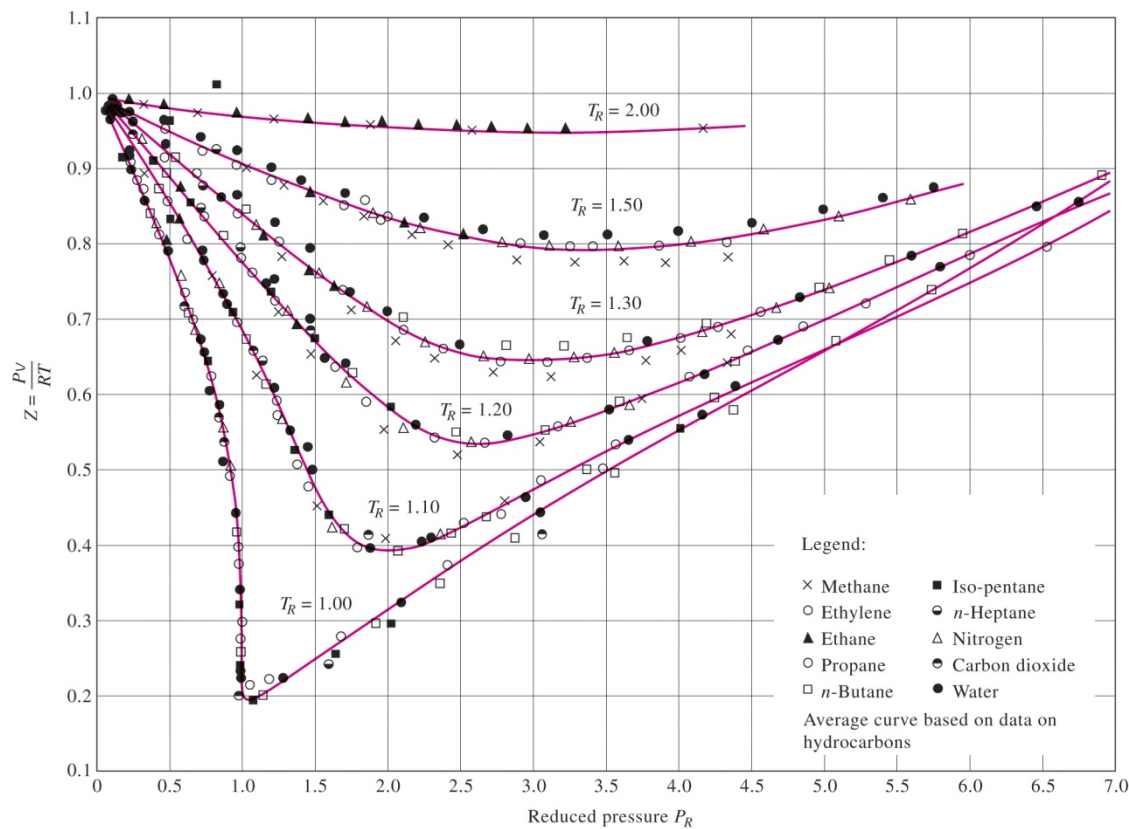
$$P_R = \frac{P}{P_{cr}} \quad \text{and} \quad T_R = \frac{T}{T_{cr}}$$

$$v_R = \frac{v_{actual}}{RT_{cr}/P_{cr}}$$

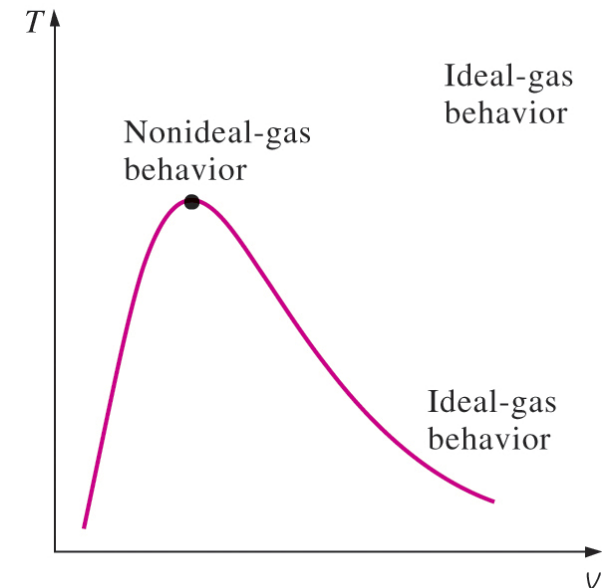
Pseudo-reduced specific volume

$$\left. \begin{aligned} P_R &= \frac{P}{P_{cr}} \\ v_R &= \frac{v}{RT_{cr}/P_{cr}} \end{aligned} \right\} Z = \dots \quad (\text{Fig. A-34})$$

Z can also be determined from a knowledge of  $P_R$  and  $v_R$ .



Comparison of Z factors for various gases.



Gases deviate from the ideal-gas behavior the most in the neighborhood of the critical point.



### EXAMPLE 3-11

Determine the specific volume of refrigerant-134a at 1 MPa and 50°C, using (a) the ideal-gas equation of state and (b) the generalized compressibility chart. Compare the values obtained to the actual value of 0.021796 m<sup>3</sup>/kg and determine the error involved in each case.

**Solution** The specific volume of refrigerant-134a is to be determined assuming ideal- and nonideal-gas behavior.

(a) The specific volume of refrigerant-134a under the ideal-gas assumption is

$$R = 0.0815 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K}$$

$$P_{\text{cr}} = 4.059 \text{ MPa}$$

$$T_{\text{cr}} = 374.2 \text{ K}$$

$$v = \frac{RT}{P} = \frac{(0.0815 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(323 \text{ K})}{1000 \text{ kPa}} = \mathbf{0.026325 \text{ m}^3/\text{kg}}$$

Therefore, treating the refrigerant-134a vapor as an ideal gas would result in an error of  $(0.026325 - 0.021796)/0.021796 = \mathbf{0.208}$ , or 20.8 percent in this case.

(b) To determine the correction factor  $Z$  from the compressibility chart, we first need to calculate the reduced pressure and temperature:

$$\left. \begin{aligned} P_R &= \frac{P}{P_{\text{cr}}} = \frac{1 \text{ MPa}}{4.059 \text{ MPa}} = 0.246 \\ T_R &= \frac{T}{T_{\text{cr}}} = \frac{323 \text{ K}}{374.2 \text{ K}} = 0.863 \end{aligned} \right\} Z = 0.84$$

$$v = Zv_{\text{ideal}} = (0.84)(0.026325 \text{ m}^3/\text{kg}) = \mathbf{0.022113 \text{ m}^3/\text{kg}}$$

# OTHER EQUATIONS OF STATE

Several equations have been proposed to represent the  $P$ - $v$ - $T$  behavior of substances accurately over a larger region with no limitations.

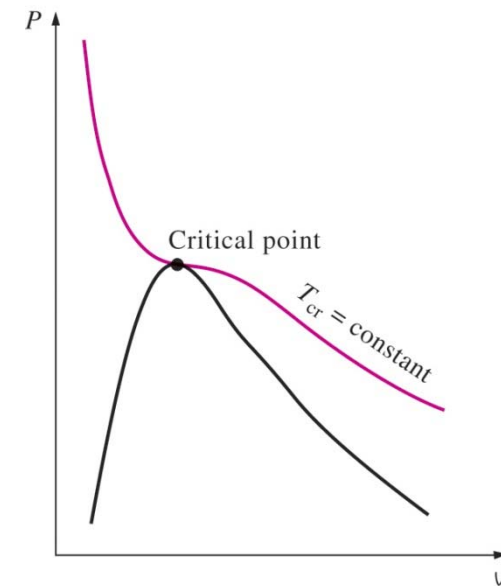
## Van der Waals Equation of State

$$\left(P + \frac{a}{v^2}\right)(v - b) = RT$$

$$a = \frac{27R^2T_{\text{cr}}^2}{64P_{\text{cr}}} \quad \text{and} \quad b = \frac{RT_{\text{cr}}}{8P_{\text{cr}}}$$

$$\left(\frac{\partial P}{\partial v}\right)_{T=T_{\text{cr}}=\text{const}} = 0 \quad \text{and} \quad \left(\frac{\partial^2 P}{\partial v^2}\right)_{T=T_{\text{cr}}=\text{const}} = 0$$

This model includes two effects not considered in the ideal-gas model: **the intermolecular attraction forces and the volume occupied by the molecules themselves**. The accuracy of the van der Waals equation of state is often inadequate.



Critical isotherm of a pure substance has an inflection point at the critical state.

# Beattie-Bridgeman Equation of State

$$P = \frac{R_u T}{\bar{V}^2} \left( 1 - \frac{c}{\bar{V} T^3} \right) (\bar{V} + B) - \frac{A}{\bar{V}^2}$$

$$A = A_0 \left( 1 - \frac{a}{\bar{V}} \right) \quad \text{and} \quad B = B_0 \left( 1 - \frac{b}{\bar{V}} \right)$$

The constants are given in Table 3–4 for various substances. It is known to be reasonably accurate for densities up to about  $0.8\rho_{\text{cr}}$ .

## Benedict-Webb-Rubin Equation of State

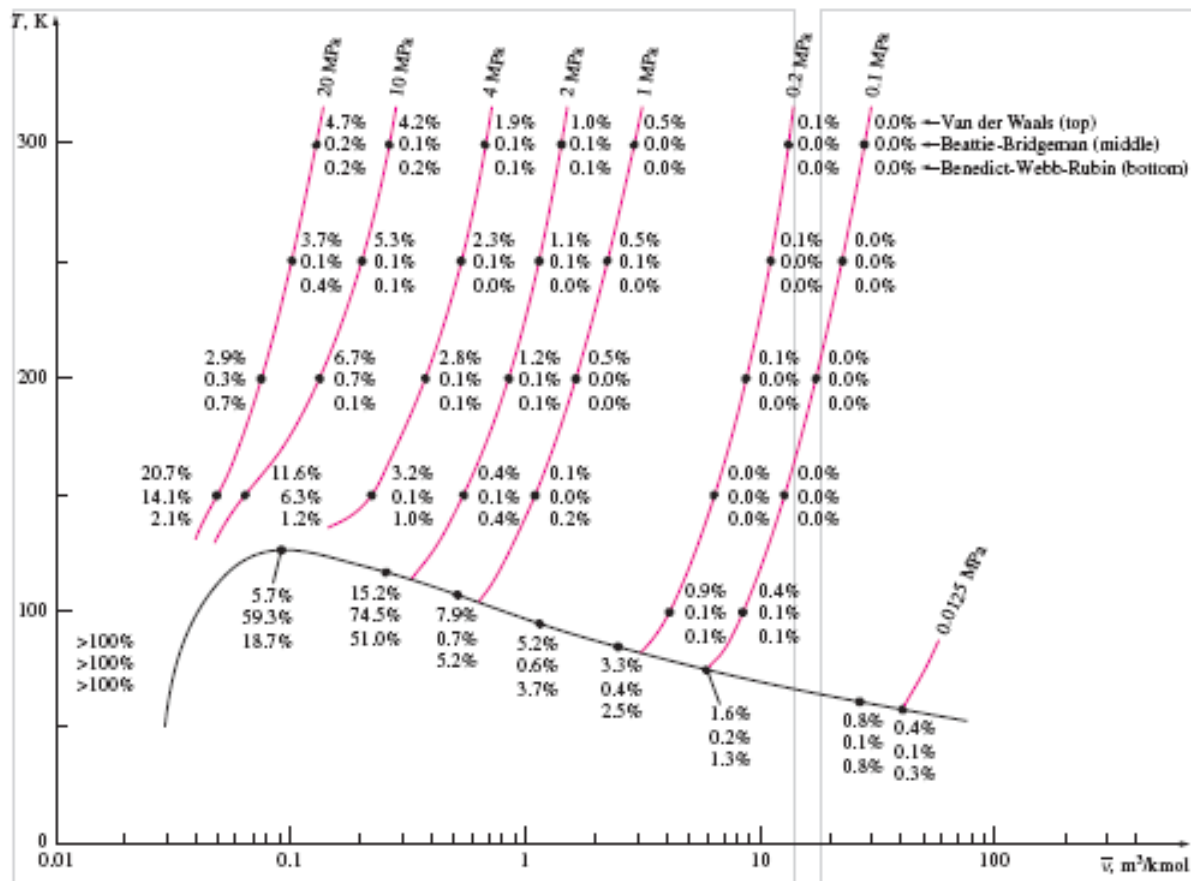
$$P = \frac{R_u T}{\bar{V}} + \left( B_0 R_u T - A_0 - \frac{C_0}{T^2} \right) \frac{1}{\bar{V}^2} + \frac{b R_u T - a}{\bar{V}^3} + \frac{a\alpha}{\bar{V}^6} + \frac{c}{\bar{V}^3 T^2} \left( 1 + \frac{\gamma}{\bar{V}^2} \right) e^{-\gamma/\bar{V}^2}$$

The constants are given in Table 3–4. This equation can handle substances at densities up to about  $2.5 \rho_{\text{cr}}$ .

## Virial Equation of State

$$P = \frac{RT}{v} + \frac{a(T)}{v^2} + \frac{b(T)}{v^3} + \frac{c(T)}{v^4} + \frac{d(T)}{v^5} + \dots$$

The coefficients  $a(T)$ ,  $b(T)$ ,  $c(T)$ , and so on, that are functions of temperature alone are called *virial coefficients*.



*van der Waals*: 2 constants.  
Accurate over a limited range.

*Beattie-Bridgeman*: 5 constants.  
Accurate for  $\rho \leq 0.8\rho_{cr}$ .

*Benedict-Webb-Rubin*: 8 constants.  
Accurate for  $\rho \leq 2.5\rho_{cr}$ .

*Strobridge*: 16 constants.  
More suitable for  
computer calculations.

*Virial*: may vary.  
Accuracy depends on the  
number of terms used.

Percentage of error involved in various equations of state for  
nitrogen ( $\% \text{ error} = [(|v_{\text{table}} - v_{\text{equation}}|)/v_{\text{table}}] \times 100$ ).

Complex equations of  
state represent the  $P$ - $v$ - $T$   
behavior of gases more  
accurately over a wider  
range.

# SUMMARY

- Pure substance
- Phases of a pure substance
- Phase-change processes of pure substances
  - Compressed liquid, Saturated liquid, Saturated vapor, Superheated vapor
  - Saturation temperature and Saturation pressure
- Property diagrams for phase change processes
  - The  $T$ - $v$  diagram, The  $P$ - $v$  diagram, The  $P$ - $T$  diagram, The  $P$ - $v$ - $T$  surface
- Property tables
  - Enthalpy
  - Saturated liquid, saturated vapor, Saturated liquid vapor mixture, Superheated vapor, compressed liquid
  - Reference state and reference values
- The ideal gas equation of state
  - Is water vapor an ideal gas?
- Compressibility factor
- Other equations of state

| Madde  | P(kPa) | T(°C) | x(%) | h(kj/kg) | Faz Durumu |
|--------|--------|-------|------|----------|------------|
| Su     | 200    | 50    |      |          |            |
| R-134a |        | 0     |      | 100      |            |
| Su     | 1700   | 300   |      |          |            |
| Hava   | 200    | 1000  |      |          |            |

| Madde  | P(kPa) | T(°C) | x(%) | h(kj/kg) | Faz Durumu         |
|--------|--------|-------|------|----------|--------------------|
| Su     | 200    | 50    | -    | 340,54   | Sıkıştırılmış sıvı |
| R-134a | 293,01 | 0     | 24   | 100      | Islak buhar        |
| Su     | 1700   | 300   | -    | 3032,65  | Kızgın buhar       |
| Hava   | 200    | 1000  | -    | 1363,95  | İdeal gaz          |



## SORU :

|    | Madde   | P(kPa) | T( $^{\circ}$ C) | h(kj/kg) | x(%) | Faz Durumu |
|----|---------|--------|------------------|----------|------|------------|
| a) | Su      | 300    |                  | 3486,6   |      |            |
| b) | Su      | 500    | 100              |          |      |            |
| c) | SA-134a |        | -20              | 100      |      |            |
| d) | SA-134a | 140    |                  |          | 60   |            |

|    | Madde   | P(kPa)        | T(°C)         | h(kj/kg)       | x(%)        | Faz Durumu                |
|----|---------|---------------|---------------|----------------|-------------|---------------------------|
| a) | Su      | 300           | <b>500</b>    | 3486,6         | -           | <b>Kızgın Bölge</b>       |
| b) | Su      | 500           | 100           | <b>419,17</b>  | -           | <b>Sıkıştırılmış sıvı</b> |
| c) | SA-134a | <b>132,82</b> | -20           | 100            | <b>34,9</b> | <b>Ara Bölge</b>          |
| d) | SA-134a | 140           | <b>-18,77</b> | <b>154,328</b> | 60          | <b>Ara Bölge</b>          |

## SORU :1

|    | Madde   | P(kPa) | T( $^{\circ}$ C) | u(kj/kg) | x(%) | Faz Durumu |
|----|---------|--------|------------------|----------|------|------------|
| a) | Su      | 500    | 200              |          |      |            |
| b) | Su      |        | 140              | 1600     |      |            |
| c) | SA-134a | 500    | -14              |          |      |            |
| d) | SA-134a | 200    |                  |          | 60   |            |

|    | Madde   | P(kPa)        | T(°C)         | u(kJ/kg)       | x(%)        | Faz Durumu                |
|----|---------|---------------|---------------|----------------|-------------|---------------------------|
| a) | Su      | 500           | 200           | <b>2643,3</b>  | -           | <b>Kızgın buhar</b>       |
| b) | Su      | <b>361,53</b> | 140           | 1600           | <b>51,5</b> | <b>Ara bölgede</b>        |
| c) | SA-134a | 500           | -14           | <b>33,17</b>   | -           | <b>Sıkıştırılmış sıvı</b> |
| d) | SA-134a | 200           | <b>-10,09</b> | <b>150,006</b> | 60          | <b>Ara bölgede</b>        |

## QUIZ-1

**SORU 1-** Aşağıda suya ait beş hal verilmiştir. Tablodaki boşlukları doldurunuz.

| Hal | P(kPa) | T(°C)  | x(%) | v(m <sup>3</sup> /kg) | Faz Durumu |
|-----|--------|--------|------|-----------------------|------------|
| 1   | 200    |        | 80   |                       |            |
| 2   | 300    | 133.52 |      |                       |            |
| 3   | 2000   | 300    |      |                       |            |
| 4   |        | 150    |      | 0.361                 |            |
| 5   | 5000   | 100    |      |                       |            |

**SORU 2-** 1 Atm basınçtaki potasyum yaklaşık 760°C sıcaklıkta buharlaşır. Bu basınca ait doymuş sıvı ve kuru doymuş buharın özgül hacimleri sırasıyla 0.0015 m<sup>3</sup>/kg ve 1.991 m<sup>3</sup>/kg'dır. Kuruluk derecesi 0.70 ise özgül hacmi bulunuz.

## QUIZ-1

**SORU 1-** Aşağıda suya ait beş hal verilmiştir. Tablodaki boşlukları doldurunuz.

| Hal | P(kPa) | T(°C) | x(%) | v(m <sup>3</sup> /kg) | Faz Durumu |
|-----|--------|-------|------|-----------------------|------------|
| 1   | 300    | 200   |      |                       |            |
| 2   | 300    |       | 65   |                       |            |
| 3   |        | 200   |      | 0.1050                |            |
| 4   | 10.000 |       |      | 0.0584                |            |
| 5   |        | 120   |      | 0.620                 |            |

**SORU 2-** 0.050 m<sup>3</sup> hacmindeki bir kabın hacminin % 80'i 25°C sıcaklıkta doymuş buhar, % 20'si aynı sıcaklıkta doymuş sıvı tarafından kaplanmıştır. Kaptaki sıvı ve buhar iyice karıştırılmaktadır. Karışımın kuruluk derecesini bulunuz.

| Hal | P(kPa) | T(°C) | x(%)  | v(m³/kg) | Faz Durumu   |
|-----|--------|-------|-------|----------|--------------|
| 1   | 300    | 200   | M     | 0.7163   | Kızgın Buhar |
| 2   | 300    | 133.6 | 65    | 0.394    | Islak Buhar  |
| 3   | 1553.7 | 200   | 0.823 | 0.1050   | Islak Buhar  |
| 4   | 10.000 | 1000  | M     | 0.0584   | Kızgın Buhar |
| 5   | 198.48 | 120   | 0.695 | 0.620    | Islak Buhar  |



Thermodynamics: An Engineering Approach, 5<sup>th</sup> Edition  
Yunus A. Cengel, Michael A. Boles  
McGraw-Hill, 2008

# Chapter 4

## ENERGY ANALYSIS OF CLOSED SYSTEMS

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# ENERGY ANALYSIS OF CLOSED SYSTEMS

4-1 Moving Boundary Work

Polytropic Process

4-2 Energy Balance for Closed Systems

4-3 Specific Heats

4-4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases

Specific Heat Relations of Ideal Gases

4-5 Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids

Internal Energy Changes

Enthalpy Changes

# Objectives

- Examine the moving boundary work or  $P dV$  work commonly encountered in reciprocating devices such as automotive engines and compressors.
- Identify the first law of thermodynamics as simply a statement of the conservation of energy principle for closed (fixed mass) systems.
- Develop the general energy balance applied to closed systems.
- Define the specific heat at constant volume and the specific heat at constant pressure.
- Relate the specific heats to the calculation of the changes in internal energy and enthalpy of ideal gases.
- Describe incompressible substances and determine the changes in their internal energy and enthalpy.
- Solve energy balance problems for closed (fixed mass) systems that involve heat and work interactions for general pure substances, ideal gases, and incompressible substances.

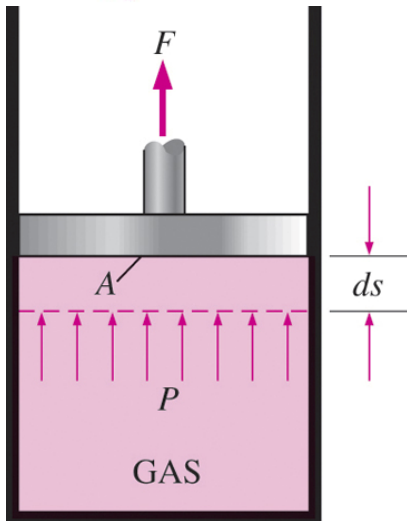
# MOVING BOUNDARY WORK

## Moving boundary work ( $P dV$ work):

The expansion and compression work in a piston-cylinder device.

$$\delta W_b = F ds = PA ds = P dV$$

$$W_b = \int_1^2 P dV \quad (\text{kJ})$$



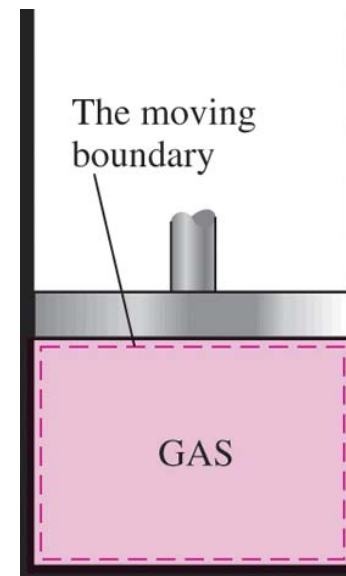
A gas does a differential amount of work  $\delta W_b$  as it forces the piston to move by a differential amount  $ds$ .

## Quasi-equilibrium process:

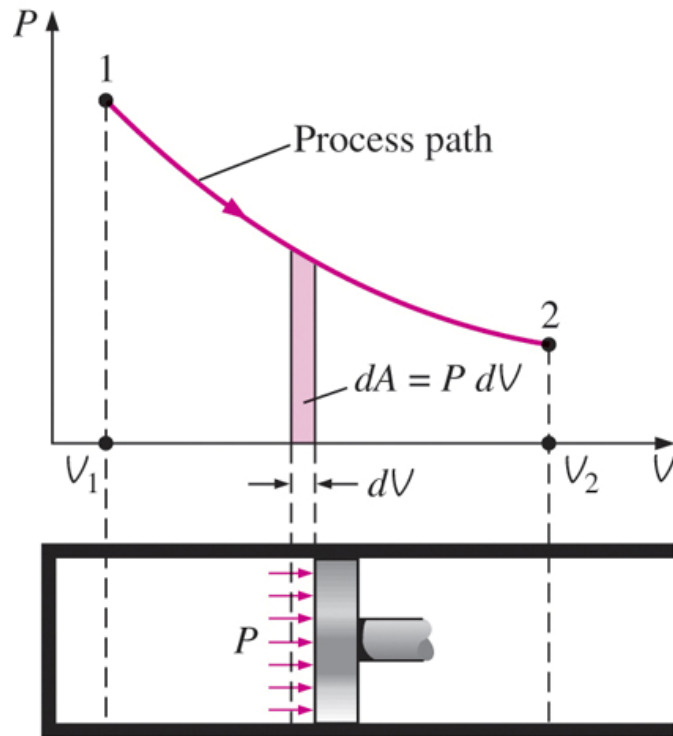
A process during which the system remains nearly in equilibrium at all times.

$W_b$  is positive  $\rightarrow$  for expansion

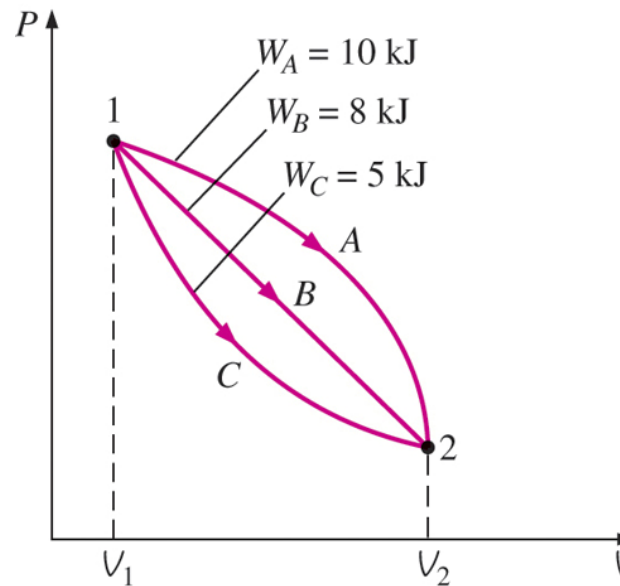
$W_b$  is negative  $\rightarrow$  for compression



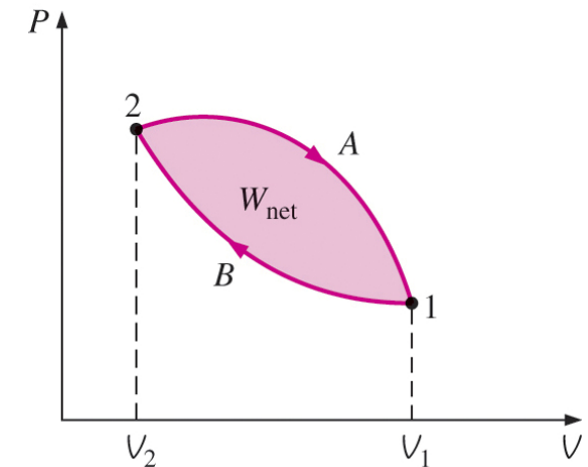
The work associated with a moving boundary is called *boundary work*.



The area under the process curve on a  $P$ - $V$  diagram represents the boundary work.



The net work done during a cycle is the difference between the work done by the system and the work done on the system.



The boundary work done during a process depends on the path followed as well as the end states.

The quasi-equilibrium expansion process described above is shown on a  $P$ - $V$  diagram.

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P dV$$

*the area under the process curve on a P-V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.*

*(On the P-V diagram, it represents the boundary work done per unit mass.)*

$$W_b = \int_1^2 P_i dV$$

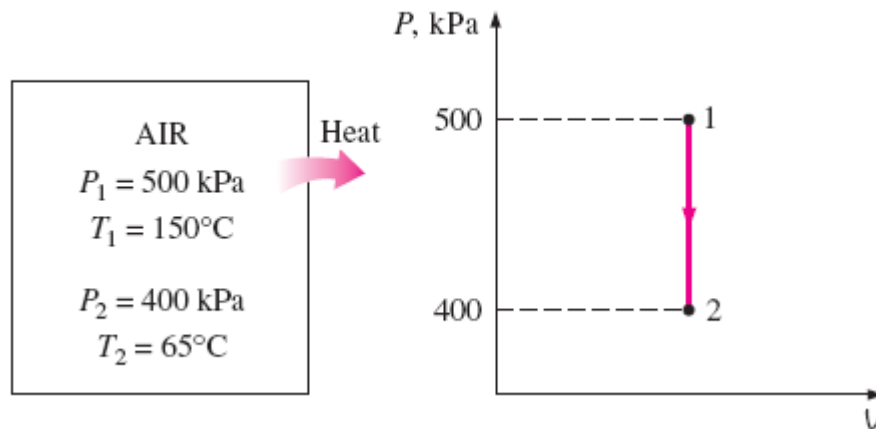
In a car engine, for example, the boundary work done by the expanding hot gases is used to overcome friction between the piston and the cylinder, to push atmospheric air out of the way, and to rotate the crankshaft. Therefore,

$$W_b = W_{\text{friction}} + W_{\text{atm}} + W_{\text{crank}} = \int_1^2 (F_{\text{friction}} + P_{\text{atm}}A + F_{\text{crank}}) dx$$

### EXAMPLE 4-1

A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.

**Solution** Air in a rigid tank is heated and the pressure rises. The boundary work done is to be determined.



$$W_b = \int_1^2 P dV = 0$$

**Discussion** This is expected since a rigid tank has a constant volume and  $dV = 0$  in this equation. Therefore, there is no boundary work done during this process. That is, the boundary work done during a constant-volume process is always zero. This is also evident from the  $P$ - $V$  diagram of the process (the area under the process curve is zero).



# EXAMPLE

Sketch a PV diagram and find the work done by the gas during the following stages.

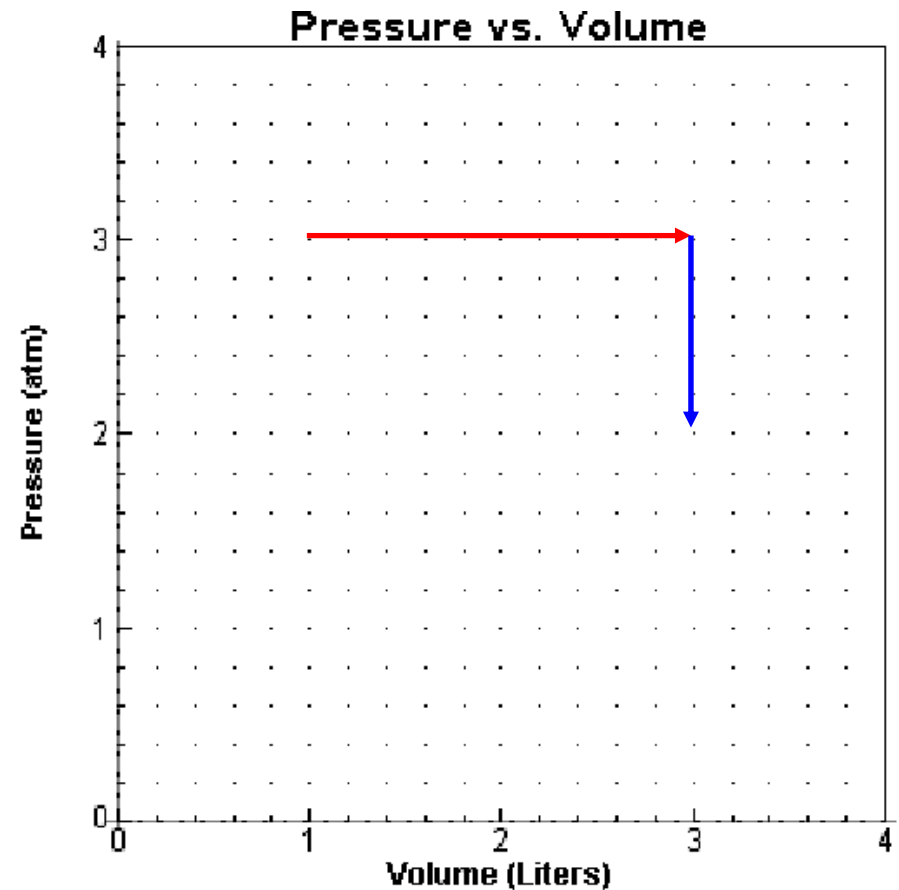
- (a) A gas is expanded from a volume of 1.0 L to 3.0 L at a constant pressure of 3.0 atm.

$$W_{BY} = P\Delta V = 3 \times 10^5 (0.003 - 0.001) = \mathbf{600 \text{ J}}$$

- (b) The gas is then cooled at a constant volume until the pressure falls to 2.0 atm

$$W = P\Delta V = 0$$

$$\text{since } \Delta V = 0$$

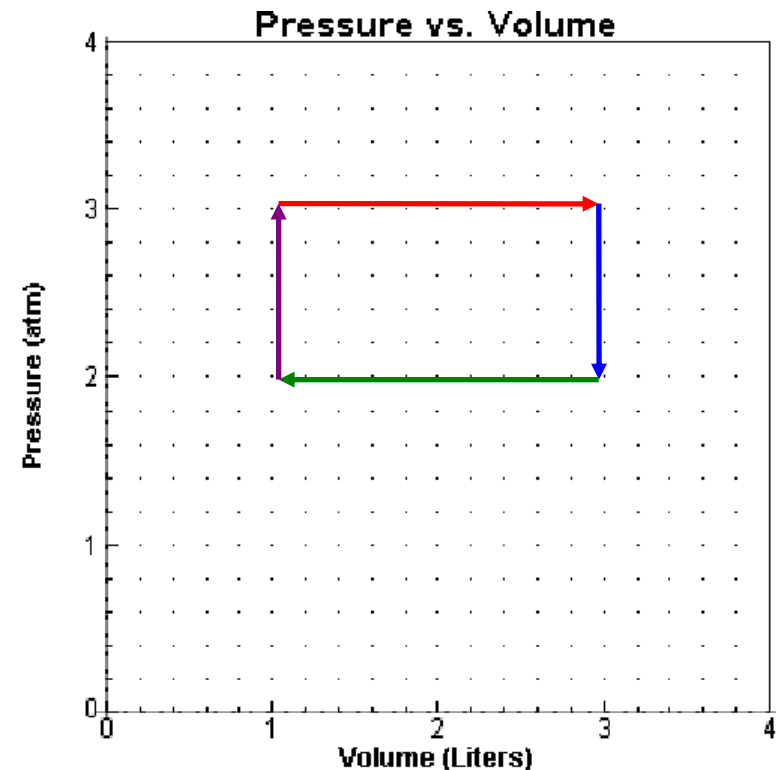


## EXAMPLE CONTINUED

- a) The gas is then compressed at a constant pressure of 2.0 atm from a volume of 3.0 L to 1.0 L.

$$W_{ON} = -P\Delta V = 2 \times 10^5 (.001 - .003) = -400 \text{ J}$$

- b) The gas is then heated until its pressure increases from 2.0 atm to 3.0 atm at a constant volume.



$$W = P\Delta V = 0$$

$$\text{since } \Delta V = 0$$

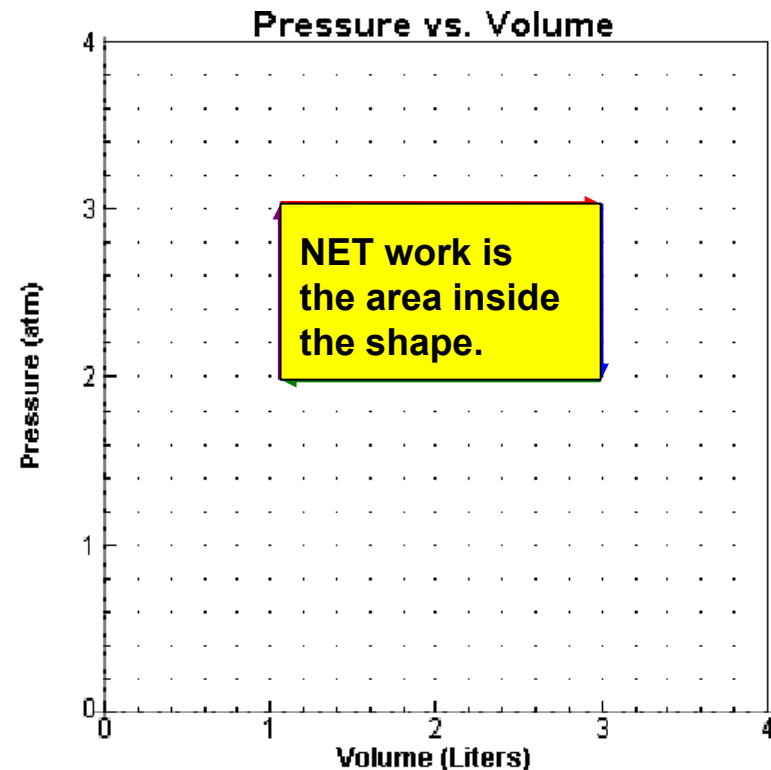
## EXAMPLE CONTINUED

What is the NET WORK?

$$600 \text{ J} + -400 \text{ J} = 200 \text{ J}$$

**Rule of thumb:** If the system rotates *CW*, the NET work is positive.

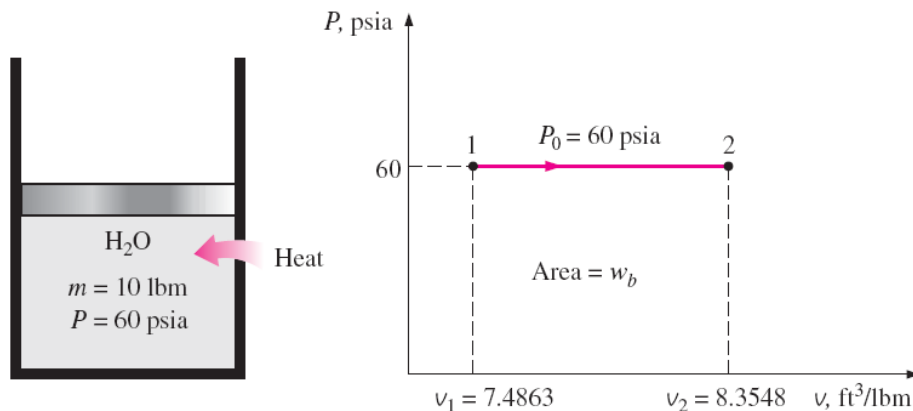
If the system rotates *CCW*, the NET work is negative.



## EXAMPLE 4-2

A frictionless piston–cylinder device contains 10 lbm of water vapor at 60 psia and 320°F. Heat is now transferred to the steam until the temperature reaches 400°F. If the piston is not attached to a shaft and its mass is constant, determine the work done by the steam during this process.

**Solution** Water vapor in a piston cylinder device is heated and the temperature rises at constant pressure. The boundary work done is to be determined.



Even though it is not explicitly stated, the pressure of the steam within the cylinder remains constant during this process since both the atmospheric pressure and the weight of the piston remain constant. Therefore, this is a constant-pressure process,

$$W_b = \int_1^2 P dV = P_0 \int_1^2 dV = P_0(V_2 - V_1)$$

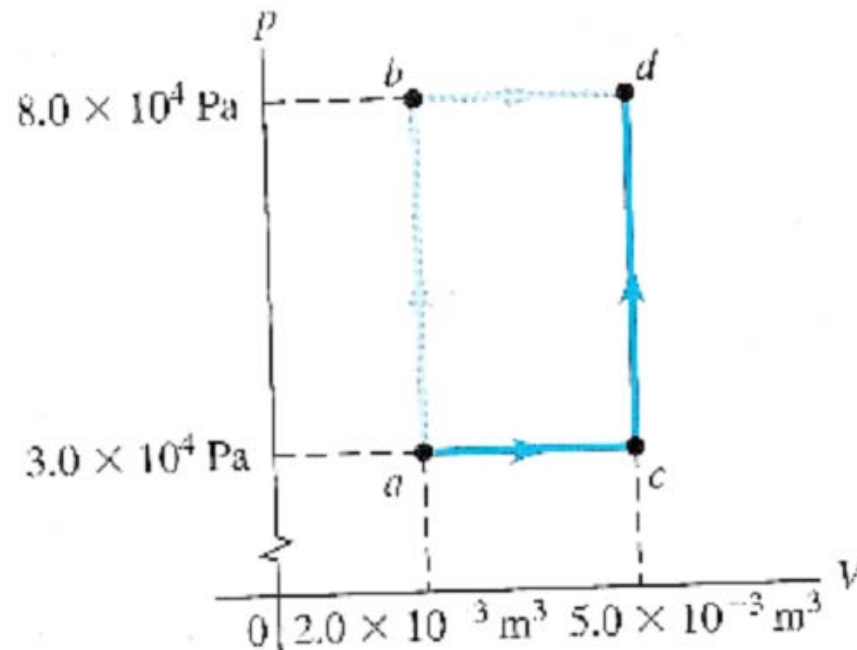
$$W_b = mP_0(v_2 - v_1)$$

$$W_b = (10 \text{ lbm})(60 \text{ psia})[(8.3458 - 7.4863) \text{ ft}^3/\text{lbm}] \left( \frac{1 \text{ Btu}}{5.404 \text{ psia} \cdot \text{ft}^3} \right) = \mathbf{96.4 \text{ Btu}}$$

**Discussion** The positive sign indicates that the work is done by the system. That is, the steam used 96.4 Btu of its energy to do this work. The magnitude of this work could also be determined by calculating the area under the process curve on the P-V diagram, which is simply  $P_0 \Delta V$  for this case.

## EXAMPLE

A series of thermodynamic processes is shown in the pV-diagram. In process **ab** 150 J of heat is added to the system, and in process **bd**, 600J of heat is added. Fill in the chart.

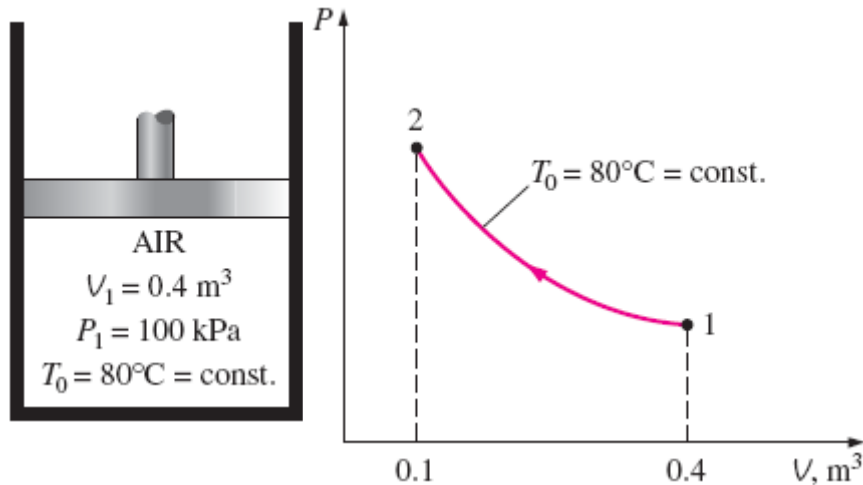


| Step       | Q   | W   | $\Delta U=Q+W$ |
|------------|-----|-----|----------------|
| <i>ab</i>  | 150 | 0   | 150 J          |
| <i>bd</i>  | 600 | 240 | 840 J          |
| <i>abd</i> | 750 | 240 | 990 J          |

| Step       | Q   | W  | $\Delta U=Q+W$ |
|------------|-----|----|----------------|
| <i>ac</i>  |     | 90 |                |
| <i>cd</i>  |     | 0  |                |
| <i>acd</i> | 900 | 90 | 990 J          |

### EXAMPLE 4-3

A piston–cylinder device initially contains  $0.4 \text{ m}^3$  of air at  $100 \text{ kPa}$  and  $80^\circ\text{C}$ . The air is now compressed to  $0.1 \text{ m}^3$  in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process..



**Solution** Air in a piston–cylinder device is compressed isothermally. The boundary work done is to be determined.

**Assumptions** 1 The compression process is quasi-equilibrium. 2 At the 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.

$$PV = mRT_0 = C \quad \text{or} \quad P = \frac{C}{V}$$

$$W_b = \int_1^2 P dV = \int_1^2 \frac{C}{V} dV = C \int_1^2 \frac{dV}{V} = C \ln \frac{V_2}{V_1} = P_1 V_1 \ln \frac{V_2}{V_1}$$

$$W_b = (100 \text{ kPa})(0.4 \text{ m}^3) \left( \ln \frac{0.1}{0.4} \right) \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) = -55.45 \text{ kJ}$$

**Discussion** The negative sign indicates that this work is done on the system (a work input), which is always the case for compression processes.

# Polytropic, Isothermal, and Isobaric processes

$$P = CV^{-n}$$

Polytropic process:  $C, n$  (polytropic exponent) constants

$$W_b = \int_1^2 P dV = \int_1^2 CV^{-n} dV = C \frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

Polytropic process

$$W_b = \frac{mR(T_2 - T_1)}{1-n} \quad n \neq 1$$

Polytropic and for ideal gas

$$W_b = \int_1^2 P dV = \int_1^2 CV^{-1} dV = PV \ln\left(\frac{V_2}{V_1}\right)$$

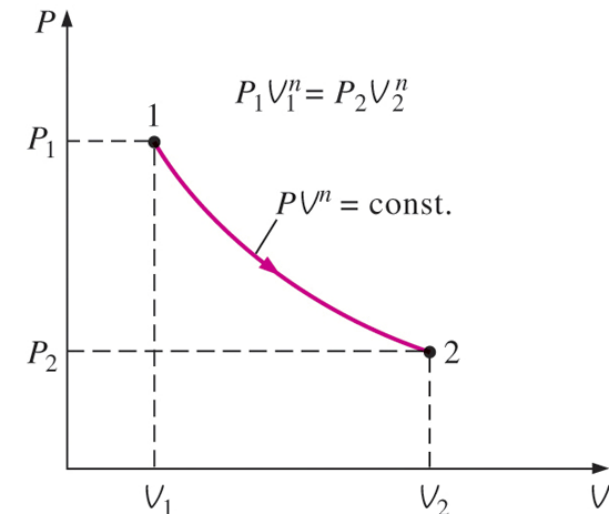
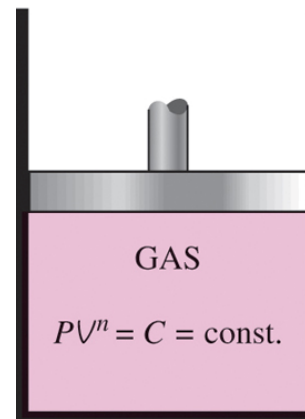
When  $n = 1$  (isothermal process)

$$W_b = \int_1^2 P dV = P_0 \int_1^2 dV = P_0(V_2 - V_1)$$

Constant pressure process

What is the boundary work for a constant-volume process?

Schematic and  $P$ - $V$  diagram for a polytropic process.



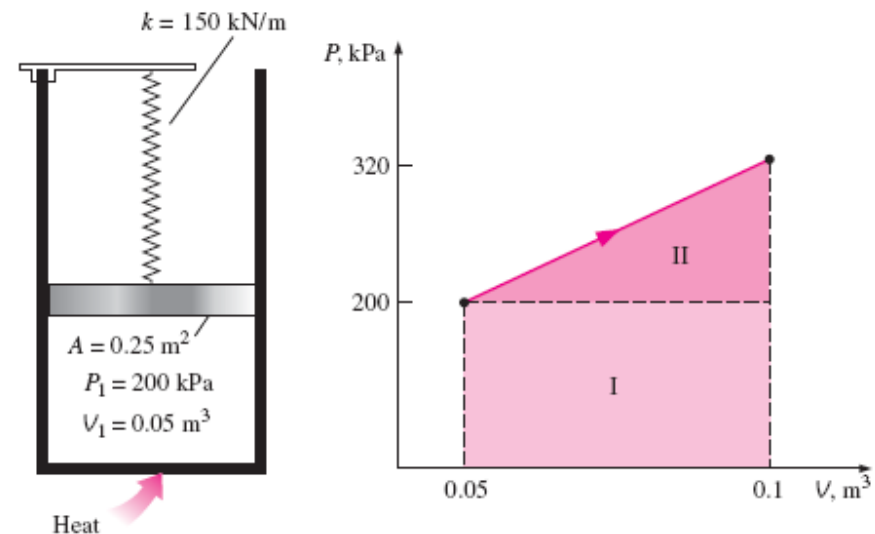


## EXAMPLE 4-4

A piston–cylinder device contains  $0.05 \text{ m}^3$  of a gas initially at  $200 \text{ kPa}$ . At this state, a linear spring that has a spring constant of  $150 \text{ kN/m}$  is touching the piston but exerting no force on it. Now heat is transferred to the gas, causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is  $0.25 \text{ m}^2$ , determine (a) the final pressure inside the cylinder, (b) the total work done by the gas, and (c) the fraction of this work done against the spring to compress it.

**Solution** A gas in a piston–cylinder device equipped with a linear spring expands as a result of heating. The final gas pressure, the total work done, and the fraction of the work done to compress the spring are to be determined.

**Assumptions** 1 The expansion process is quasi-equilibrium. 2 The spring is linear in the range of interest.



(a) The enclosed volume at the final state is

Then the displacement of the piston (and of the spring) becomes

The force applied by the linear spring at the final state is

$$V_2 = 2V_1 = (2)(0.05 \text{ m}^3) = 0.1 \text{ m}^3$$

$$x = \frac{\Delta V}{A} = \frac{(0.1 - 0.05) \text{ m}^3}{0.25 \text{ m}^2} = 0.2 \text{ m}$$

$$F = kx = (150 \text{ kN/m})(0.2 \text{ m}) = 30 \text{ kN}$$

The additional pressure applied by the spring on the gas at this state is

$$P = \frac{F}{A} = \frac{30 \text{ kN}}{0.25 \text{ m}^2} = 120 \text{ kPa}$$

Without the spring, the pressure of the gas would remain constant at 200 kPa while the piston is rising. But under the effect of the spring, the pressure rises linearly from 200 kPa to

$$200 + 120 = \mathbf{320 \text{ kPa}}$$

(b) An easy way of finding the work done is to plot the process on a  $P$ - $V$  diagram and find the area under the process curve.

$$W = \text{area} = \frac{(200 + 320) \text{ kPa}}{2} [(0.1 - 0.05) \text{ m}^3] \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}} \right) = \mathbf{13 \text{ kJ}}$$

(c) The work represented by the rectangular area (region I) is done against the piston and the atmosphere, and the work represented by the triangular area (region II) is done against the spring. Thus,

$$W_{\text{spring}} = \frac{1}{2} [(320 - 200) \text{ kPa}] (0.05 \text{ m}^3) \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}} \right) = \mathbf{3 \text{ kJ}}$$

**Discussion** This result could also be obtained from

$$W_{\text{spring}} = \frac{1}{2} k (x_2^2 - x_1^2) = \frac{1}{2} (150 \text{ kN/m}) [(0.2 \text{ m})^2 - 0^2] \left( \frac{1 \text{ kJ}}{1 \text{ kN} \cdot \text{m}} \right) = 3 \text{ kJ}$$

# ENERGY BALANCE FOR CLOSED SYSTEMS

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

Energy balance for any system undergoing any process

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad (\text{kW})$$

Energy balance in the rate form

The total quantities are related to the quantities per unit time is

$$Q = \dot{Q} \Delta t, \quad W = \dot{W} \Delta t, \quad \text{and} \quad \Delta E = \Delta \dot{E} \Delta t$$

$$e_{\text{in}} - e_{\text{out}} = \Delta e_{\text{system}}$$

Energy balance per unit mass basis

Energy balance in differential form

$$\delta E_{\text{in}} - \delta E_{\text{out}} = dE_{\text{system}} \quad \text{or} \quad \delta e_{\text{in}} - \delta e_{\text{out}} = de_{\text{system}}$$

$$W_{\text{net, out}} = Q_{\text{net, in}} \quad \text{or} \quad \dot{W}_{\text{net, out}} = \dot{Q}_{\text{net, in}}$$

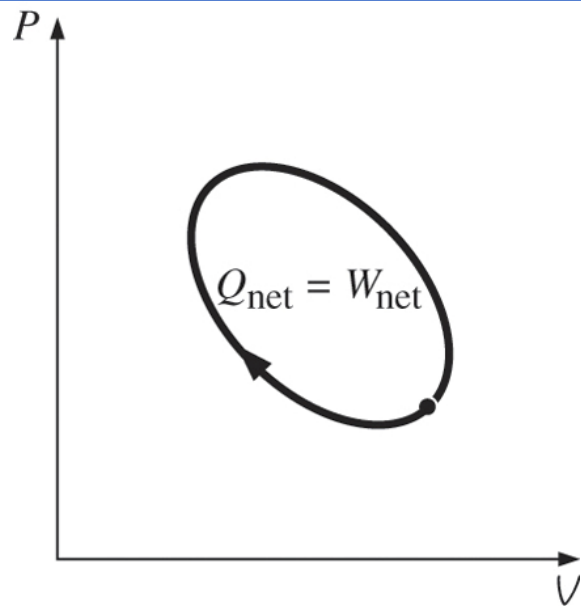
Energy balance for a cycle

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

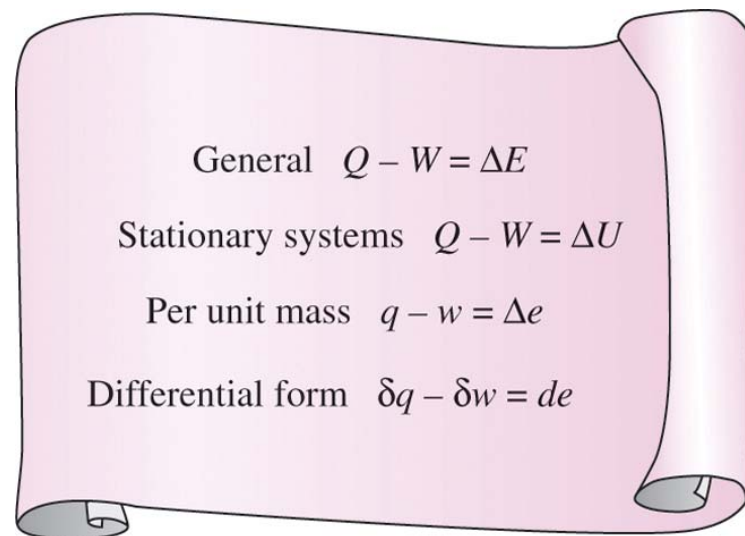
$$Q = Q_{\text{net, in}} = Q_{\text{in}} - Q_{\text{out}}$$

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

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



For a cycle  $\Delta E = 0$ , thus  $Q = W$ .



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

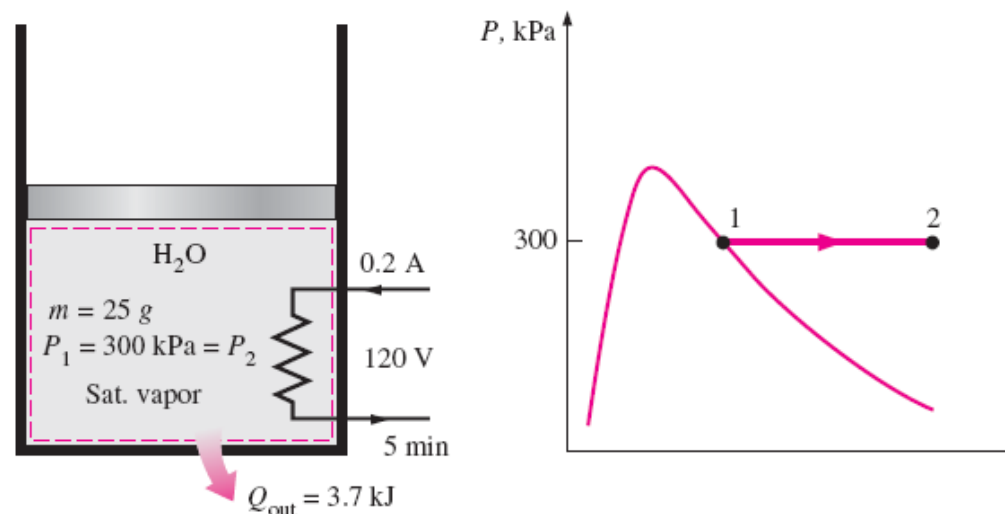
The first law cannot be proven mathematically, but no process in nature is known to have violated the first law, and this should be taken as sufficient proof.

### EXAMPLE 4-5

A piston–cylinder device contains 25 g of saturated water vapor that is maintained at a constant pressure of 300 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.2 A for 5 min from a 120-V source. At the same time, a heat loss of 3.7 kJ occurs. (a) Show that for a closed system the boundary work  $W_b$  and the change in internal energy  $\Delta U$  in the first-law relation can be combined into one term,  $\Delta H$ , for a constant pressure process. (b) Determine the final temperature of the steam.

**Solution** Saturated water vapor in a piston–cylinder device expands at constant pressure as a result of electric resistance heating. It is to be shown that  $\Delta U + W_b = \Delta H$ , and the final temperature is to be determined.

**Assumptions 1** The tank is stationary and thus the kinetic and potential energy changes are zero,  $\Delta KE = \Delta PE = 0$ . Therefore,  $\Delta E = \Delta U$  and internal energy is the only form of energy of the system that may change during this process. **2** Electrical wires constitute a very small part of the system, and thus the energy change of the wires can be neglected.



(a) for a closed system the boundary work  $W_b$  and the change in internal energy  $\Delta U$  in the first-law relation can be combined into one term,  $\Delta H$ , for a constant pressure process.

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

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

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

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

$$P_0 = P_2 = P_1 \rightarrow Q - W_{\text{other}} = (U_2 + P_2 V_2) - (U_1 + P_1 V_1)$$

$$H = U + PV,$$

$$Q - W_{\text{other}} = H_2 - H_1 \quad (\text{kJ})$$

(b) The only other form of work in this case is the electrical work, which can be determined from

$$W_e = VI \Delta t = (120 \text{ V})(0.2 \text{ A})(300 \text{ s}) \left( \frac{1 \text{ kJ/s}}{1000 \text{ VA}} \right) = 7.2 \text{ kJ}$$

$$\text{State 1: } \left. \begin{array}{l} P_1 = 300 \text{ kPa} \\ \text{sat, vapor} \end{array} \right\} h_1 = h_g @ 300 \text{ kPa} = 2724.9 \text{ kJ/kg}$$

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

$$W_{e, \text{in}} - Q_{\text{out}} = \Delta H = m(h_2 - h_1) \quad (\text{since } P = \text{constant})$$

$$7.2 \text{ kJ} - 3.7 \text{ kJ} = (0.025 \text{ kg})(h_2 - 2724.9) \text{ kJ/kg}$$

$$h_2 = 2864.9 \text{ kJ/kg}$$

$$\text{State 2:} \quad \left. \begin{array}{l} P_2 = 300 \text{ kPa} \\ h_2 = 2864.9 \text{ kJ/kg} \end{array} \right\} T_2 = 200^\circ\text{C}$$

**Discussion** Strictly speaking, the potential energy change of the steam is not zero for this process since the center of gravity of the steam rose somewhat. Assuming an elevation change of 1 m (which is rather unlikely), the change in the potential energy of the steam would be 0.0002 kJ, which is very small compared to the other terms in the first-law relation. Therefore, in problems of this kind, the potential energy term is always neglected.



## EXAMPLE 4-6

A rigid tank is divided into two equal parts by a partition. Initially, one side of the tank contains 5 kg of water at 200 kPa and 25°C, and the other side is evacuated. The partition is then removed, and the water expands into the entire tank. The water is allowed to exchange heat with its surroundings until the temperature in the tank returns to the initial value of 25°C. Determine (a) the volume of the tank, (b) the final pressure, and (c) the heat transfer for this process.

**Solution** One half of a rigid tank is filled with liquid water while the other side is evacuated. The partition between the two parts is removed and water is allowed to expand and fill the entire tank while the temperature is maintained constant. The volume of tank, the final pressure, and the heat transfer are to be determined.

**Assumptions** **1** The system is stationary and thus the kinetic and potential energy changes are zero,  $\Delta KE = \Delta PE = 0$  and  $\Delta E = \Delta U$ . **2** The direction of heat transfer is to the system (heat gain,  $Q_{in}$ ). A negative result for  $Q_{in}$  will indicate the assumed direction is wrong and thus it is heat loss. **3** The volume of the rigid tank is constant, and thus there is no energy transfer as boundary work. **4** The water temperature remains constant during the process. **5** There is no electrical, shaft, or any other kind of work involved.

(a) the volume of the tank

$$v_1 \cong v_{f@25^\circ\text{C}} = 0.001003 \text{ m}^3/\text{kg} \cong 0.001 \text{ m}^3/\text{kg}$$

$$V_1 = m v_1 = (5 \text{ kg})(0.001 \text{ m}^3/\text{kg}) = 0.005 \text{ m}^3$$

The total volume of the tank is twice this amount:

$$V_{\text{tank}} = (2)(0.005 \text{ m}^3) = \mathbf{0.01 \text{ m}^3}$$

(b) At the final state, the specific volume of the water is

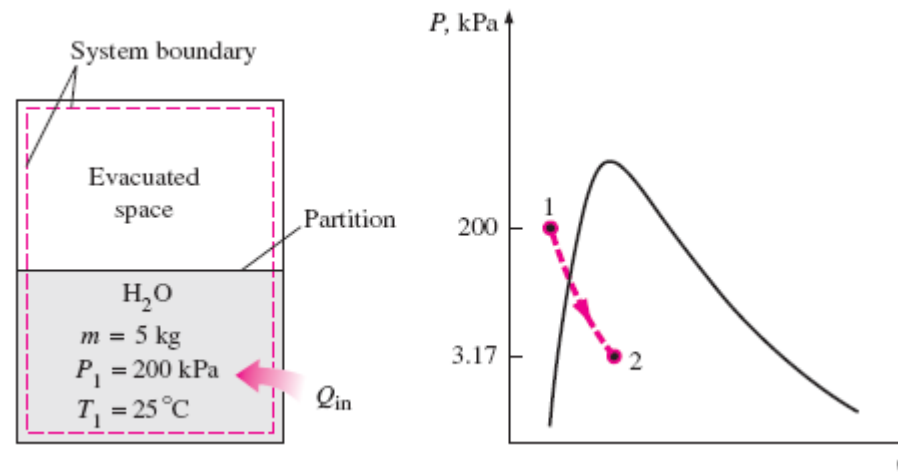
$$v_2 = \frac{V_2}{m} = \frac{0.01 \text{ m}^3}{5 \text{ kg}} = 0.002 \text{ m}^3/\text{kg}$$

which is twice the initial value of the specific volume. This result is expected since the volume doubles while the amount of mass remains constant.

$$\text{At } 25^\circ\text{C: } v_f = 0.001003 \text{ m}^3/\text{kg} \quad \text{and} \quad v_g = 43.340 \text{ m}^3/\text{kg}$$

Since  $v_f < v_2 < v_g$ , the water is a saturated liquid–vapor mixture at the final state, and thus the pressure is the saturation pressure at  $25^\circ\text{C}$ :

$$P_2 = P_{\text{sat @ } 25^\circ\text{C}} = \mathbf{3.1698 \text{ kPa}}$$



(c) Under stated assumptions and observations, the energy balance on the system can be expressed as

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

$$u_1 \cong u_f @ 25^\circ\text{C} = 104.83 \text{ kJ/kg}$$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.002 - 0.001}{43.34 - 0.001} = 2.3 \times 10^{-5}$$

$$\begin{aligned} u_2 &= u_f + x_2 u_{fg} \\ &= 104.83 \text{ kJ/kg} + (2.3 \times 10^{-5})(2304.3 \text{ kJ/kg}) \\ &= 104.88 \text{ kJ/kg} \end{aligned}$$

$$Q_{\text{in}} = (5 \text{ kg})[(104.88 - 104.83) \text{ kJ/kg}] = \mathbf{0.25 \text{ kJ}}$$

**Discussion** The positive sign indicates that the assumed direction is correct, and heat is transferred to the water.

# 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.

For a constant-pressure expansion or compression process:

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

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

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

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

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

$$Q - W_{\text{other}} = (U_2 + P_2V_2) - (U_1 + P_1V_1)$$

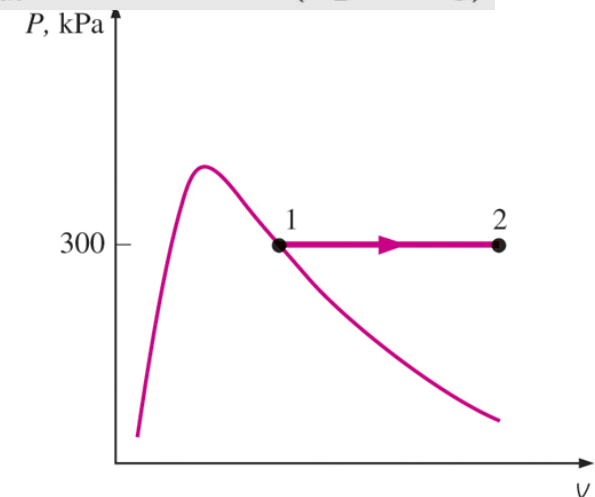
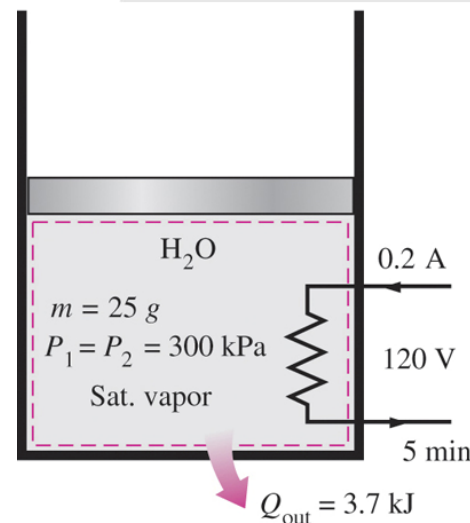
$$H = U + PV$$

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

An example of constant-pressure process

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

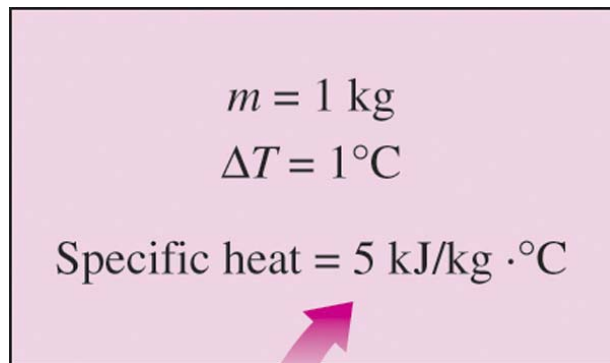
$$W_{e,\text{in}} - Q_{\text{out}} = \Delta H = m(h_2 - h_1)$$



# SPECIFIC HEATS

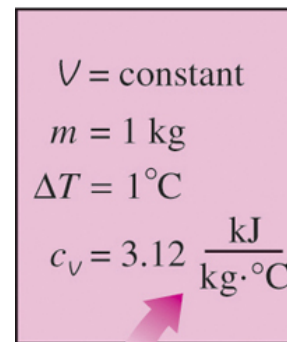
**Specific heat at constant volume,  $c_v$ :** The energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

**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.

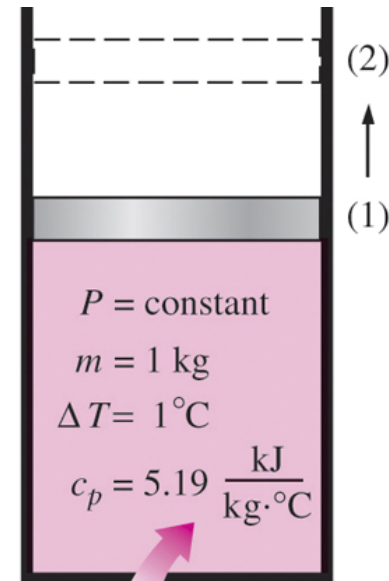


5 kJ

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



3.12 kJ

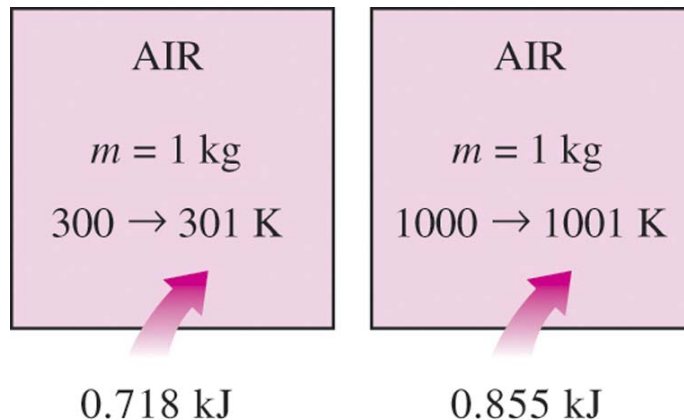


5.19 kJ

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

- The equations in the figure 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?**



The specific heat of a substance changes with temperature.

**True or False?**

$c_p$  is always greater than  $c_v$ .

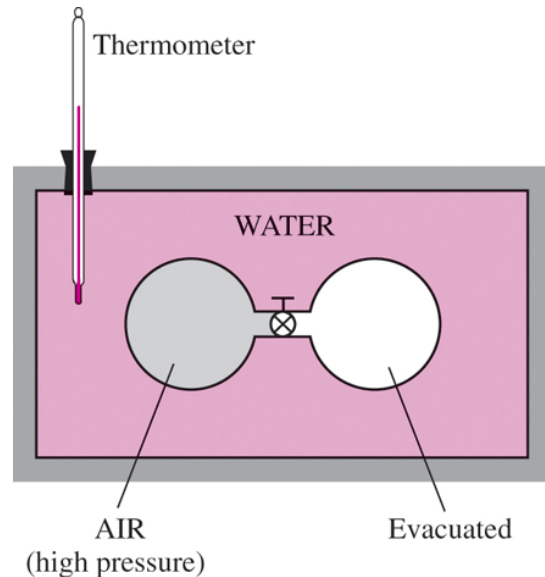
$$c_v = \left( \frac{\partial u}{\partial T} \right)_v$$

= 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

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



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

$$\begin{aligned} u &= u(T) \\ h &= h(T) \\ c_v &= c_v(T) \\ c_p &= c_p(T) \end{aligned}$$

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

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

$$u = u(T)$$

$$h = h(T)$$

$$du = c_v(T) dT$$

$$dh = c_p(T) dT$$

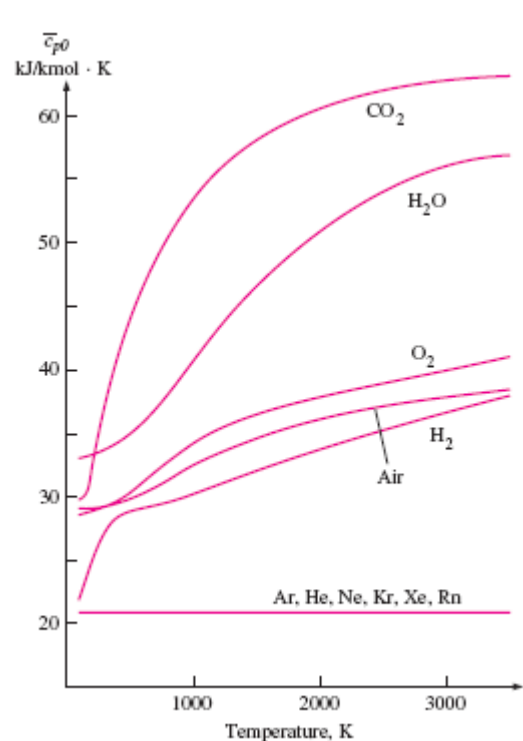
$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T) dT$$

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

Internal energy and enthalpy change of an ideal gas



- 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.



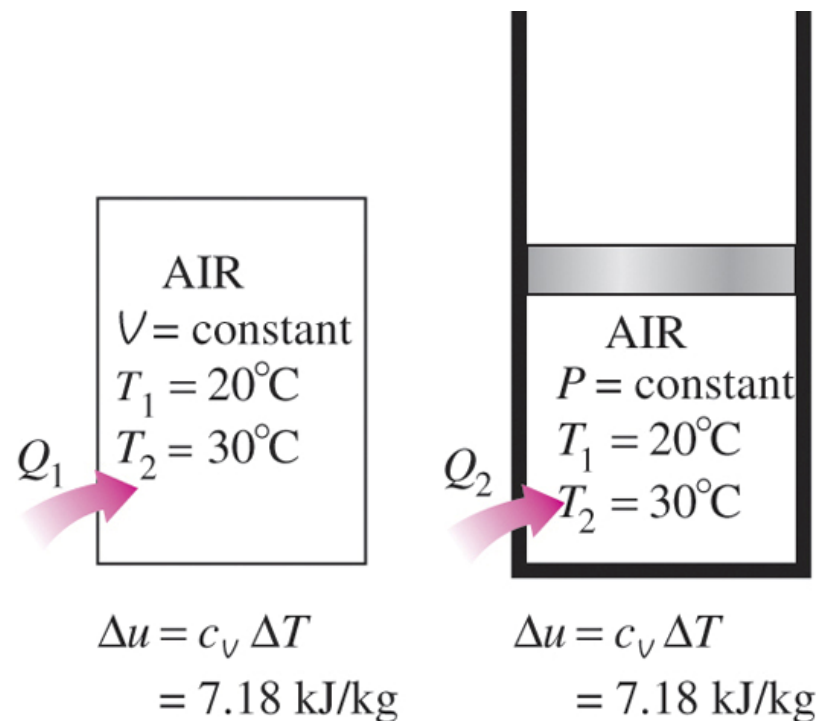
Ideal-gas constant-pressure specific heats for some gases (see Table A-2c for  $c_p$  equations).

| AIR           |                   |                   |
|---------------|-------------------|-------------------|
| $T, \text{K}$ | $u, \text{kJ/kg}$ | $h, \text{kJ/kg}$ |
| 0             | 0                 | 0                 |
| .             | .                 | .                 |
| .             | .                 | .                 |
| 300           | 214.07            | 300.19            |
| 310           | 221.25            | 310.24            |
| .             | .                 | .                 |
| .             | .                 | .                 |

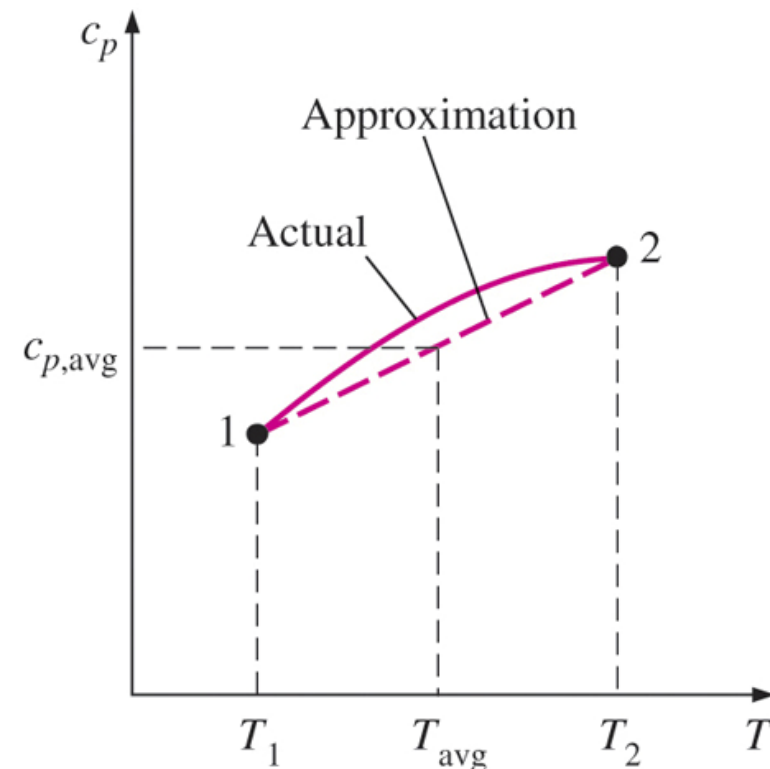
In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

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

$$u_2 - u_1 = c_{v,av}(T_2 - T_1) \quad (\text{kJ/kg}) \quad h_2 - h_1 = c_{p,av}(T_2 - T_1) \quad (\text{kJ/kg})$$



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



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

# Three ways of calculating $\Delta u$ and $\Delta h$

1. By using the tabulated  $u$  and  $h$  data. 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.

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

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

$$\Delta u \cong c_{v,av} \Delta T$$

Three ways of calculating  $\Delta u$ .

# SPECIFIC HEAT RELATIONS OF IDEAL GASES

$$\left. \begin{aligned} dh &= du + R dT \\ dh &= c_p dT \text{ and } du = c_v dT \end{aligned} \right\} \longrightarrow$$

The relationship between  $c_p$ ,  $c_v$  and  $R$

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

On a molar basis

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

$$dh = c_p dT \text{ ve } du = c_v dT$$

AIR at 300 K

$$\left. \begin{aligned} c_v &= 0.718 \text{ kJ/kg} \cdot \text{K} \\ R &= 0.287 \text{ kJ/kg} \cdot \text{K} \end{aligned} \right\} c_p = 1.005 \text{ kJ/kg} \cdot \text{K}$$

or

$$\left. \begin{aligned} \bar{c}_v &= 20.80 \text{ kJ/kmol} \cdot \text{K} \\ R_u &= 8.314 \text{ kJ/kmol} \cdot \text{K} \end{aligned} \right\} \bar{c}_p = 29.114 \text{ kJ/kmol} \cdot \text{K}$$

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

Specific heat ratio

$$k = \frac{c_p}{c_v}$$

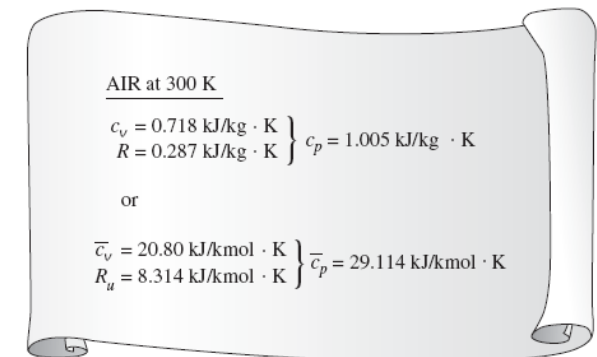
- The specific ratio varies with temperature, but this variation is very mild.
- For monatomic gases (helium, argon, etc.), its value is essentially constant at 1.667.
- Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

## EXAMPLE 4-7

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–2c), and (c) the average specific heat value (Table A–2b).

**Solution** The internal energy change of air is to be determine in three different ways.

**Assumptions** 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.



(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–21 and take the difference:

$$u_1 = u @ 300 \text{ K} = 214.07 \text{ kJ/kg}$$

$$u_2 = u @ 600 \text{ K} = 434.78 \text{ kJ/kg}$$

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

(b) The  $\bar{c}_p(T)$  of air is given in Table A–2c 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. 4–30,

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

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

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

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

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

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

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

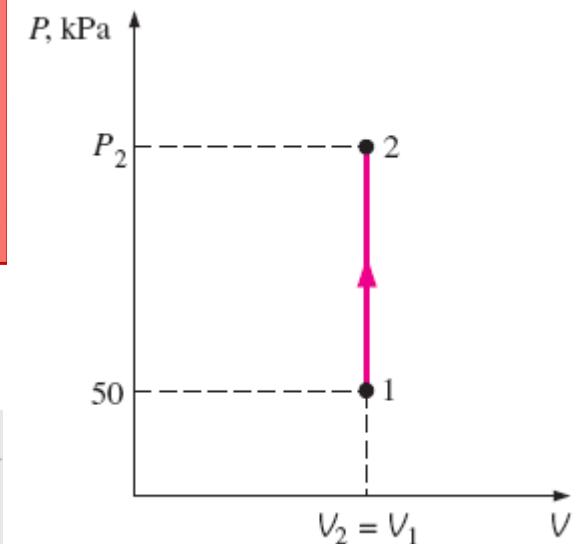
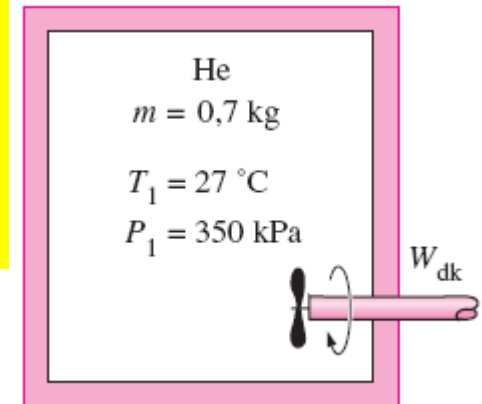
**Discussion** This answer differs from the exact result (220.71 kJ/kg) by only 0.4 percent. This close agreement is not surprising since the assumption that  $c_v$  varies linearly with temperature is a reasonable one at temperature intervals of only a few hundred degrees. If we had used the  $c_v$  value at  $T_1 = 300 \text{ K}$  instead of at  $T_{\text{av}}$ , the result would be 215 kJ/kg, which is in error by about 2 percent. Errors of this magnitude are acceptable for most engineering purposes.

### EXAMPLE 4-8

An insulated rigid tank initially contains 0.7 kg of helium at 27°C and 350 kPa. A paddle wheel with a power rating of 0.015 kW is operated within the tank for 30 min. Determine (a) the final temperature and (b) the final pressure of the helium gas.

**Solution** Helium gas in an insulated rigid tank is stirred by a paddle wheel. The final temperature and pressure of helium are to be determined.

**Assumptions** **1** Helium is an ideal gas since it is at a very high temperature relative to its critical-point value of -268°C. **2** Constant specific heats can be used for helium. **3**  $\Delta KE = \Delta PE = 0$  and  $\Delta E = \Delta U$ . **4** The volume of the tank is constant,  $V_2 = V_1$ . **5** The system is adiabatic and thus there is no heat transfer.



(a) The amount of paddle-wheel work done on the system is

$$W_{dk} = \dot{W}_{dk} \Delta t = (0.015 \text{ kW})(30 \text{ dak}) \left( \frac{60 \text{ s}}{1 \text{ dak}} \right) = 27 \text{ kJ}$$

$$W_{dk, \text{giren}} = \Delta U = m(u_2 - u_1) = mc_{v, \text{ort}} (T_2 - T_1)$$

$$27 \text{ kJ} = (0.7 \text{ kg})(3.1156 \text{ kJ/kg} \cdot ^\circ\text{C})(T_2 - 27^\circ\text{C})$$

$$T_2 = 39.4^\circ\text{C}$$



(b) The final pressure is determined from the ideal-gas relation

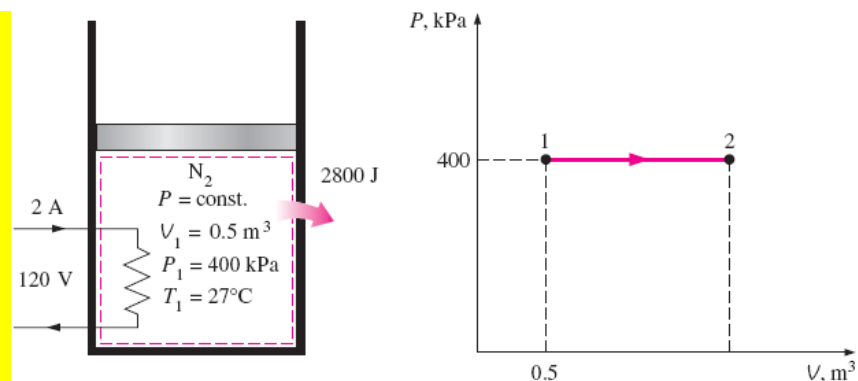
$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{350 \text{ kPa}}{(27 + 273) \text{ K}} = \frac{P_2}{(39.4 + 273) \text{ K}}$$
$$P_2 = \mathbf{364.5 \text{ kPa}}$$

where  $V_1$  and  $V_2$  are identical and cancel out. Then the final pressure becomes

### EXAMPLE 4-9

A piston–cylinder device initially contains  $0.5 \text{ m}^3$  of nitrogen gas at  $400 \text{ kPa}$  and  $27^\circ\text{C}$ . An electric heater within the device is turned on and is allowed to pass a current of  $2 \text{ A}$  for  $5 \text{ min}$  from a  $120\text{-V}$  source. Nitrogen expands at constant pressure, and a heat loss of  $2800 \text{ J}$  occurs during the process. Determine the final temperature of nitrogen.



**Solution** Nitrogen gas in a piston–cylinder device is heated by an electric resistance heater. Nitrogen expands at constant pressure while some heat is lost. The final temperature of nitrogen is to be determined.

**Assumptions** **1** Nitrogen is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values of  $147^\circ\text{C}$ , and  $3.39 \text{ MPa}$ . **2** The system is stationary and thus the kinetic and potential energy changes are zero,  $\Delta\text{KE} = \Delta\text{PE} = 0$  and  $\Delta E = \Delta U$ . **3** The pressure remains constant during the process and thus  $P_2 = P_1$ . **4** Nitrogen has constant specific heats at room temperature.

First, let us determine the electrical work done on the nitrogen:

$$W_e = VI \Delta t = (120 \text{ V})(2 \text{ A})(5 \times 60 \text{ s}) \left( \frac{1 \text{ kJ/s}}{1000 \text{ VA}} \right) = 72 \text{ kJ}$$

The mass of nitrogen is determined from the ideal-gas relation:

$$m = \frac{P_1 V_1}{RT_1} = \frac{(400 \text{ kPa})(0.5 \text{ m}^3)}{(0.297 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(300 \text{ K})} = 2.245 \text{ kg}$$

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

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

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

since  $\Delta U + W_b = \Delta H$  for a closed system undergoing a quasi-equilibrium expansion or compression process at constant pressure. From Table A-2a,  $c_p = 1.039 \text{ kJ/kg} \cdot \text{K}$  for *nitrogen at room temperature*. The only unknown quantity in the above equation is  $T_2$ , and it is found to be

$$72 \text{ kJ} - 2.8 \text{ kJ} = (2.245 \text{ kg})(1.039 \text{ kJ/kg} \cdot \text{K})(T_2 - 27^\circ\text{C})$$

$$T_2 = \mathbf{56.7^\circ\text{C}}$$

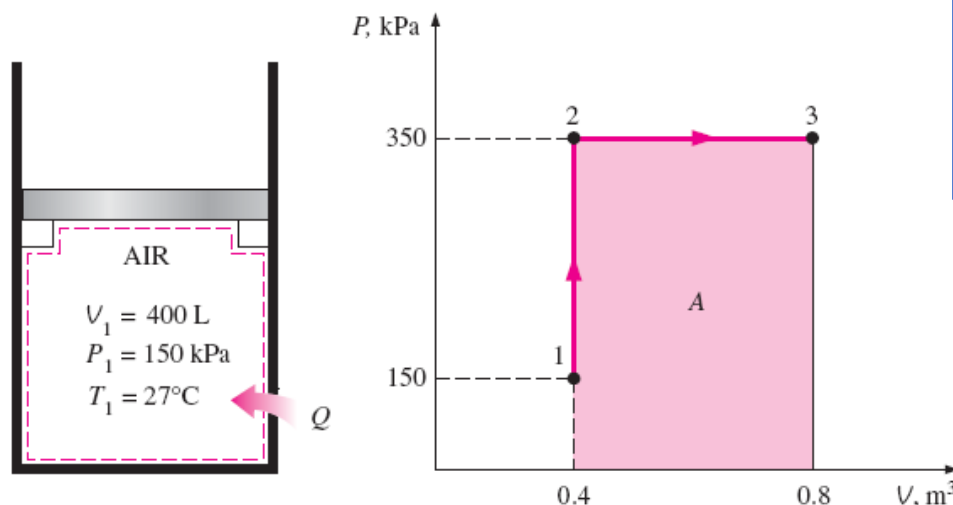
**Discussion** Note that we could also solve this problem by determining the boundary work and the internal energy change rather than the enthalpy change.

## EXAMPLE 4-10

A piston–cylinder device initially contains air at 150 kPa and 27°C. At this state, the piston is resting on a pair of stops, and the enclosed volume is 400 L. The mass of the piston is such that a 350-kPa pressure is required to move it. The air is now heated until its volume has doubled. Determine (a) the final temperature, (b) the work done by the air, and (c) the total heat transferred to the air.

**Solution** Air in a piston–cylinder device with a set of stops is heated until its volume is doubled. The final temperature, work done, and the total heat transfer are to be determined.

**Assumptions** 1 Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values. 2 The system is stationary and thus the kinetic and potential energy changes are zero,  $\Delta KE = \Delta PE = 0$  and  $\Delta E = \Delta U$ . 3 The volume remains constant until the piston starts moving, and the pressure remains constant afterwards. 4 There are no electrical, shaft, or other forms of work involved.



(a) The final temperature can be determined easily by using the ideal-gas relation between states 1 and 3 in the following form:

$$\frac{P_1 V_1}{T_1} = \frac{P_3 V_3}{T_3}$$

$$\frac{(150 \text{ kPa})(V_1)}{300 \text{ K}} = \frac{(350 \text{ kPa})(2V_1)}{T_3}$$

$$T_3 = 1400 \text{ K}$$

(b) The work done could be determined by integration, but for this case it is much easier to find it from the area under the process curve on a  $P$ - $V$  diagram,

$$A = (V_2 - V_1)(P_2) = (0.4 \text{ m}^3)(350 \text{ kPa}) = 140 \text{ m}^3 \text{ kPa}$$

$$W_{13} = \mathbf{140 \text{ kJ}}$$

The work is done by the system (to raise the piston and to push the atmospheric air out of the way), and thus it is work output.

(c) Under the stated assumptions and observations, the energy balance on the system between the initial and final states (process 1–3) can be expressed as

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

$$u_1 = u @ 300 \text{ K} = 214.07 \text{ kJ/kg}$$

$$u_3 = u @ 1400 \text{ K} = 1113.52 \text{ kJ/kg}$$

$$m = \frac{P_1 V_1}{RT_1} = \frac{(150 \text{ kPa})(0.4 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(300 \text{ K})} = 0.697 \text{ kg}$$

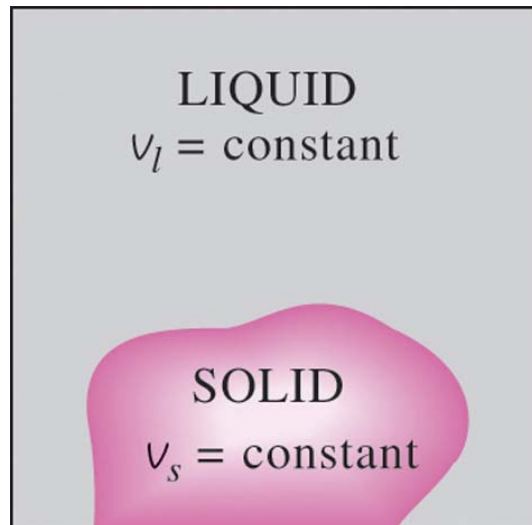
$$Q_{\text{in}} - 140 \text{ kJ} = (0.697 \text{ kg})[(1113.52 - 214.07) \text{ kJ/kg}]$$

$$Q_{\text{in}} = \mathbf{766.9 \text{ kJ}}$$

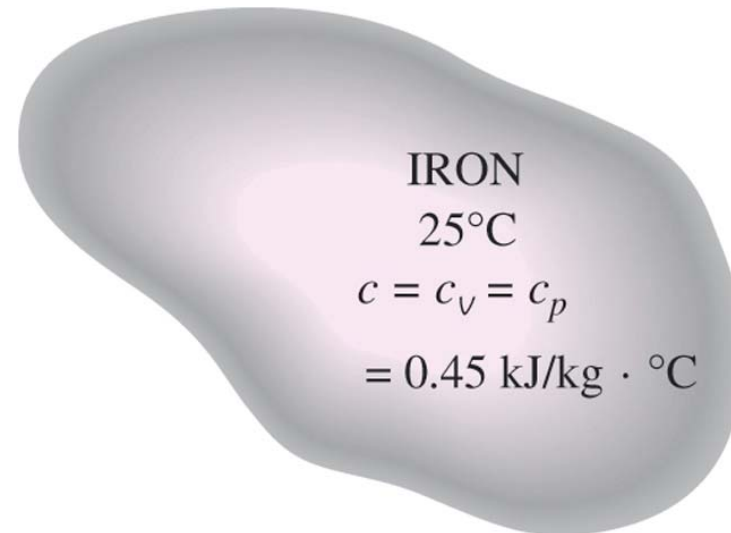
**Discussion** The positive sign verifies that heat is transferred to the system.

# INTERNAL ENERGY, ENTHALPY, AND SPECIFIC HEATS OF SOLIDS AND LIQUIDS

**Incompressible substance:** A substance whose specific volume (or density) is constant. Solids and liquids are incompressible substances.



The specific volumes of incompressible substances remain constant during a process.



The  $c_v$  and  $c_p$  values of incompressible substances are identical and are denoted by  $c$ .

# INTERNAL ENERGY CHANGES

$$du = c_v dT = c(T) dT$$

$$\Delta u = u_2 - u_1 = \int_1^2 c(T) dT \quad (\text{kJ/kg})$$

$$\Delta u \cong c_{\text{avg}}(T_2 - T_1) \quad (\text{kJ/kg})$$

## Enthalpy Changes

$$h = u + Pv$$
$$dh = du + v dP + P d\overset{\nearrow 0}{v} = du + v dP$$

$$\Delta h = \Delta u + v \Delta P \cong c_{\text{avg}} \Delta T + v \Delta P \quad (\text{kJ/kg})$$

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

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

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

A more accurate relation than

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

The enthalpy of a compressed liquid



## EXAMPLE 4-11

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. 4-38.

**Solution** The enthalpy of liquid water is to be determined exactly and approximately.

**Analysis** At 100°C, the saturation pressure of water is 101.42 kPa, and since  $P > P_{\text{sat}}$ , the water exists as a compressed liquid at the specified state.

(a) From compressed liquid tables, we read

$$\left. \begin{array}{l} P = 15 \text{ MPa} \\ T = 100^\circ\text{C} \end{array} \right\} h = \mathbf{430.39 \text{ kJ/kg}}$$

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

$$h \cong h_{f@100^\circ\text{C}} = \mathbf{419.17 \text{ kJ/kg}}$$

This value is in error by about 2.6 %.

(c) From Eq. 4-38,

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

$$\begin{aligned} &= (419.14 \text{ kJ/kg}) + (0.001 \text{ m}^3/\text{kg})[(15,000 - 101.42) \text{ kPa}]\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right) \\ &= \mathbf{434.07 \text{ kJ/kg}} \end{aligned}$$

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

# SUMMARY

- Moving boundary work
  - $W_b$  for an isothermal process
  - $W_b$  for a constant-pressure process
  - $W_b$  for a polytropic process
- Energy balance for closed systems
  - Energy balance for a constant-pressure expansion or compression process
- Specific heats
  - Constant-pressure specific heat,  $c_p$
  - Constant-volume specific heat,  $c_v$
- Internal energy, enthalpy, and specific heats of ideal gases
  - Specific heat relations of ideal gases
- Internal energy, enthalpy, and specific heats of incompressible substances (solids and liquids)