가톨릭대학교
THE CATHOLIC UNIVERSITY OF KOREA

Energy balance and thermodynamics

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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.
- Discuss properties of a system and define density, specific gravity, and specific weight.
- Review concepts of temperature, temperature scales, pressure, and absolute and gage pressure.
- Introduce an intuitive systematic problem-solving technique.

1-1 Thermodynamics and Energy

Thermodynamics: The science of *energy*.

Energy: The ability to cause changes.

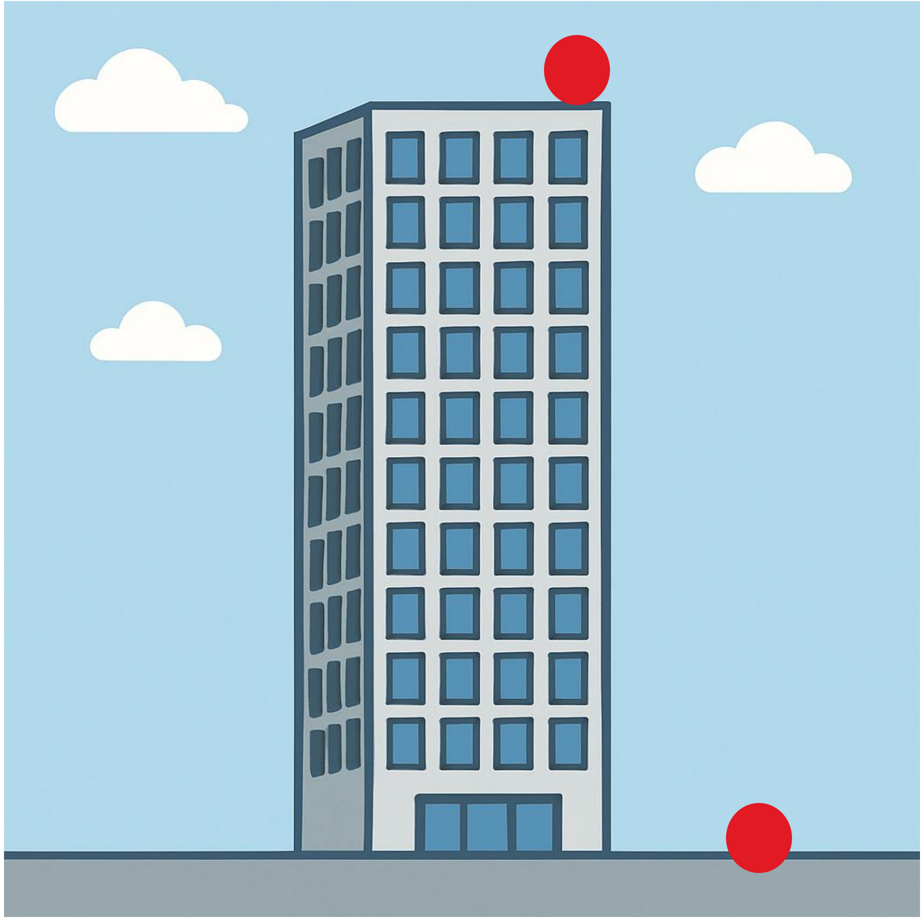
The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).

1-1 Thermodynamics and Energy

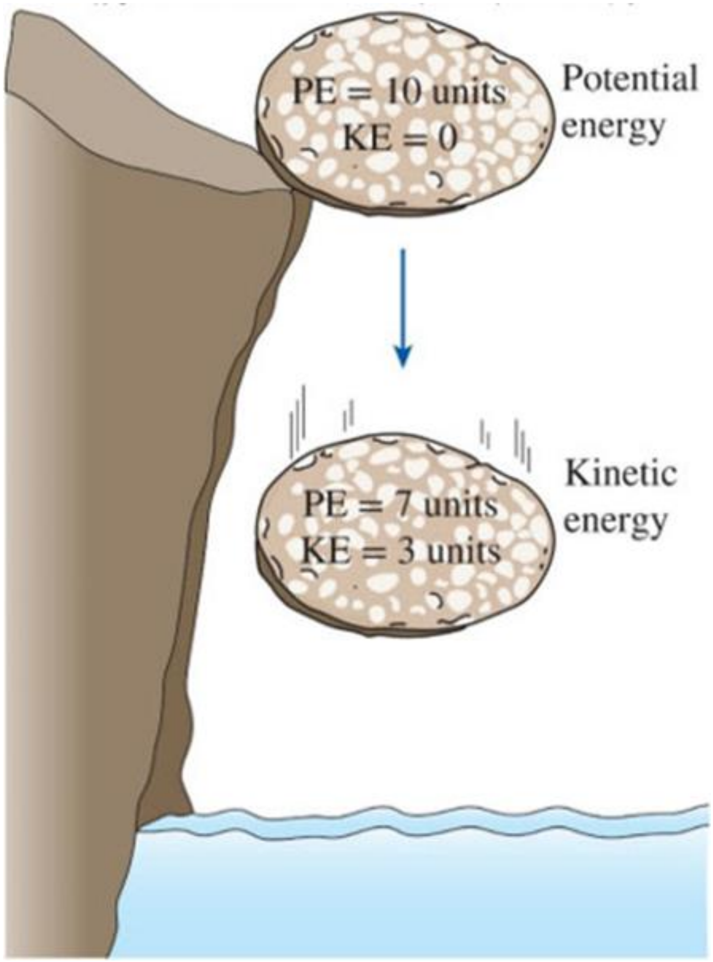
Kinetic energy

1-1 Thermodynamics and Energy

Potential energy

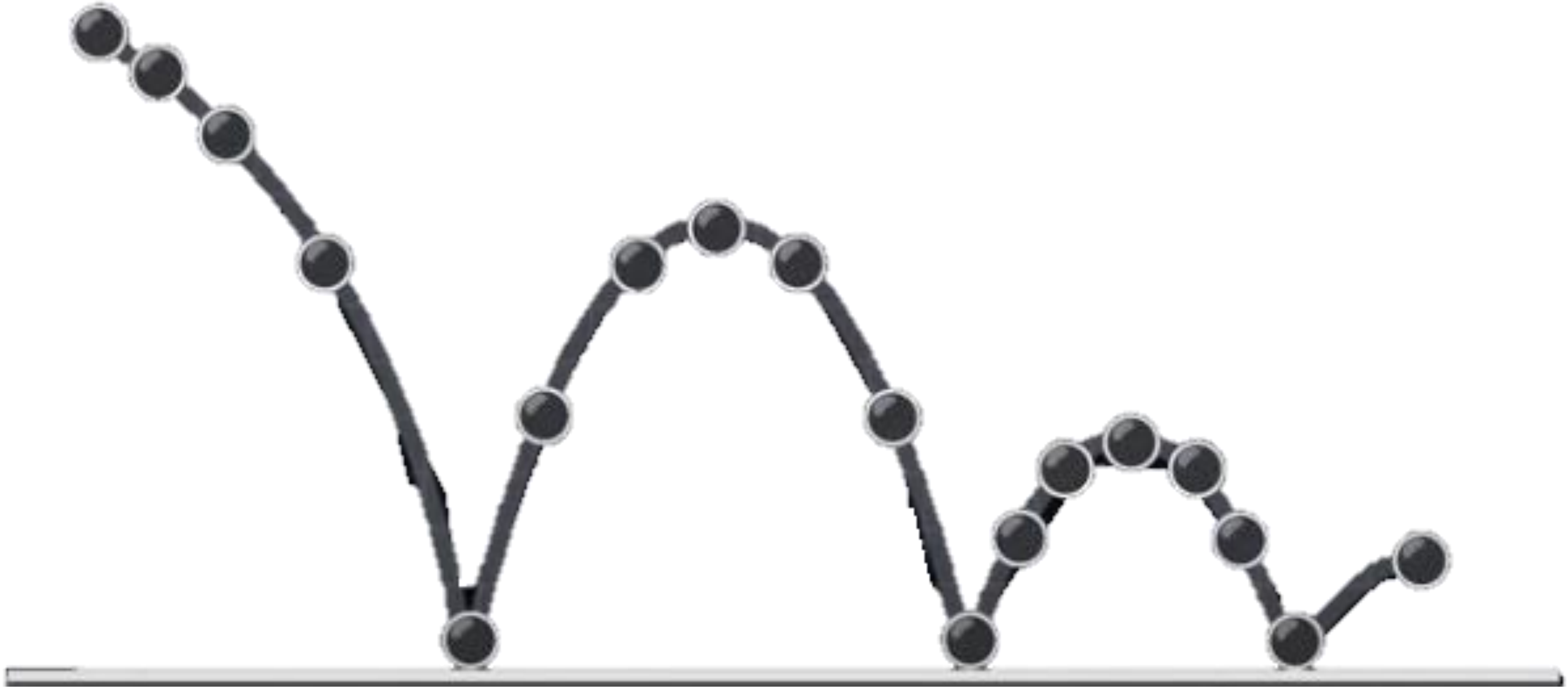


1-1 Thermodynamics and Energy



Energy can change forms

1-1 Thermodynamics and Energy



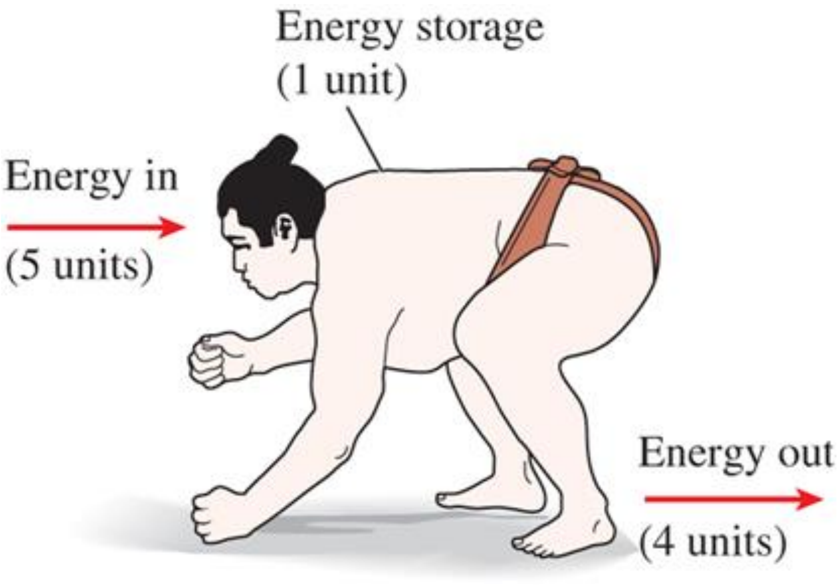
1-1 Thermodynamics and Energy

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.

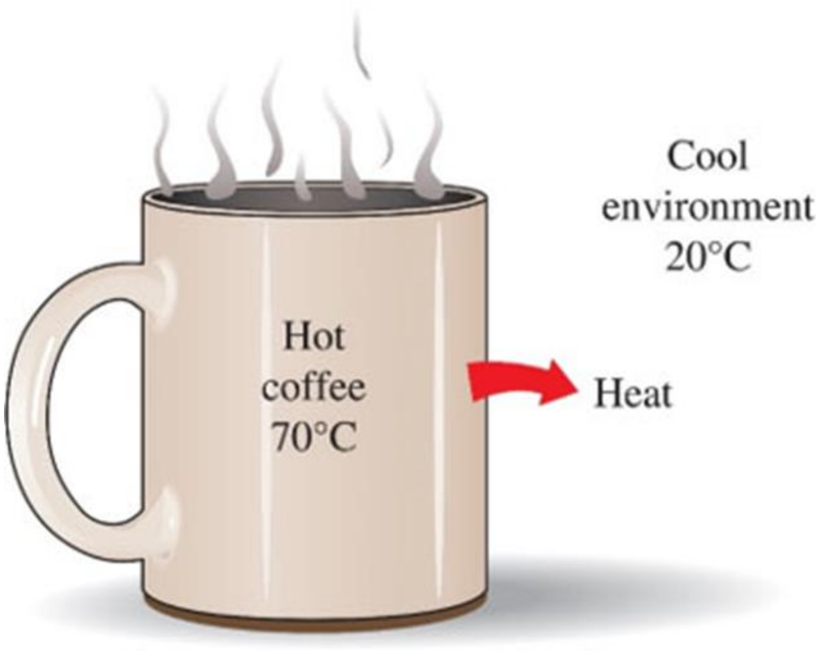
The first law of thermodynamics: An expression of the conservation of energy principle.

The first law asserts that *energy* is a thermodynamic property.



1-1 Thermodynamics and Energy

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.



Heat flows in the direction of decreasing temperature.

1-1 Thermodynamics and Energy

Heat -> Mechanical energy

1-1 Thermodynamics and 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.

1-1 Thermodynamics and Energy

Choose the wrong statement about the first law of thermodynamics.

(a) During an interaction, energy can change from one form to another.

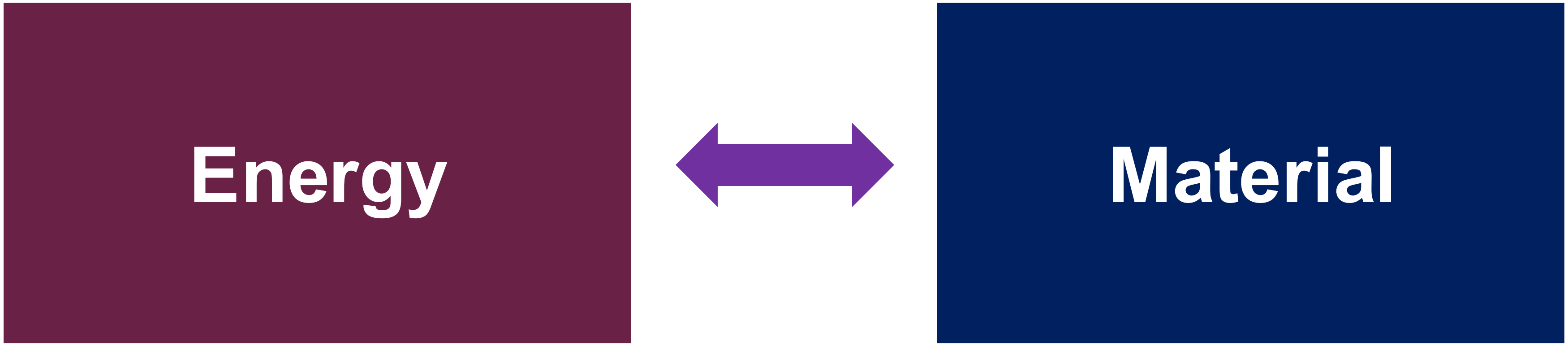
(b) During an interaction, the total amount of energy remains constant.

(c) Energy can be destroyed but it cannot be created.

(d) Energy is a thermodynamic property.

(e) A system with more energy input than output will gain energy.

Thermodynamics



Energy

Material

1-1 Thermodynamics and Energy

Application Areas of Thermodynamics


(*a*) Refrigerator


(*b*) Boats


(*c*) Aircraft and spacecraft


(*d*) Power plants


(*e*) Human body


(*f*) Cars


(*g*) Wind turbines


(*h*) Food processing


(*i*) A piping network in an industrial facility.

All activities in nature involve some interaction between energy and matter; thus, it is hard to imagine an area that does not relate to thermodynamics in some manner.

1-2 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.

1-2 Importance of Dimensions and Units

Table

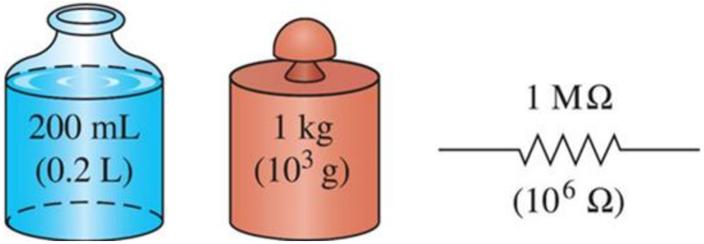
The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current (A)	ampere
Amount of light (cd)	candela
Amount of matter	mole (mol)

1-2 Importance of Dimensions and Units

- Standard prefixes in SI units

Multiple	Prefix
10^{24}	yotta, Y
10^{21}	zetta, Z
10^{18}	exa, E
10^{15}	peta, P
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, μ
10^{-9}	nano, n
10^{-12}	pico, p
10^{-15}	femto, f
10^{-18}	atto, a
10^{-21}	zepto, z
10^{-24}	yocto, y



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

1-2 Importance of Dimensions and Units

Some SI and English Units

kg ↔ **lbm (pound)**

m ↔ **ft (feet)**

$$1 \text{ lbm} = 0.45356 \text{ kg}$$

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

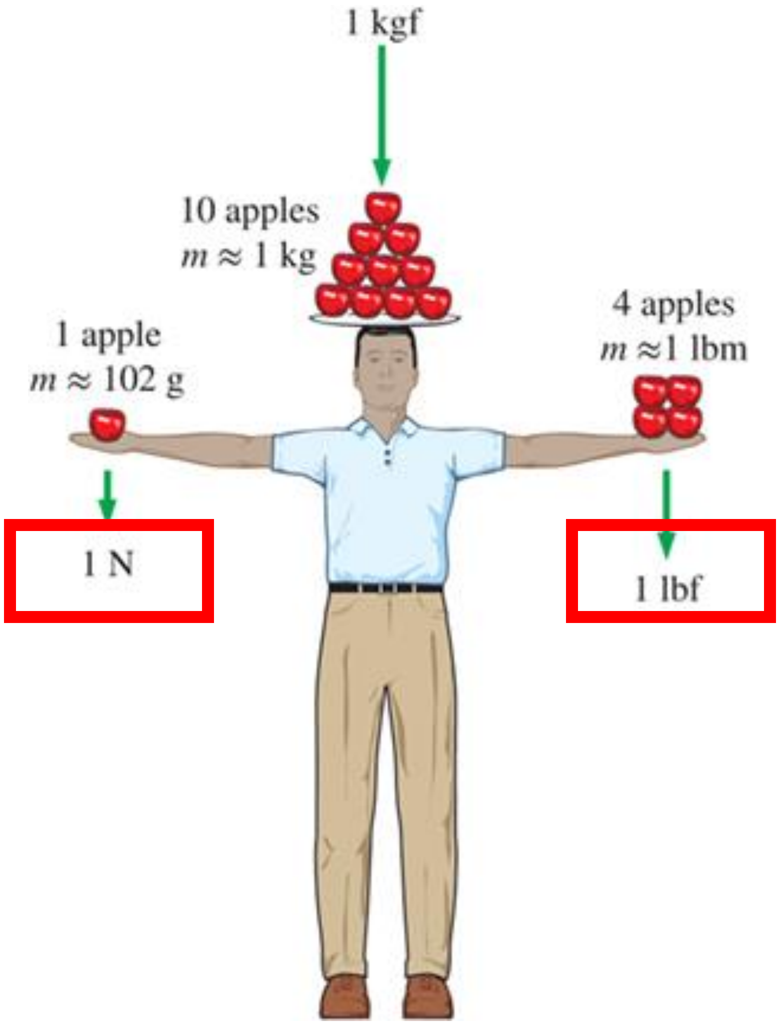
1-2 Importance of Dimensions and Units

Force = (Mass) x (Acceleration)

$F = ma$

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

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



1-2 Importance of Dimensions and Units

Work = (Force) x (Distance)

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

1 cal = 4.1868 J

1 Btu = 1.0551 kJ

1-2 Importance of Dimensions and Units

Work = (Force) x (Distance)

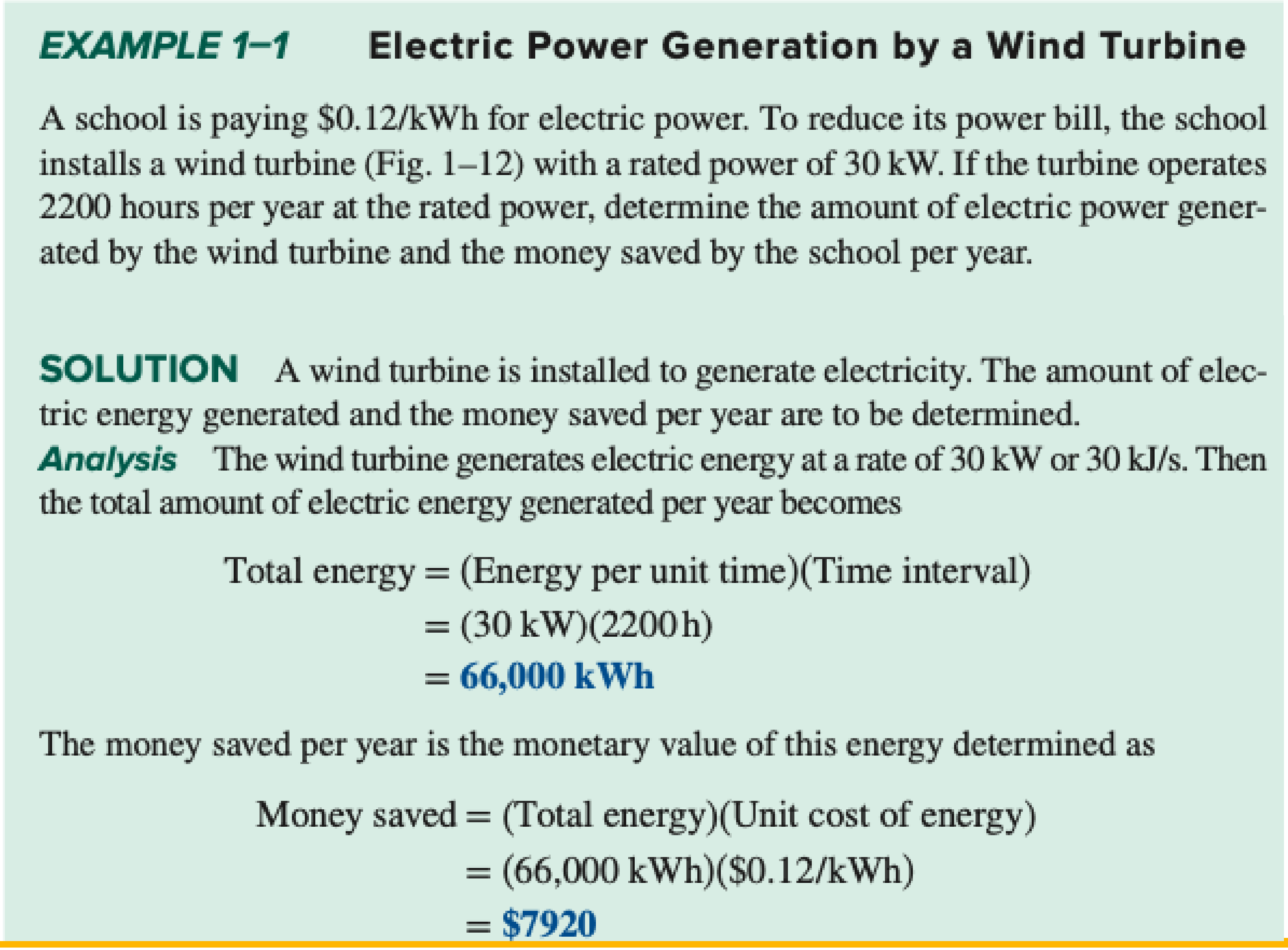
1-2 Importance of Dimensions and Units

Watt (W)= time rate of change of energy (or work) = power (일률)

Joule per second = J/s =W

1 kWh = 1kW x 1hour

1-2 Importance of Dimensions and Units



EXAMPLE 1–1 **Electric Power Generation by a Wind Turbine**

A school is paying \$0.12/kWh for electric power. To reduce its power bill, the school installs a wind turbine (Fig. 1–12) with a rated power of 30 kW. If the turbine operates 2200 hours per year at the rated power, determine the amount of electric power generated by the wind turbine and the money saved by the school per year.

SOLUTION A wind turbine is installed to generate electricity. The amount of electric energy generated and the money saved per year are to be determined.

Analysis The wind turbine generates electric energy at a rate of 30 kW or 30 kJ/s. Then the total amount of electric energy generated per year becomes

$$\begin{aligned}\text{Total energy} &= (\text{Energy per unit time})(\text{Time interval})\\ &= (30\ \text{kW})(2200\,\text{h})\\ &= \mathbf{66{,}000\ kWh}\end{aligned}$$

The money saved per year is the monetary value of this energy determined as

$$\begin{aligned}\text{Money saved} &= (\text{Total energy})(\text{Unit cost of energy})\\ &= (66{,}000\ \text{kWh})(\$0.12/\text{kWh})\\ &= \mathbf{\$7920}\end{aligned}$$

1-2 Importance of Dimensions and Units

Dimensional Homogeneity

All equations must be dimensionally **homogeneous.**

Unity Conversion Ratios

All nonprimary units (secondary units) can be formed by combinations of primary units.

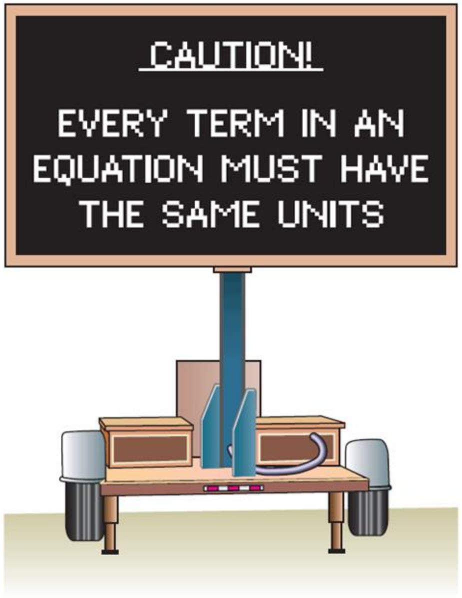
$$1\ \text{N} = 1\ \text{kg}\,\frac{\text{m}}{\text{s}^2} \quad \text{and} \quad 1\ \text{lbf} = 32.174\ \text{lbm}\,\frac{\text{ft}}{\text{s}^2}$$

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

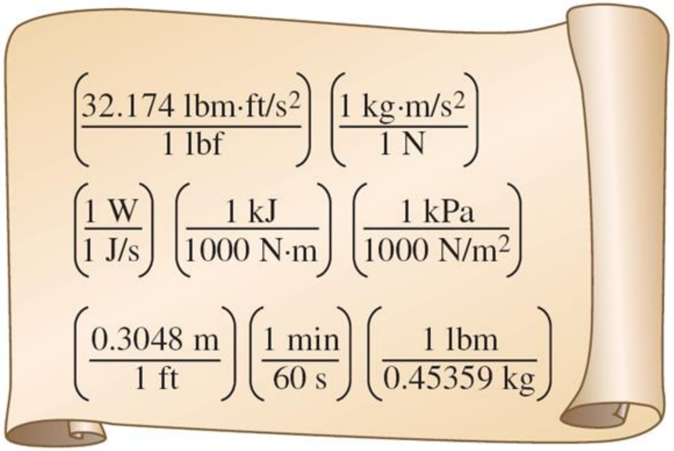
$$\frac{1\ \text{N}}{1\ \text{kg}\cdot\dfrac{\text{m}}{\text{s}^2}} = 1 \quad \text{and} \quad \frac{1\ \text{lbf}}{32.174\ \text{lbm}\cdot\dfrac{\text{ft}}{\text{s}^2}} = 1$$

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.

1-2 Importance of Dimensions and Units



Always check the units in your calculations.



$$\left(\frac{32.174\ \text{lbm}\cdot\text{ft/s}^2}{1\ \text{lbf}}\right)\left(\frac{1\ \text{kg}\cdot\text{m/s}^2}{1\ \text{N}}\right)$$

$$\left(\frac{1\ \text{W}}{1\ \text{J/s}}\right)\left(\frac{1\ \text{kJ}}{1000\ \text{N}\cdot\text{m}}\right)\left(\frac{1\ \text{kPa}}{1000\ \text{N/m}^2}\right)$$

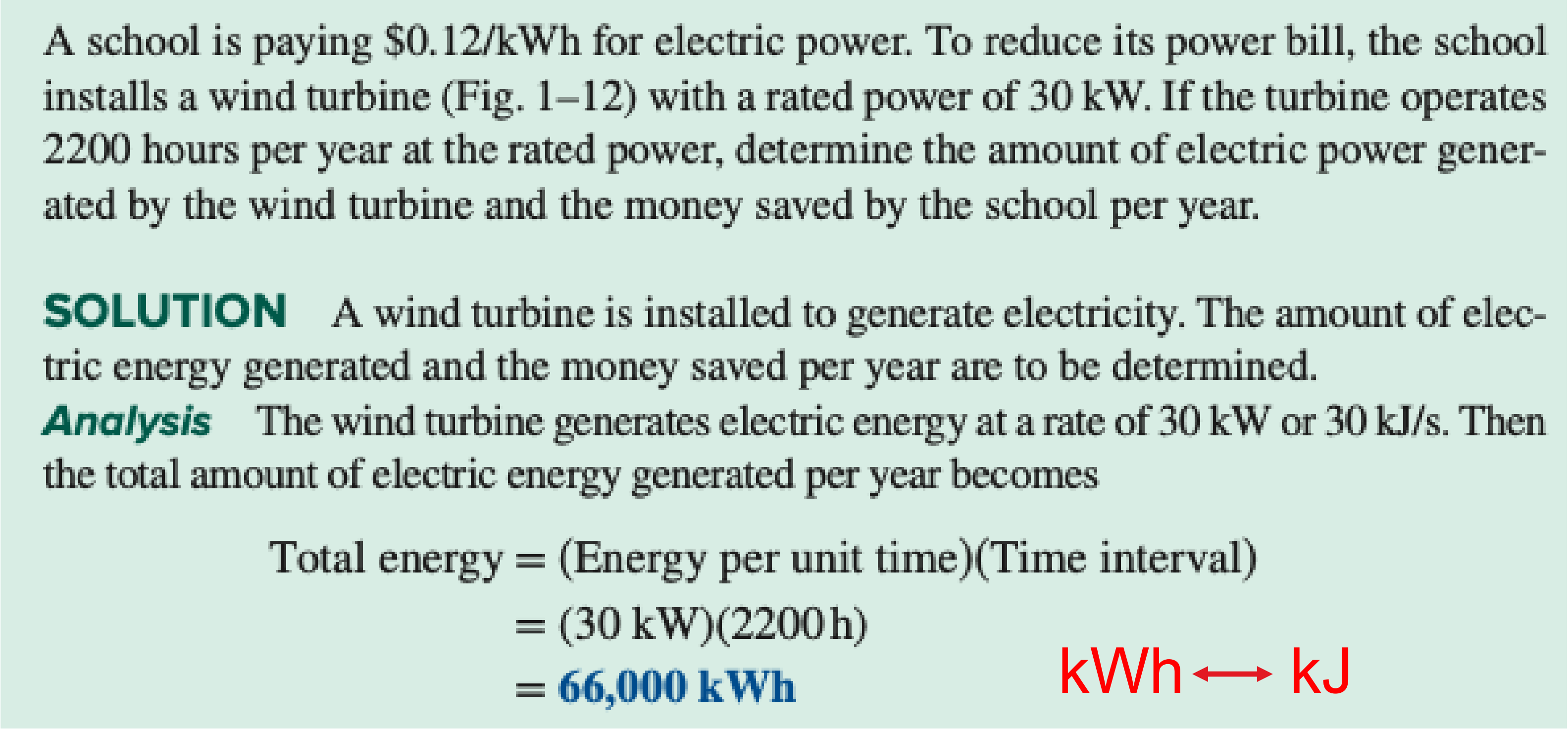
$$\left(\frac{0.3048\ \text{m}}{1\ \text{ft}}\right)\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(\frac{1\ \text{lbm}}{0.45359\ \text{kg}}\right)$$

Every unity conversion ratio (as well as its inverse) is exactly equal to 1. Shown here are a few commonly used unity conversion ratios, each within its own set of parentheses.

1-2 Importance of Dimensions and Units

$$W = mg = (453.6\,\text{g})\left(9.81\,\frac{\text{m}}{\text{s}^2}\right)\left(\frac{1\,\text{N}}{1\,\text{kg}\,\frac{\text{m}}{\text{s}^2}}\right)\left(\frac{1\,\text{kg}}{1000\,\text{g}}\right) = 4.4\,\text{N}$$

1-2 Importance of Dimensions and Units



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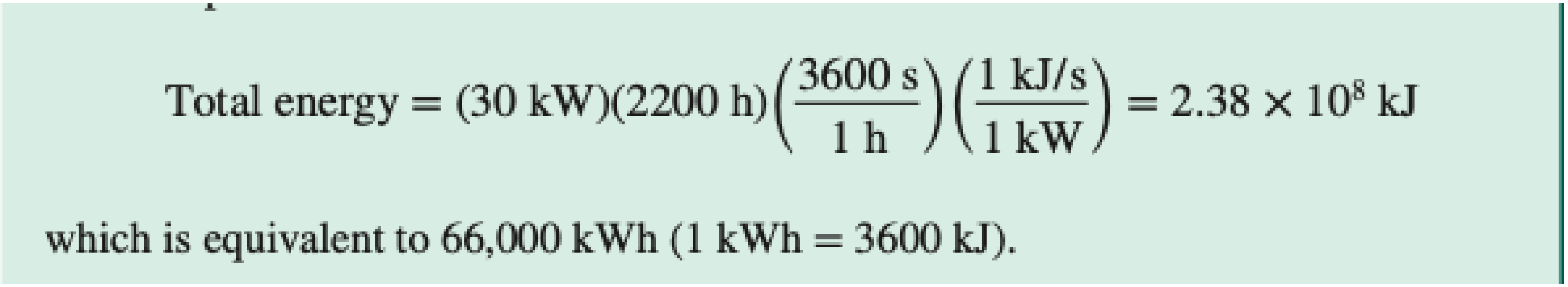
kWh ⟷ kJ



$$\text{Total energy} = (30\text{ kW})(2200\text{ h})\left(\frac{3600\text{ s}}{1\text{ h}}\right)\left(\frac{1\text{ kJ/s}}{1\text{ kW}}\right) = 2.38\times10^{8}\text{ kJ}$$

which is equivalent to 66,000 kWh (1 kWh = 3600 kJ).

1-2 Importance of Dimensions and Units

Using unit considerations, select the correct equations.

I. Mass = Force × Acceleration
II. Work = Force × Distance
III. Work = Power × Time
IV. Density = Mass × Volume

(a) I and II
(b) I and III
(c) II and III
(d) I, II, and III
(e) II, III, and IV

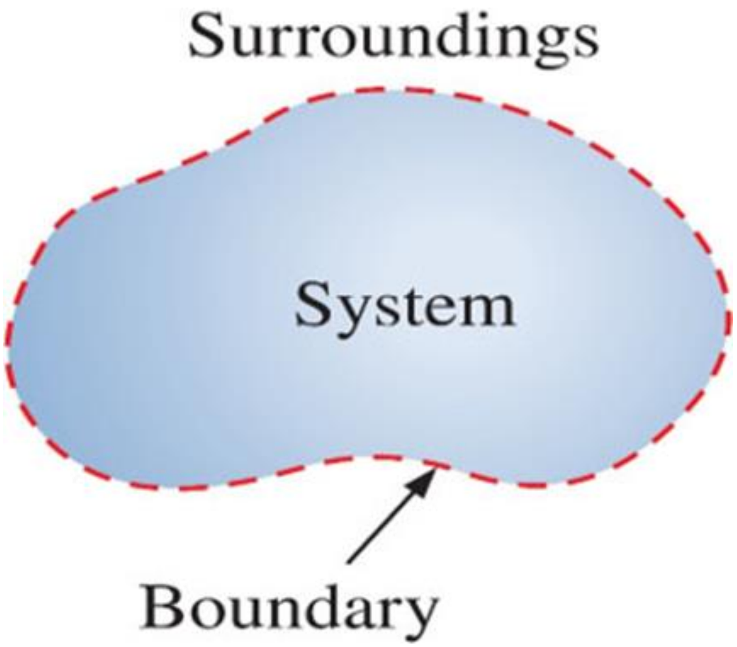
1-3 Systems and Control Volumes

System: A quantity of matter or a region in space chosen for study.

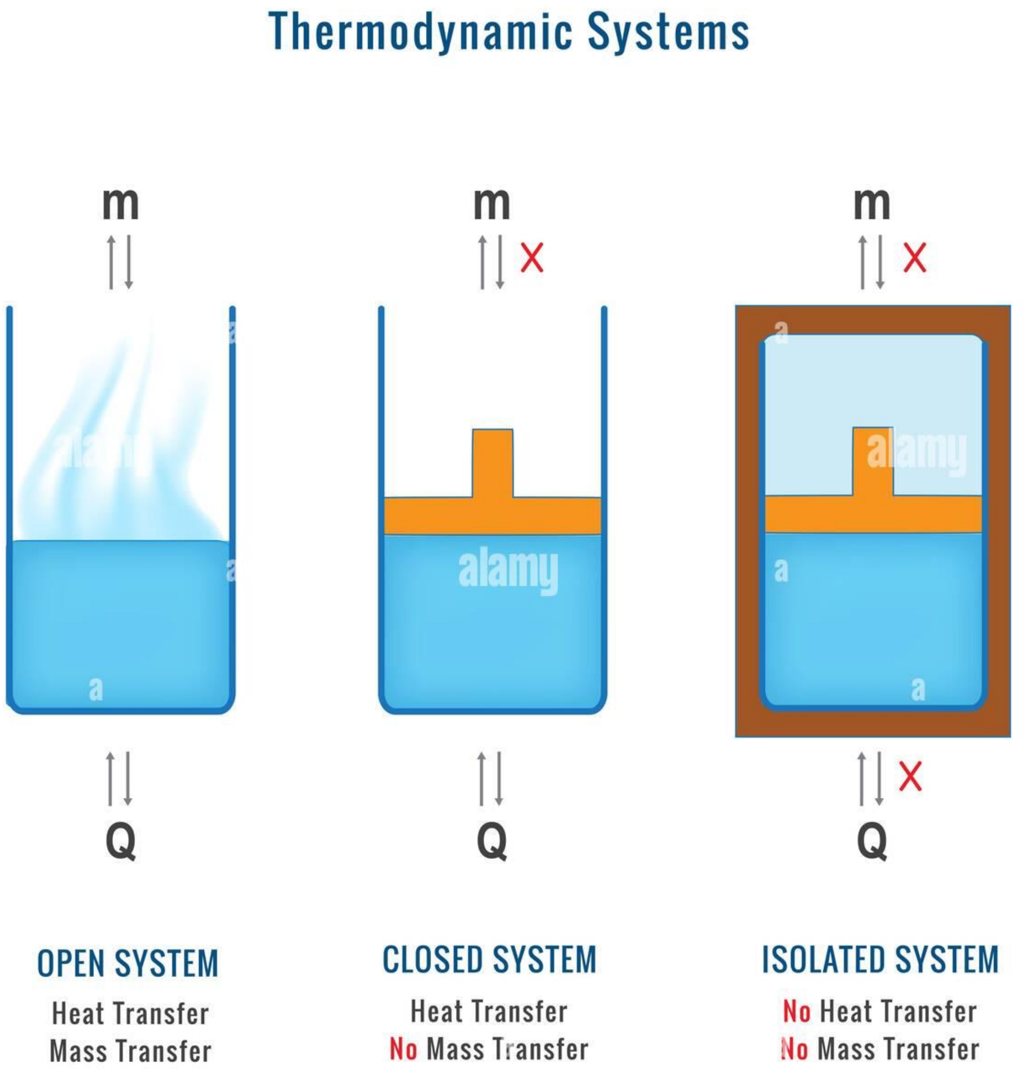
Surroundings: The mass or region outside the system

Boundary: The real or imaginary surface that separates the system from its surroundings.

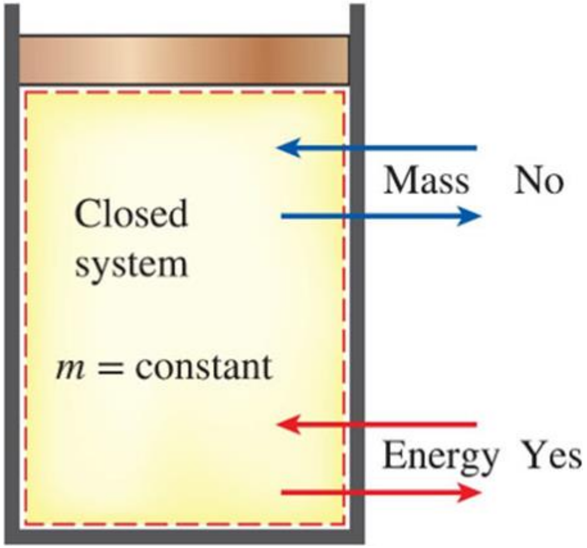
The boundary of a system can be *fixed* or *movable.*

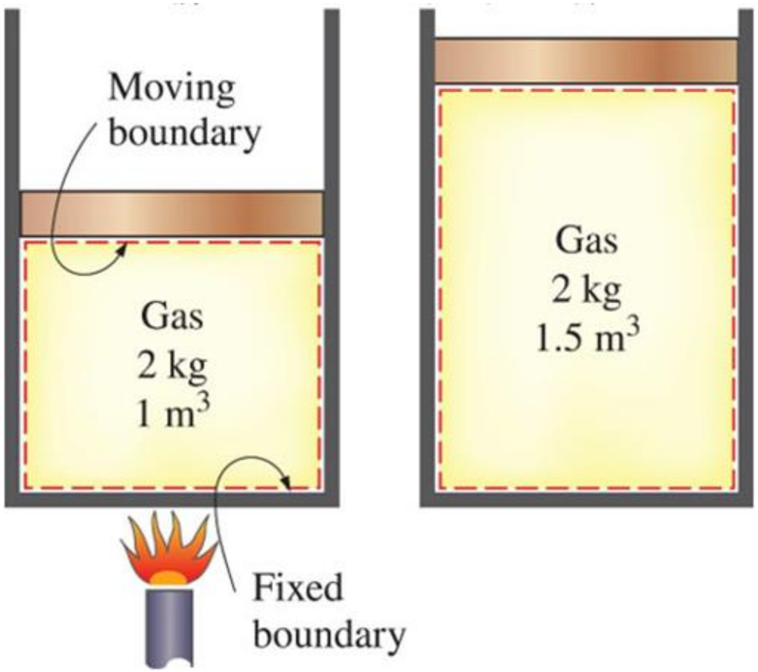


1-3 Systems and Control Volumes



1-3 Systems and Control Volumes

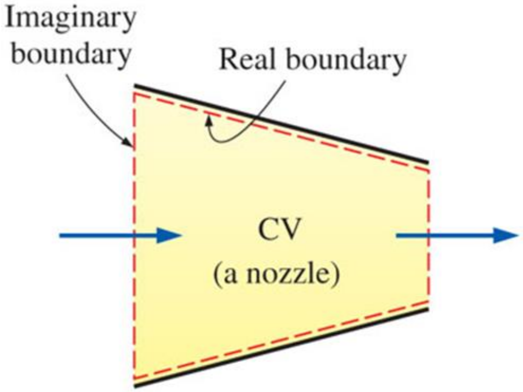




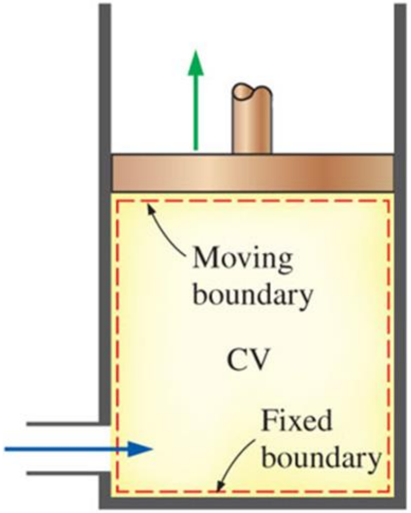
A closed system with a moving boundary.

1-3 Systems and Control Volumes 3

- Open system



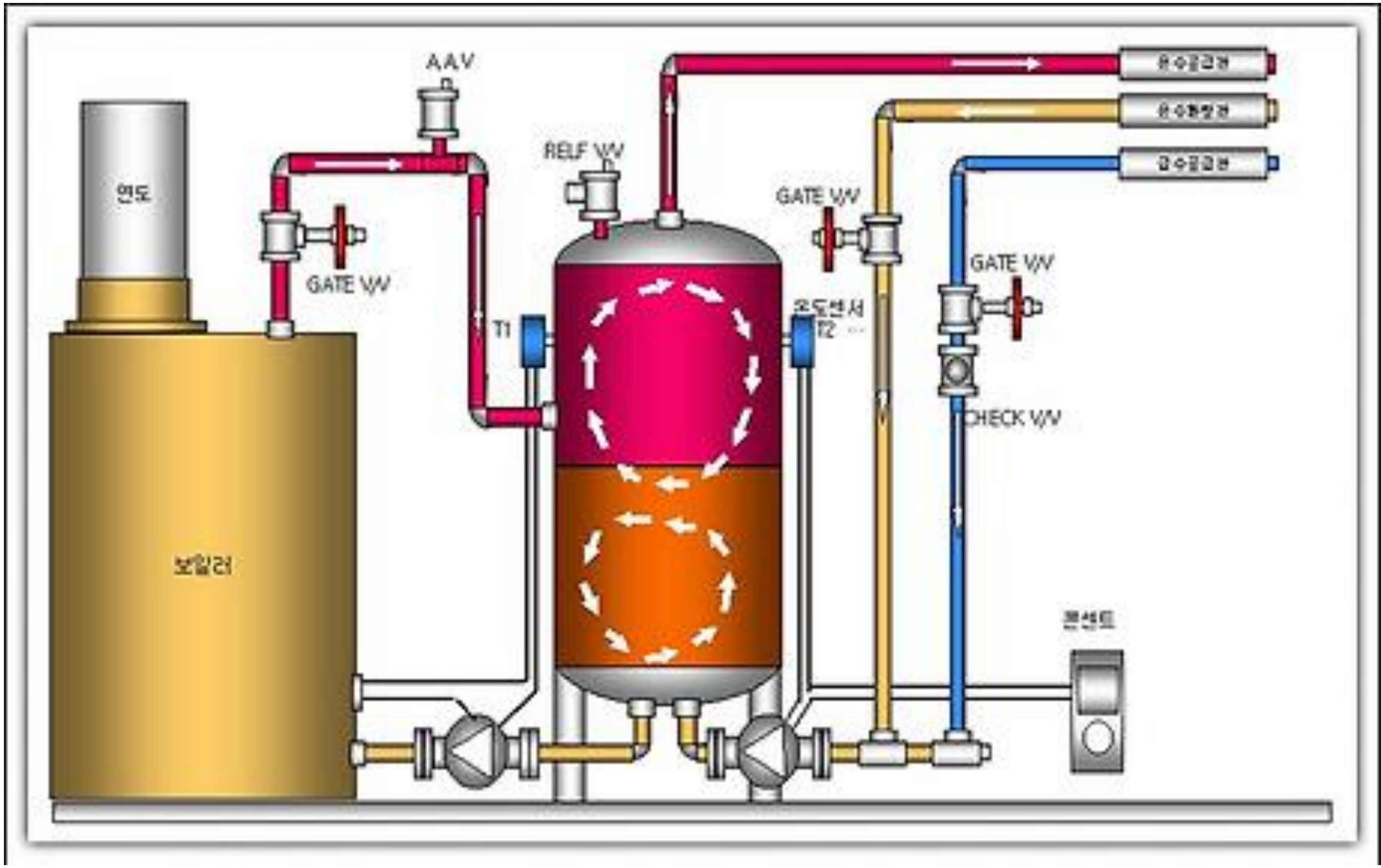
(*a*) A control volume (CV) with real and imaginary boundaries



(*b*) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

A control volume can involve fixed, moving, real, and imaginary boundaries.

1-3 Systems and Control Volumes 4



1-3 Systems and Control Volumes 4

Choose the wrong statement regarding systems and control volumes.

(a) The mass or region outside the system is called the surroundings.

(b) The real or imaginary surface that separates the system from its surroundings is called the boundary.

(c) The boundary has zero thickness.

(d) The boundary can neither contain any mass nor occupy any volume in space.

(e) The boundary of a system is fixed; it cannot move.

1-3 Systems and Control Volumes 4

Choose the wrong statement regarding systems and control volumes.

(a) Both mass and energy can cross the boundary of a control volume.

(b) Mass cannot enter or leave a closed system but energy can.

(c) Mass can enter or leave an isolated system but energy cannot.

(d) The boundaries of a control volume can be real or imaginary.

(e) The volume of a closed system does not have to be fixed.

1-4 Properties of a System

Continuum

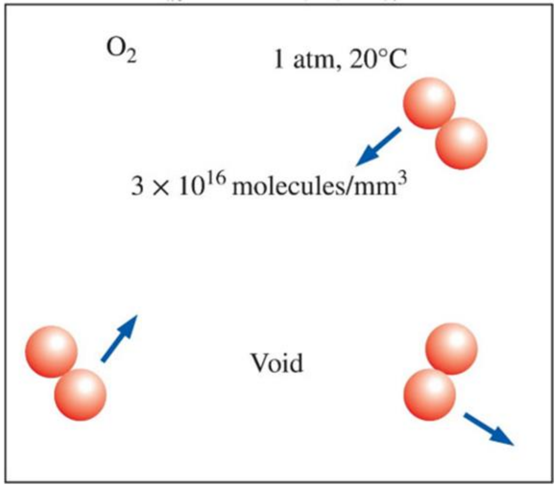
Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is, a **continuum.**

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.



Figure

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

1-4 Properties of a System

Property: Any characteristic of a system.

Some familiar properties are pressure *P*, temperature *T*, volume *V*, and mass *m*.

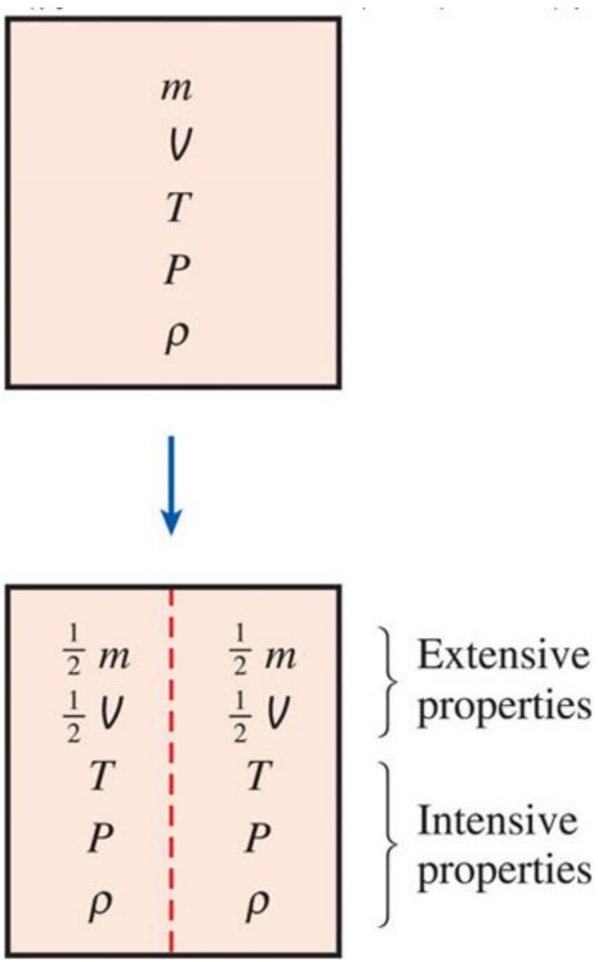
Properties are considered to be either *intensive* or *extensive*.

Intensive properties: Those that are independent of the size of a system, such as temperature, pressure, and density.

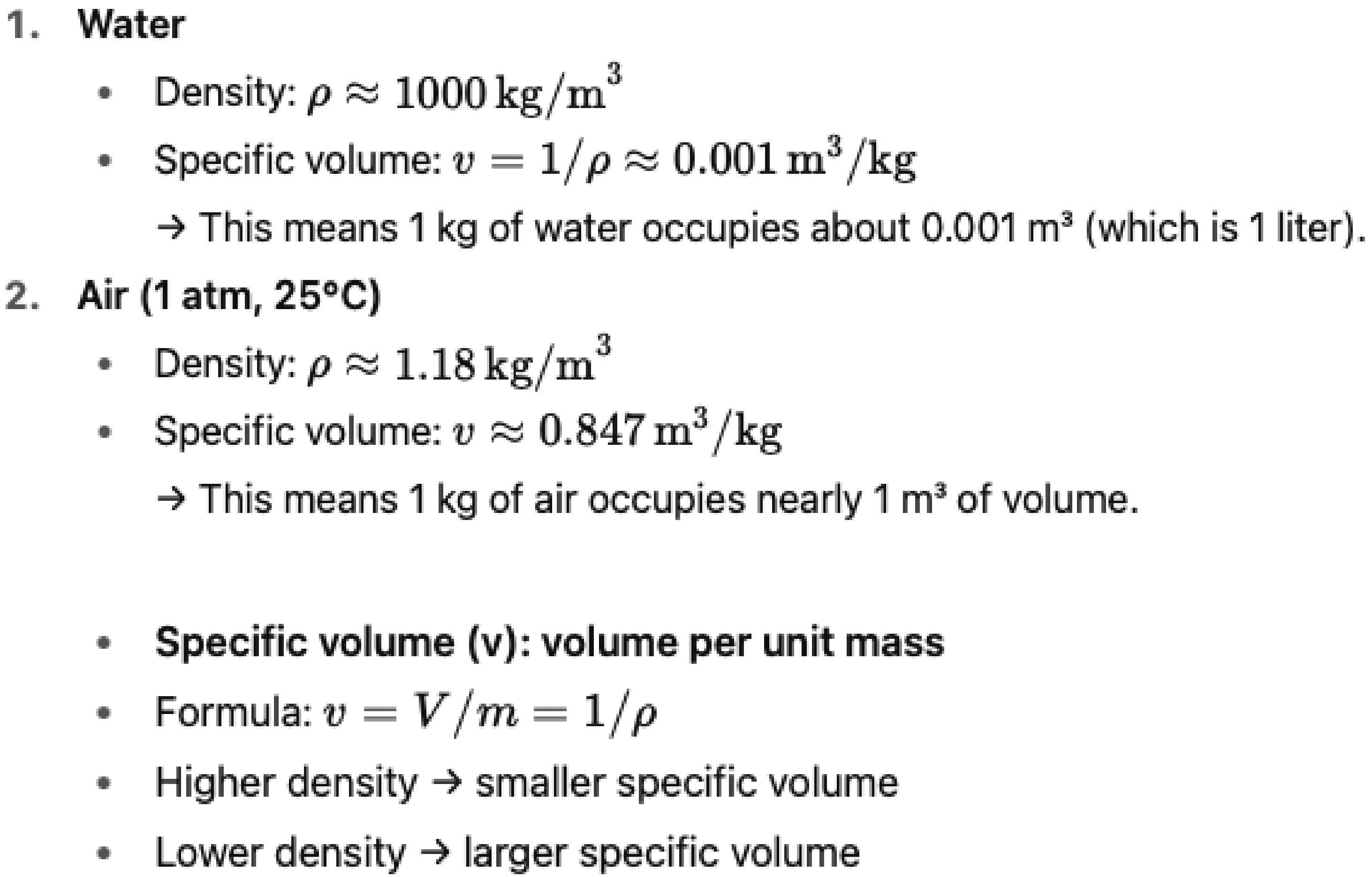
Extensive properties: Those whose values depend on the size—or extent—of the system.

Specific properties: Extensive properties per unit mass.

$$(v = V / m) \qquad (e = E / m)$$



1-5 Density and Specific Gravity



1. **Water**
   - Density: $\rho \approx 1000\,\mathrm{kg/m^3}$
   - Specific volume: $v = 1/\rho \approx 0.001\,\mathrm{m^3/kg}$

   → This means 1 kg of water occupies about 0.001 m³ (which is 1 liter).
2. **Air (1 atm, 25°C)**
   - Density: $\rho \approx 1.18\,\mathrm{kg/m^3}$
   - Specific volume: $v \approx 0.847\,\mathrm{m^3/kg}$

   → This means 1 kg of air occupies nearly 1 m³ of volume.

- **Specific volume (v): volume per unit mass**
- Formula: $v = V/m = 1/\rho$
- Higher density → smaller specific volume
- Lower density → larger specific volume

1-5 Density and Specific Gravity

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).

$$\mathrm{SG} = \frac{\rho}{\rho_{\mathrm{H_2O}}}$$

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

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

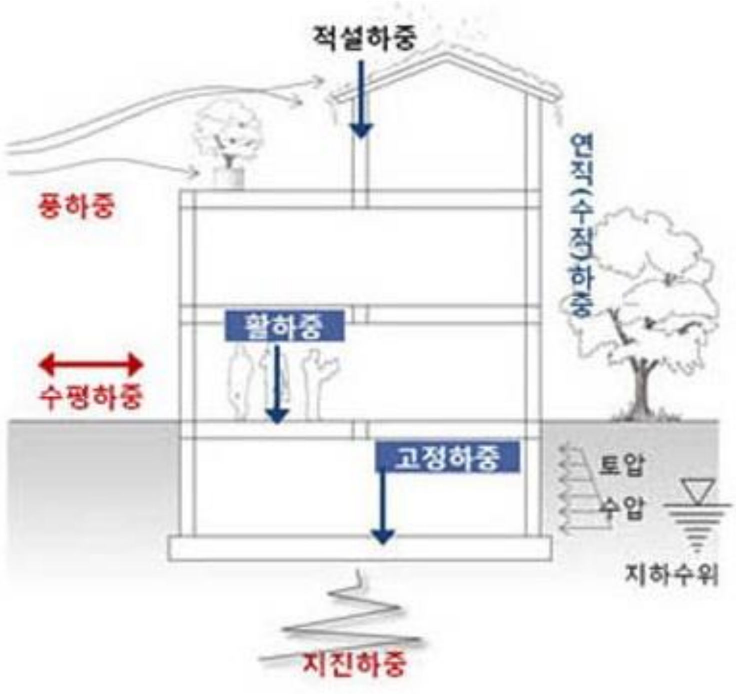
Table 1-3 Specific gravities of some substances at 0°C

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

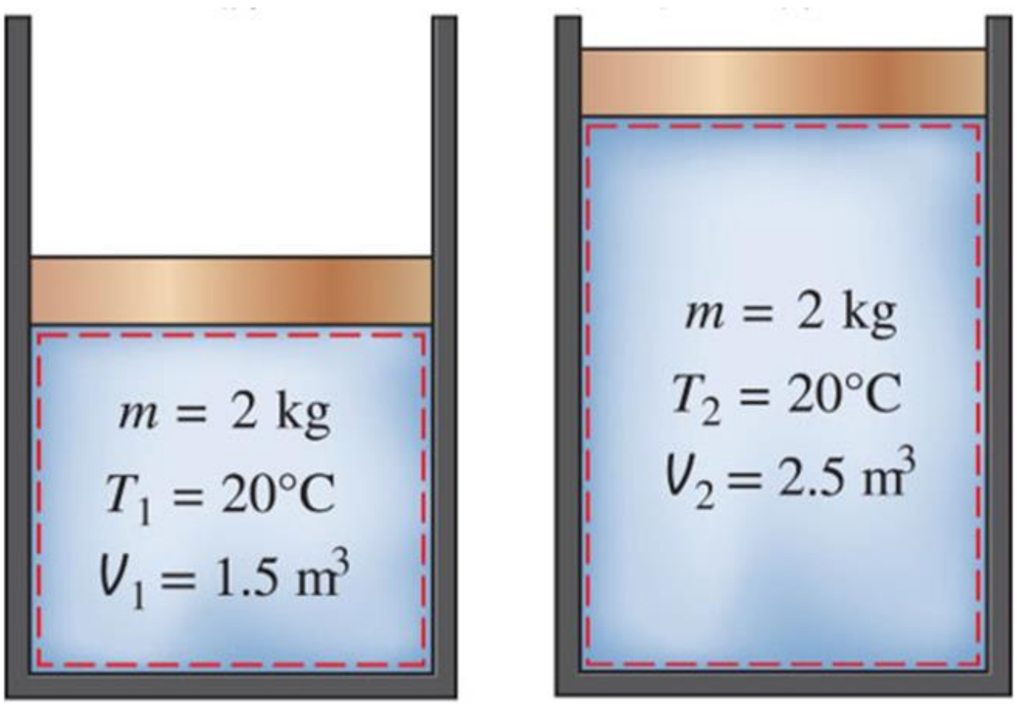
1-5 Density and Specific Gravity

- **Specific gravity:** Ratio of densities, dimensionless → useful for relative comparisons such as whether a material will float or sink.

- **Specific weight :** Weight per unit volume, with units of N/m^3 → directly used in calculating fluid pressure, structural loads, and soil pressures.



1-6 State and Equilibrium



(*a*) State 1 (*b*) State 2

Consider a system not undergoing any change. At this point, all the properties can be measured or calculated throughout the entire system, which gives us a set of properties that completely describes the condition, or the state, of the system.

1-6 State and Equilibrium

Thermodynamics deals with *equilibrium* states.

Equilibrium (평형): 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.

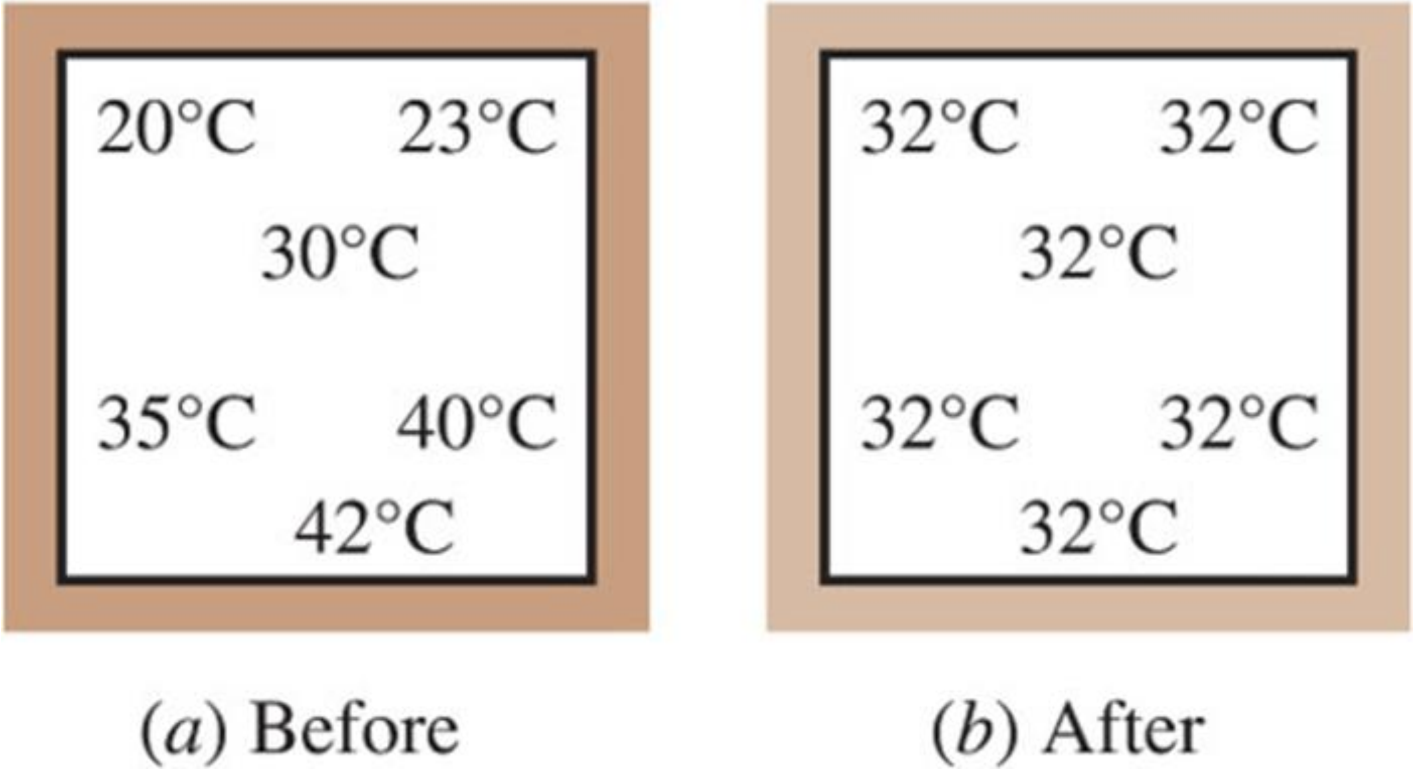
Mechanical equilibrium: If there is no change in **pressure** at any point of the system with time.

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 system in equilibrium experiences no changes when it is isolated from its surroundings.

1-6 State and Equilibrium



(*a*) Before (*b*) After

A closed system reaching thermal equilibrium.

The system involves no temperature differential, which is the driving force for heat flow.

1-6 State and Equilibrium

The State Postulate

(상태의 원리, 상태의 가정)

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*****.**

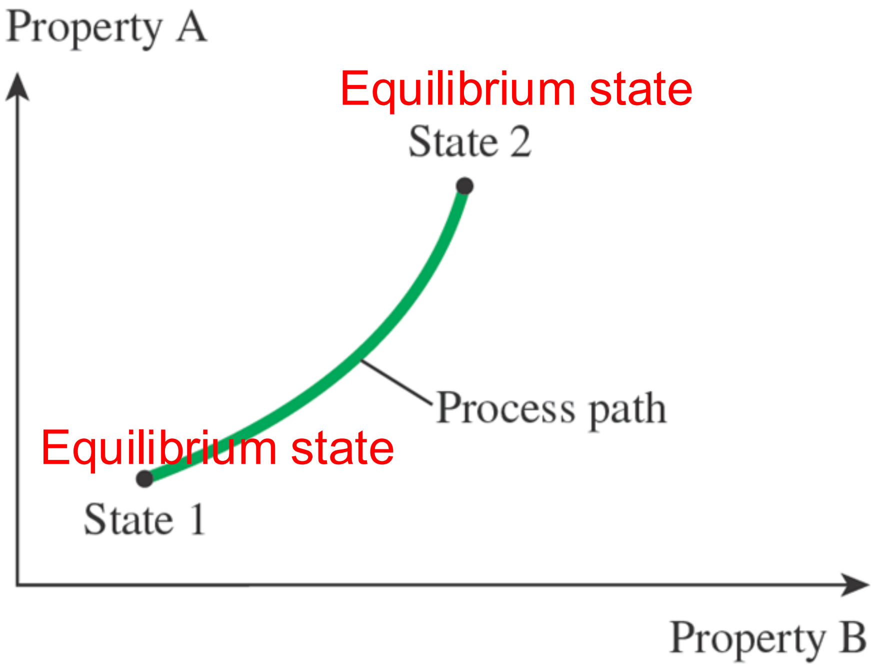
Simple compressible system: If a system involves no electrical, magnetic, gravitational, motion, and surface tension effects.

1-7 Processes and Cycles

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

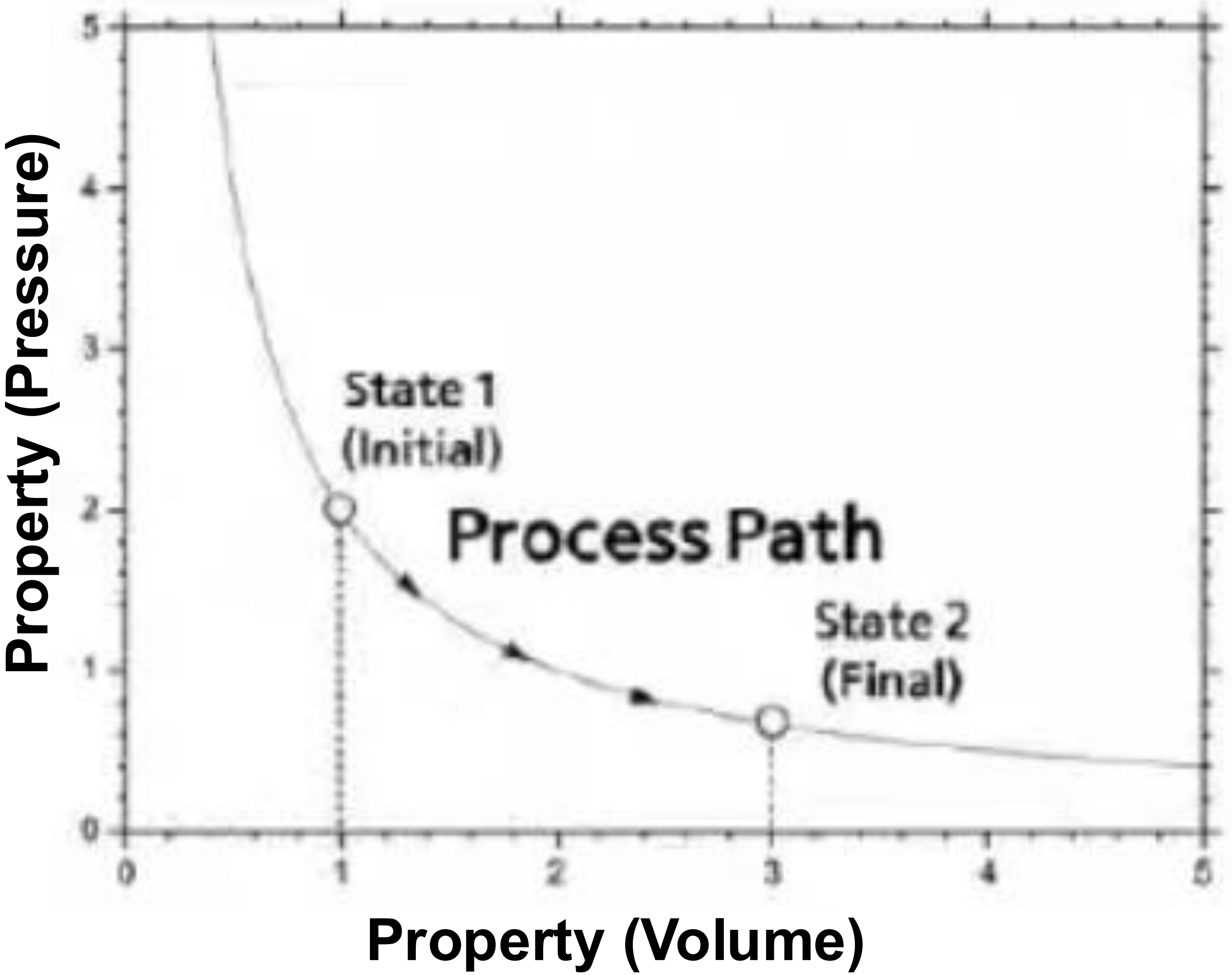
Path: The series of states through which a system passes during a process.

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.***



A process between states 1 and 2 and the process path.

1-7 Processes and Cycles

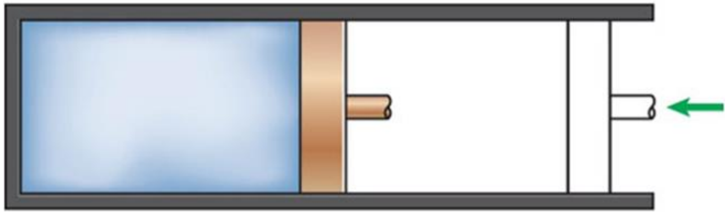


1-7 Processes and Cycles

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.

→ 과정이 진행되는 동안 계(System)가 평형상태에 근접하여 유지되고 있을 때

(*a*) Slow compression
(quasi-equilibrium)



(*b*) Very fast compression
(nonquasi-equilibrium)

1-7 Processes and Cycles

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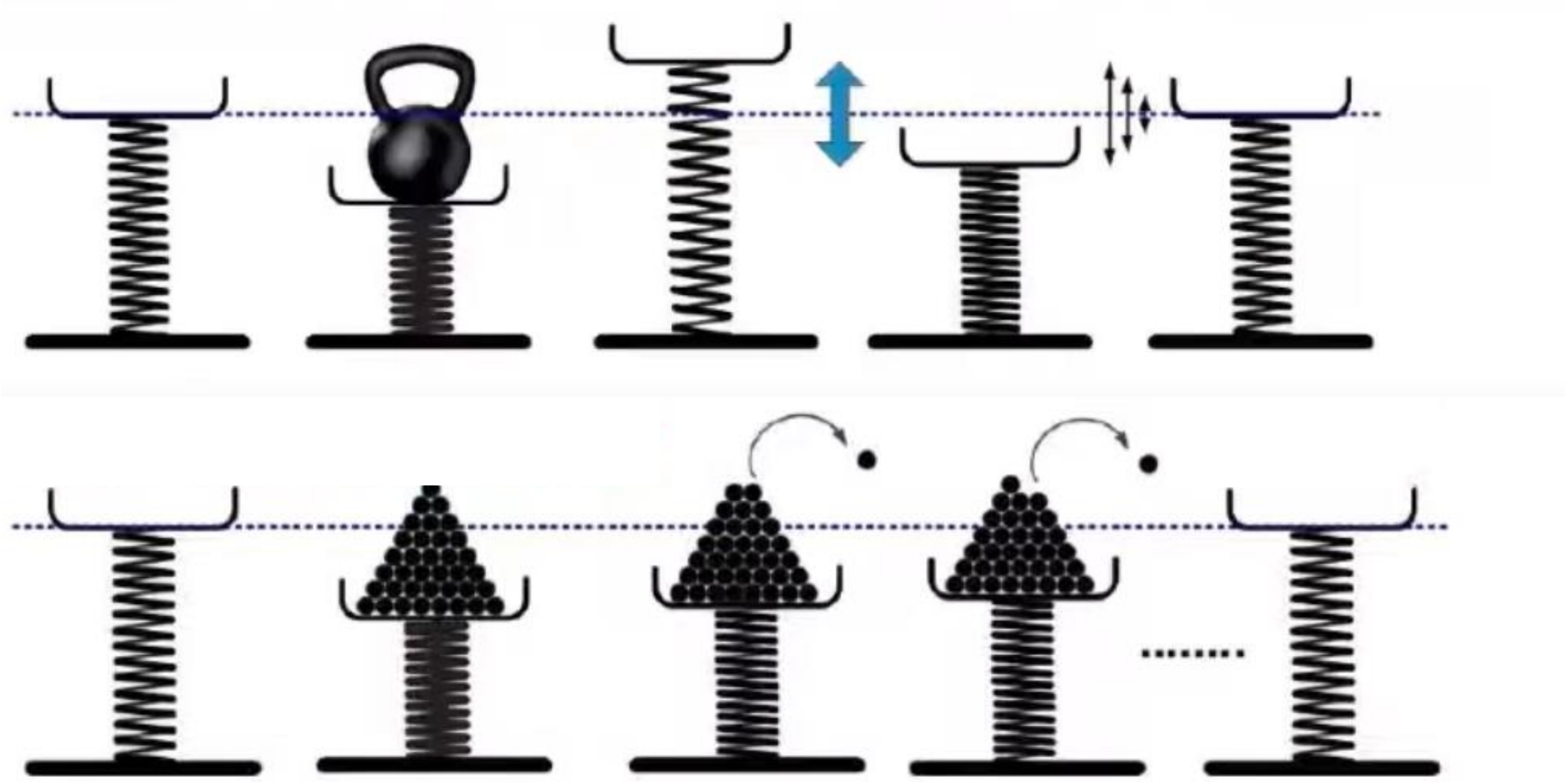
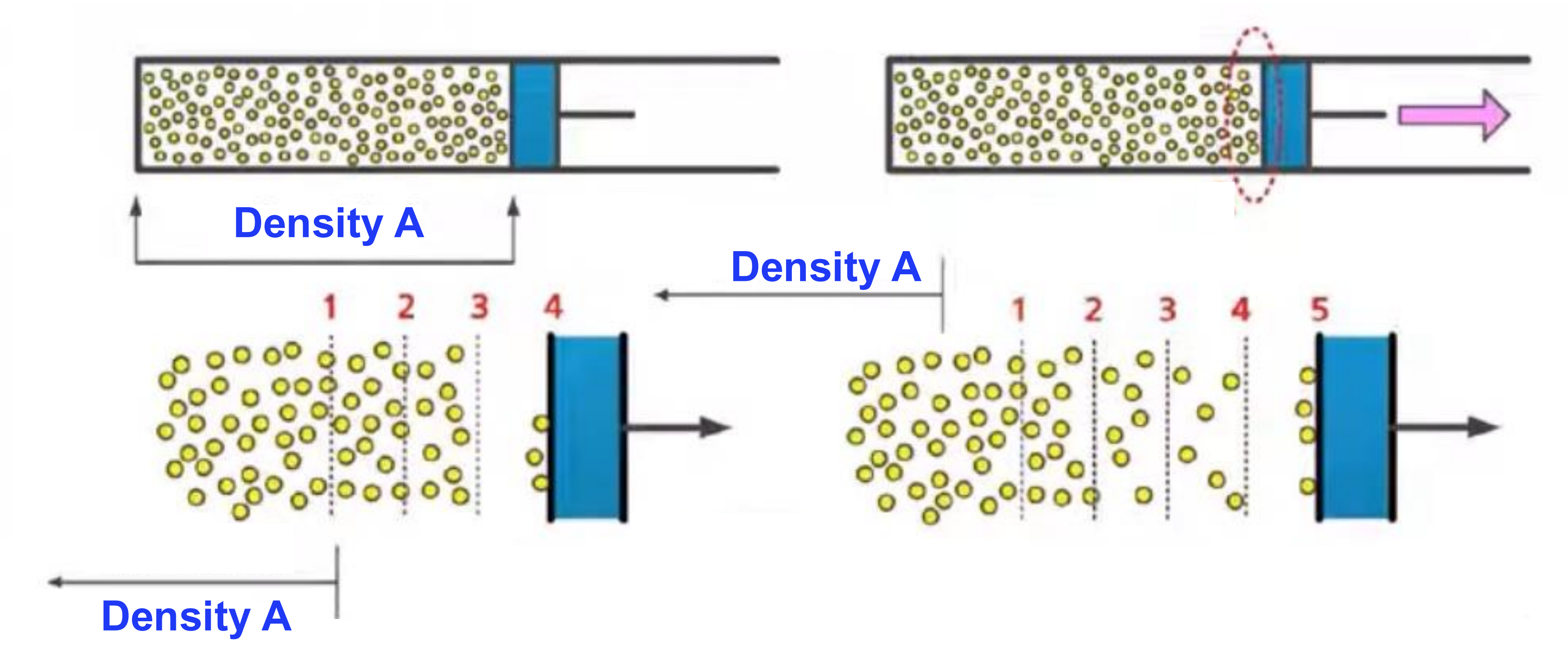


1-7 Processes and Cycles

nonquasi-equilibrium process



Density A

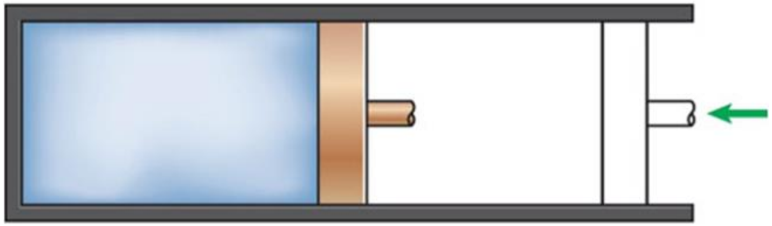
Density A

Density A

1-7 Processes and Cycles

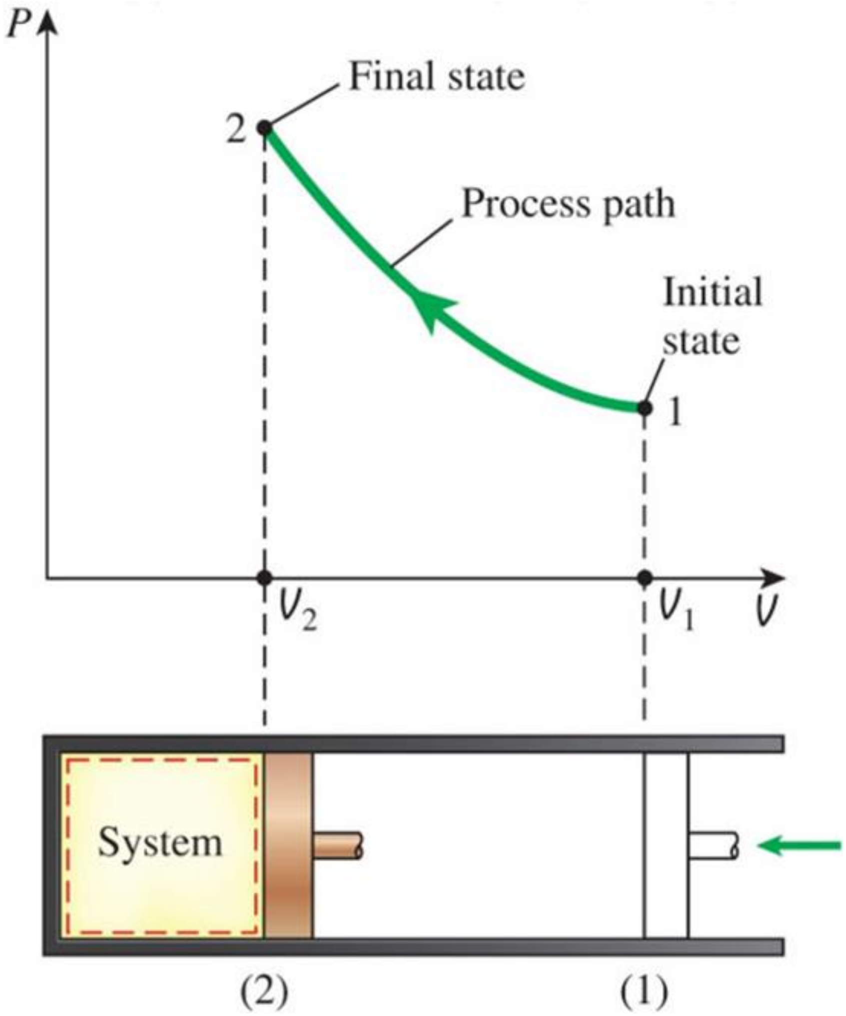
Quasistatic or quasi-equilibrium process: When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.

(*a*) Slow compression
(quasi-equilibrium)

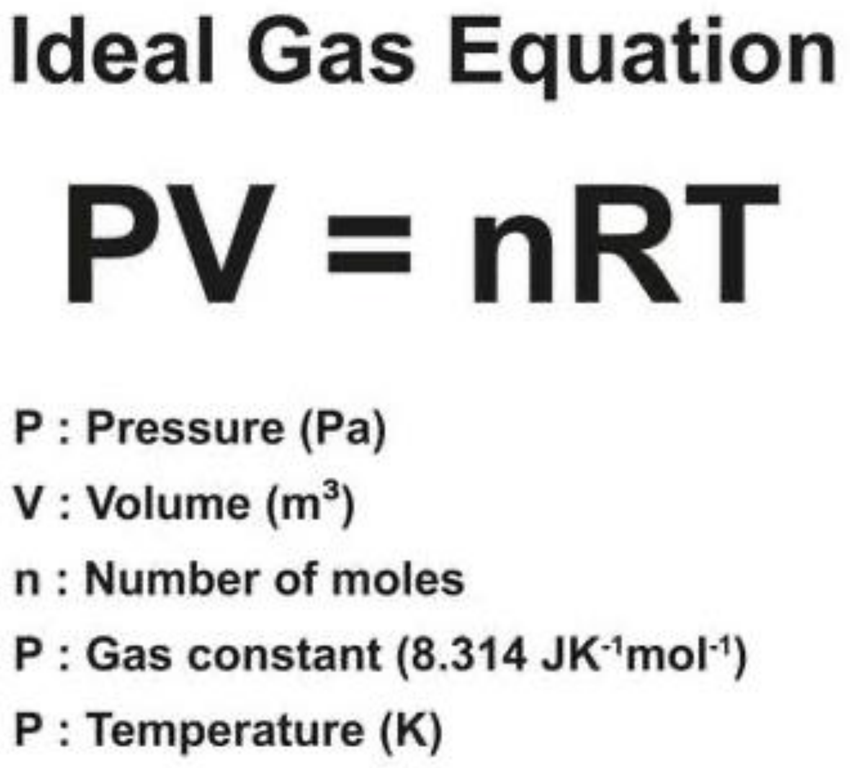


(*b*) Very fast compression
(nonquasi-equilibrium)

1-7 Processes and Cycles 3



Isothermal process: A process during which the temperature *T* remains constant.



Ideal Gas Equation

$$PV = nRT$$

P : Pressure (Pa)
V : Volume (m^3)
n : Number of moles
P : Gas constant (8.314 $JK^{-1}mol^{-1}$)
P : Temperature (K)

1-7 Processes and Cycles 3

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.

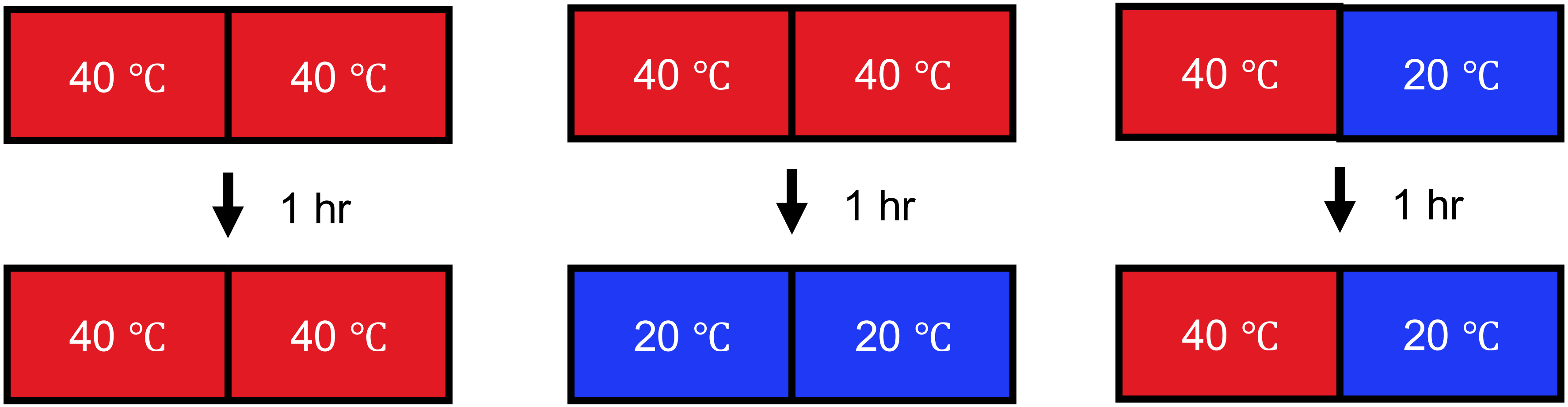
Isochoric (or isometric) process: A process during which the **specific volume** *v* remains constant.

Cycle: A process during which the initial and final states are identical.

1-7 Processes and Cycles 4

Steady vs unsteady (Transient), Uniform

The term *steady* implies no change with time. The opposite of steady is *unsteady,* or *transient.* The term *uniform,* however, implies *no change with location* over a specified region.



40 °C | 40 °C
1 hr
40 °C | 40 °C

40 °C | 40 °C
1 hr
20 °C | 20 °C

40 °C | 20 °C
1 hr
40 °C | 20 °C

1-7 Processes and Cycles 4

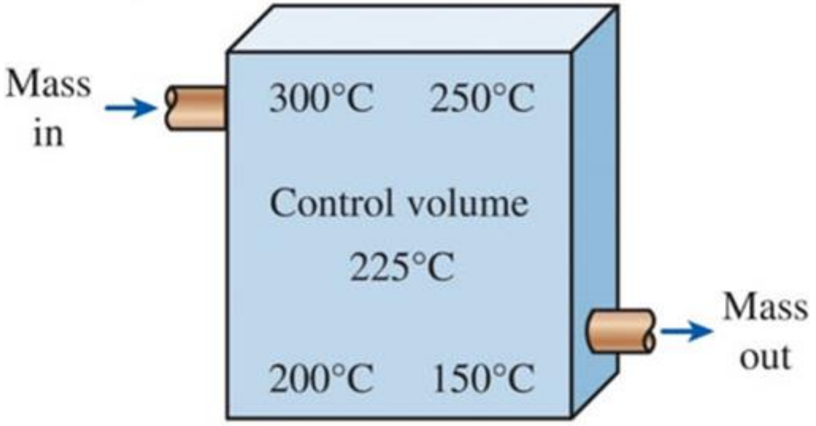
The Steady-Flow Process

The term *steady* implies *no change with time*. The opposite of steady is *unsteady*, or *transient*.

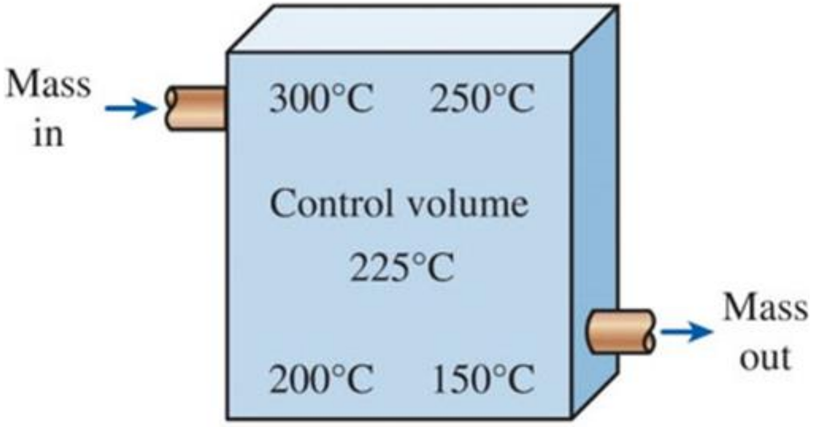
A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*.

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.**

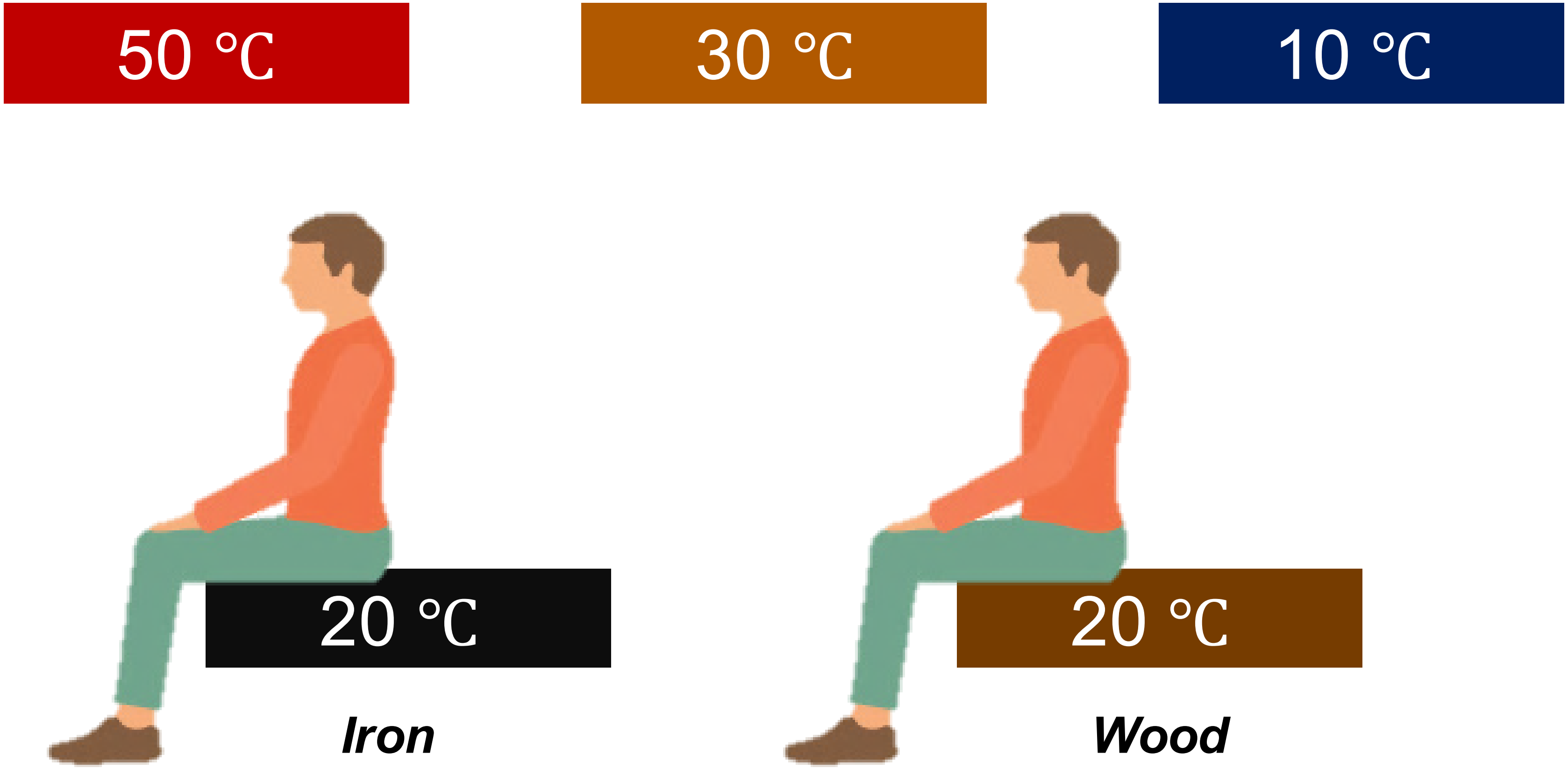


Time: 1 PM



Time: 3 PM

1-8 Temperature



50 °C

30 °C

10 °C

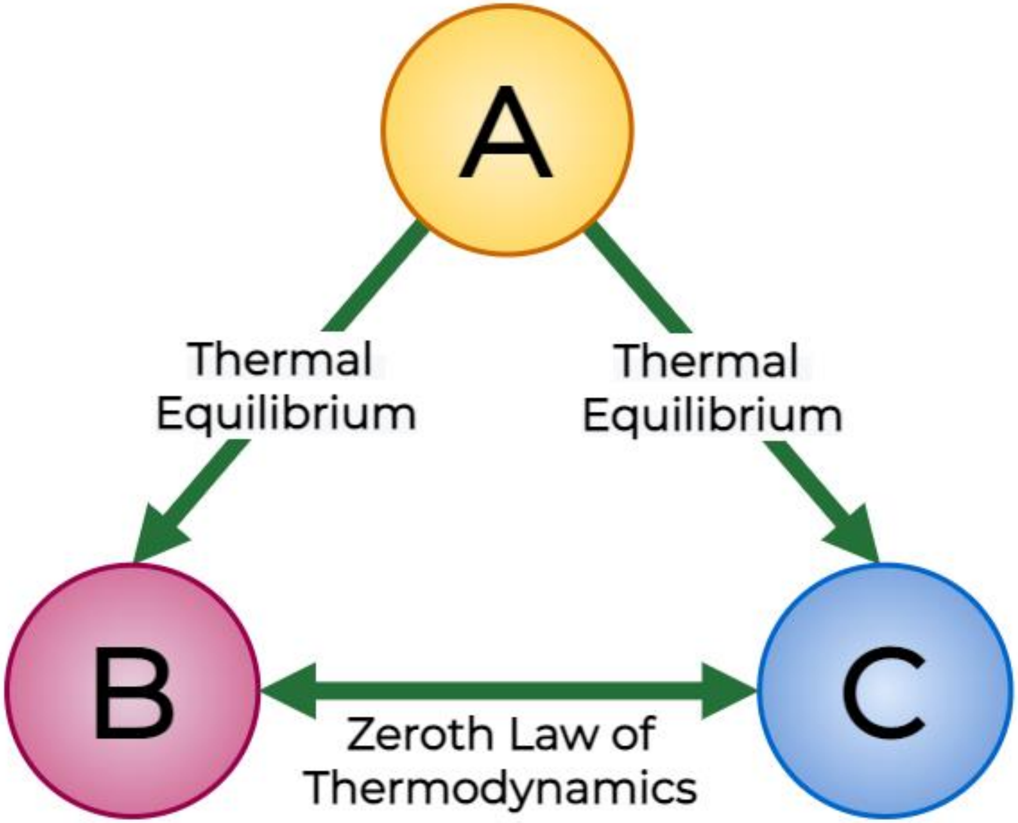
20 °C

20 °C

Iron

Wood

1-8 Zeroth Law of Thermodynamics



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

1-8 Temperature and the Zeroth Law of Thermodynamics

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: Temperature in SI unit system

Fahrenheit scale: Temperature 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.

1-8 Temperature and the Zeroth Law of Thermodynamics 4

$T(\text{K}) = T(°\text{C}) + 273.15$

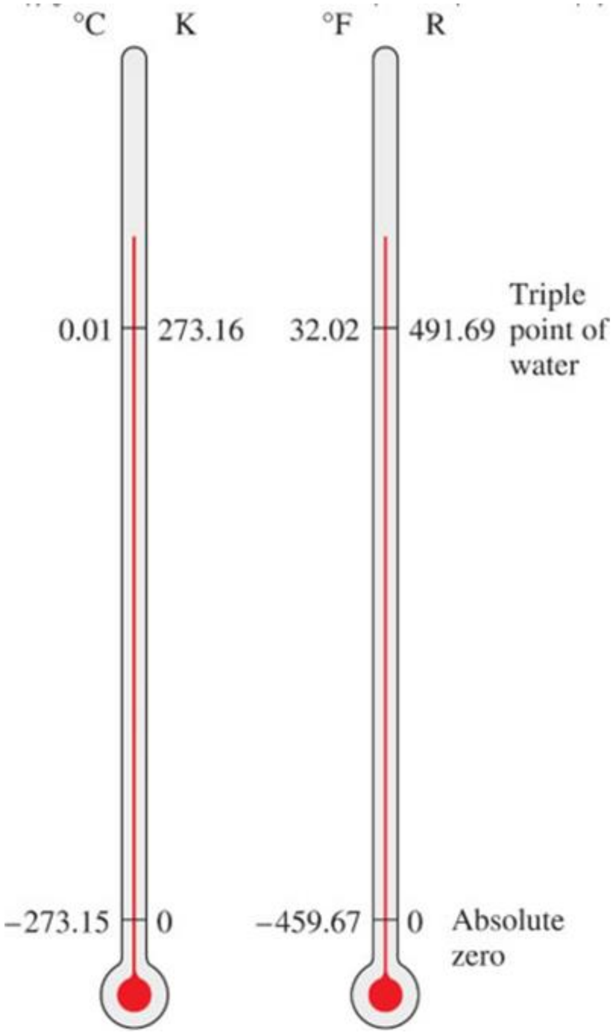
$T(\text{R}) = T(°\text{F}) + 459.67$

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

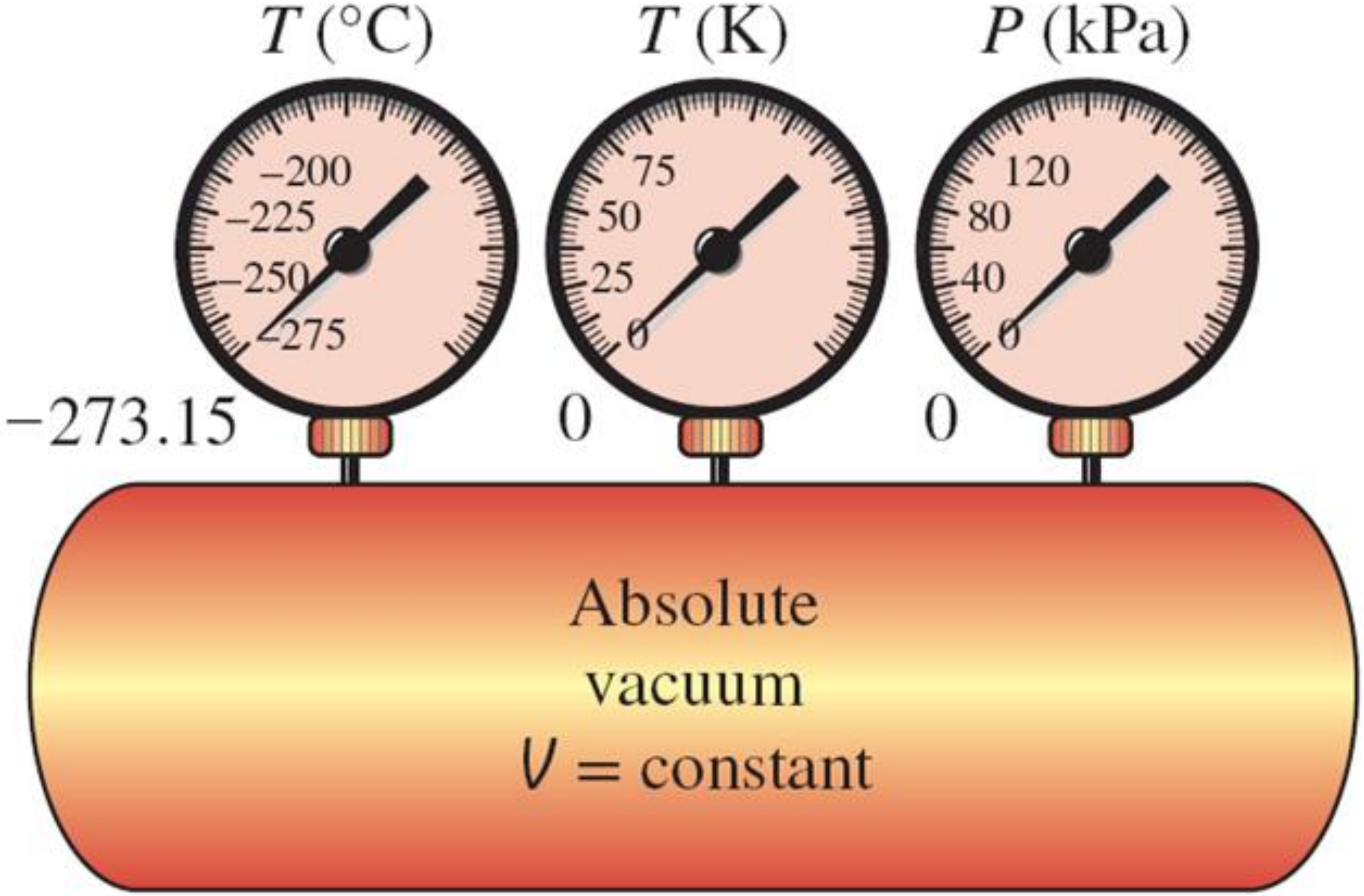
$T(°\text{F}) = 1.8T(°\text{C}) + 32$

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.



1-8 Temperature and the Zeroth Law of Thermodynamics



가톨릭대학교
THE CATHOLIC UNIVERSITY OF KOREA

Energy balance and thermodynamics

Kangmin Lee
Dept. of Energy and Environmental Engineering

1-9 Pressure

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

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

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

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

$$\begin{aligned}1\ \text{kgf/cm}^2 &= 9.807\,\text{N/cm}^2 = 9.807\times10^4\,\text{N/m}^2\\ &= 9.807\times10^4\,\text{Pa}\\ &= 0.9807\,\text{bar}\\ &= 0.9679\,\text{atm}\end{aligned}$$

Oil and Gas Photographer/Shutterstock

1-9 Pressure

1-9 Pressure

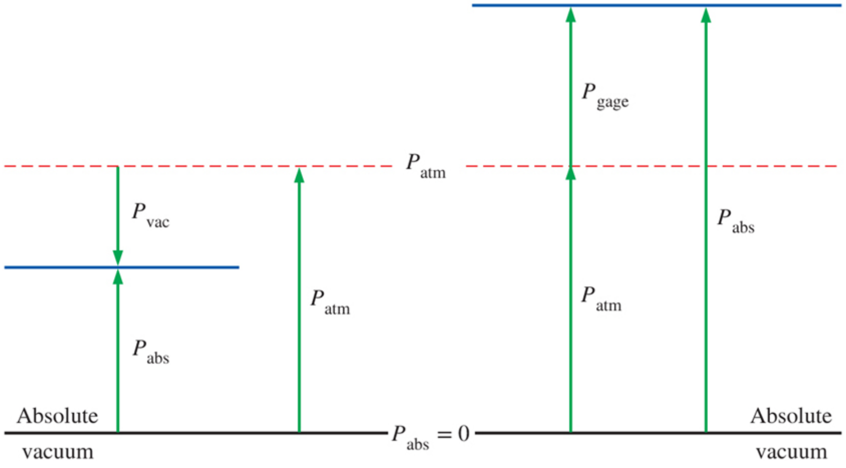
Absolute pressure: The actual pressure at a given position. It is measured relative to absolute vacuum (that is, absolute zero pressure).

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.

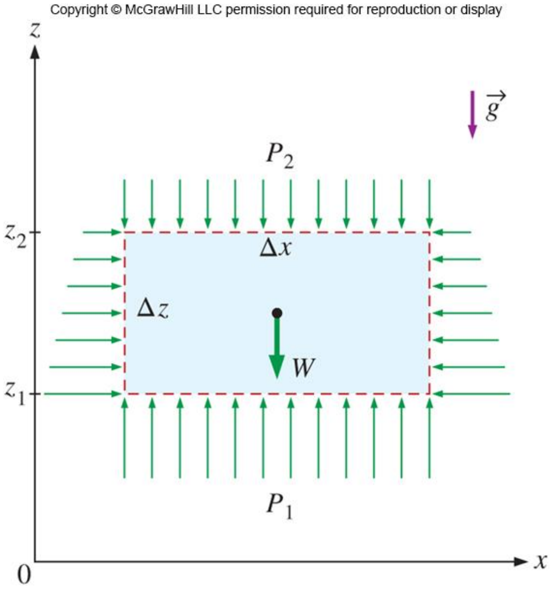
$$P_{\text{gage}} = P_{\text{abs}} - P_{\text{atm}}$$

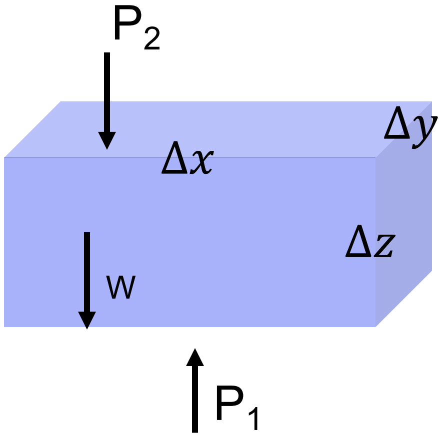
$$P_{\text{vac}} = P_{\text{atm}} - P_{\text{abs}}$$



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

1-9 Pressure





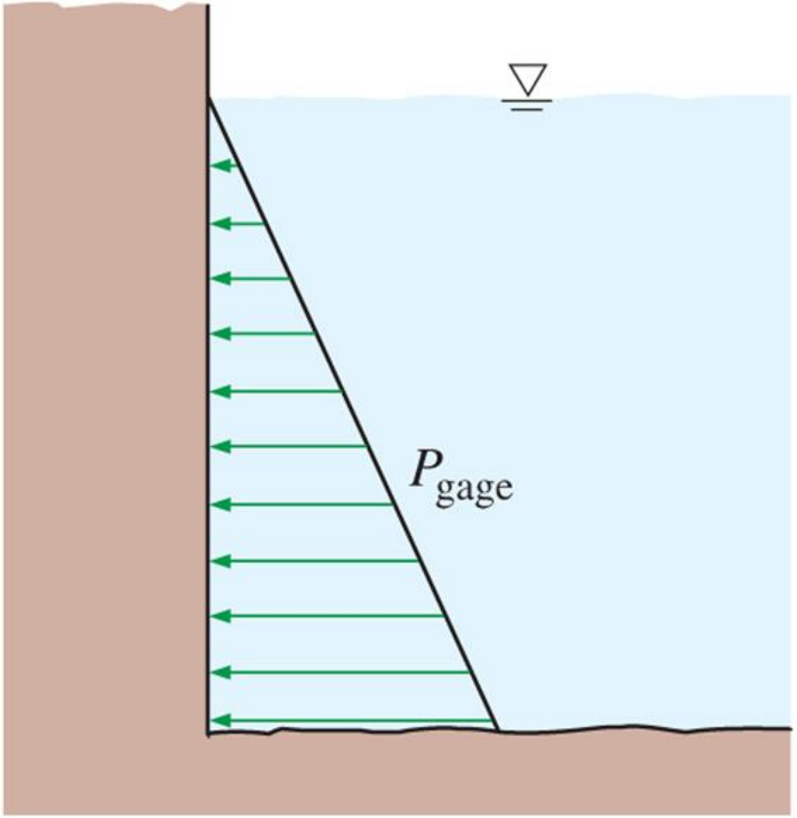
$$\sum F_z = ma_z = 0$$

$$P_1 \Delta x \Delta y - P_2 \Delta x \Delta y - \rho g \Delta x \Delta y \Delta z = 0$$

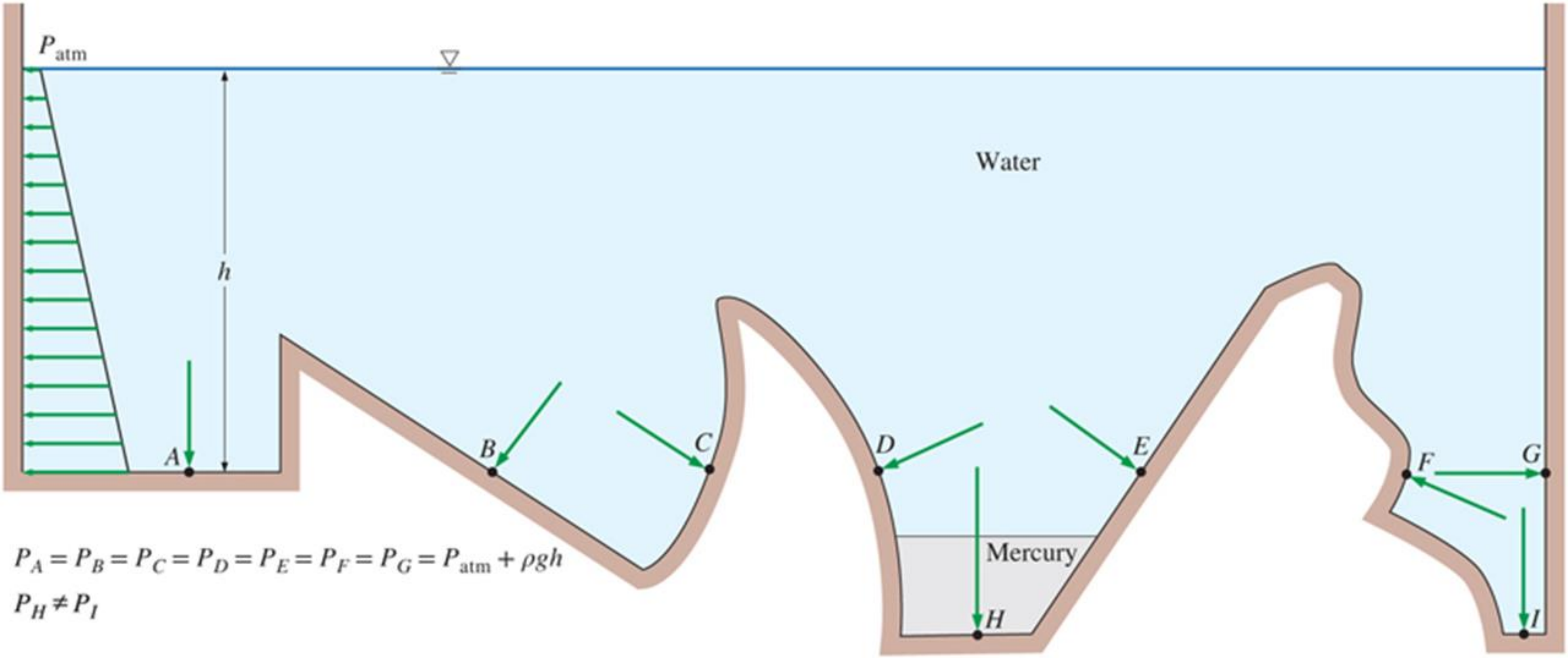
$$\Delta P = P_2 - P_1 = -\rho g \Delta z = -\gamma_s \Delta z$$

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

1-9 Pressure



1-9 Pressure



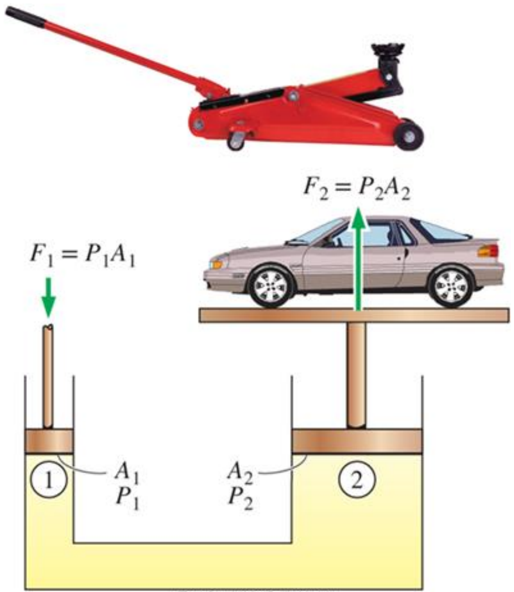
Under hydrostatic conditions, the pressure is the same at all points on a horizontal plane in a given fluid regardless of geometry, provided that the points are interconnected by the same fluid.

1-9 Pressure

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.



(Top) Stockbyte/Getty Images

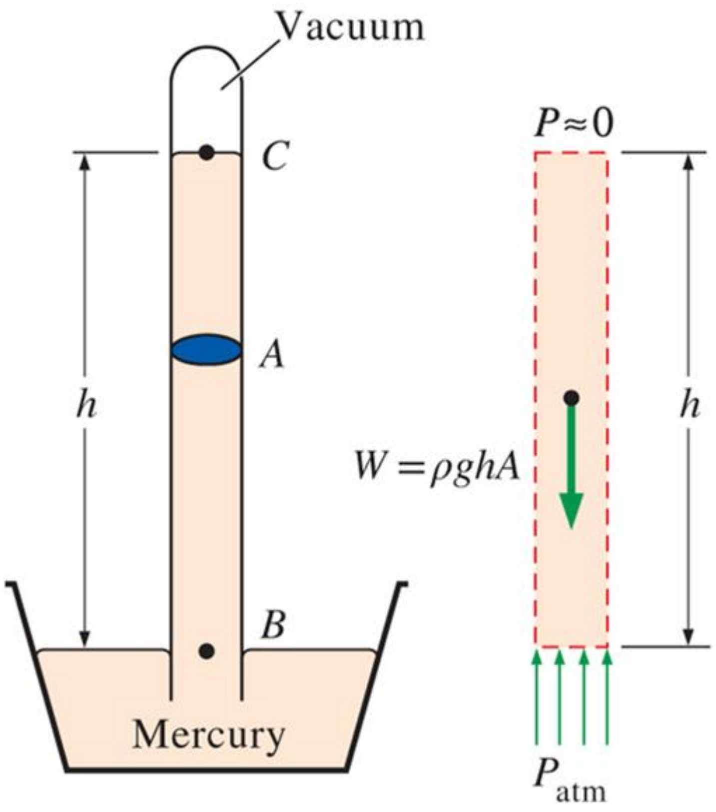
Figure

Lifting of a large weight by a small force by the application of Pascal's law. A common example is a hydraulic jack.

1-9 Pressure

https://youtube.com/shorts/HKkIKJ_CbRI?si=kEtlDbJGUoV7YjPP

1-10 Pressure Measurement Device



Evangelista Torricelli (1608~1647)

The Barometer (기압계)

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 $\left(\rho_{Hg} = 13{,}595 \text{ kg}/\text{m}^3\right)$ under standard gravitational acceleration $(g = 9.807 \text{ m}/\text{s}^2)$

$$P_{atm} = \rho g h$$

1-10 Pressure Measurement Device

$$P_{\text{atm}} = \rho g h$$

$$\left(\rho_{\text{Hg}} = 13{,}595 \text{ kg/m}^3\right)$$

$$(g = 9.807 \text{ m/s}^2)$$

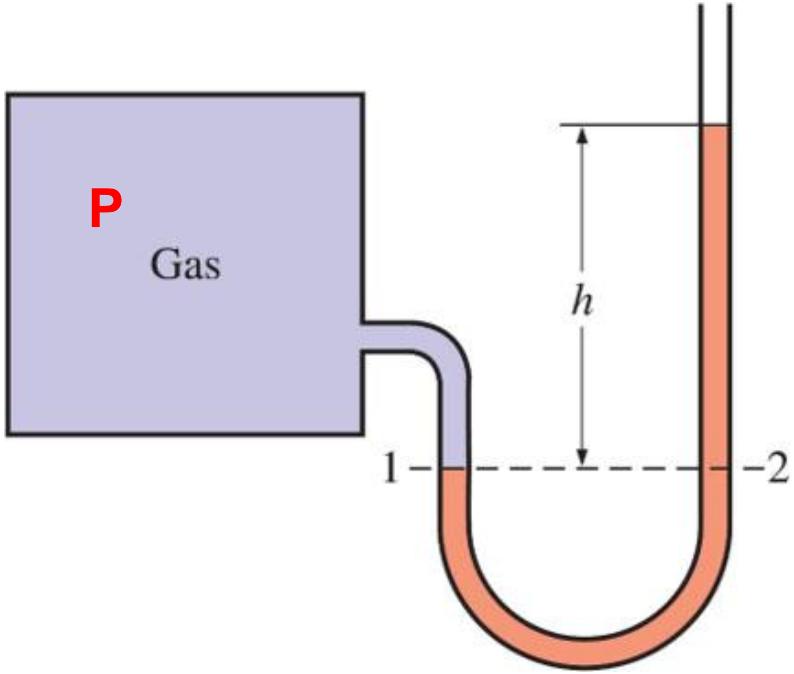
$= 13{,}595 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 \times 760 \text{ mm}$

$= 101.325 \text{ kPa} = 760 \text{ mmHg} = 760 \text{ torr}$

1-10 Pressure Measurement Devices

The Manometer (액주식 압력계)

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.



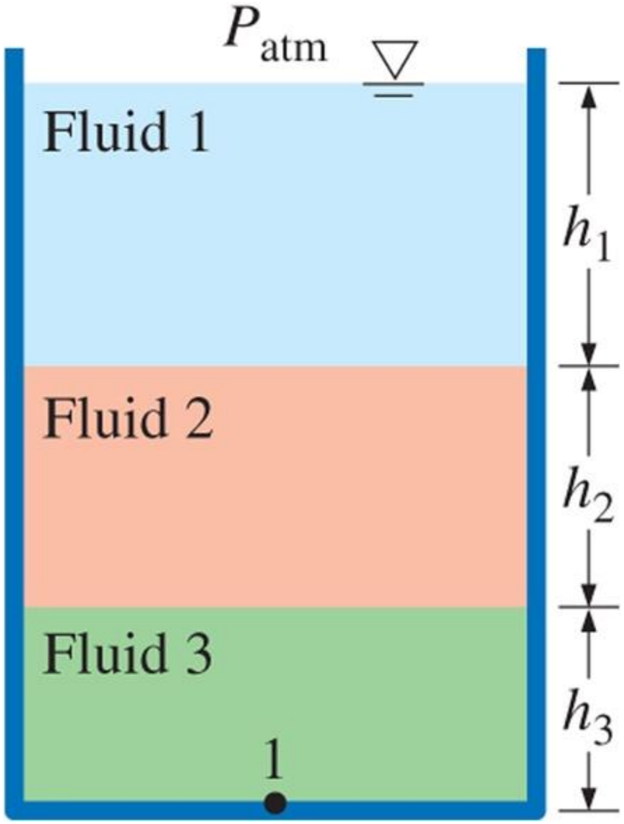
P = P1

P1=P2

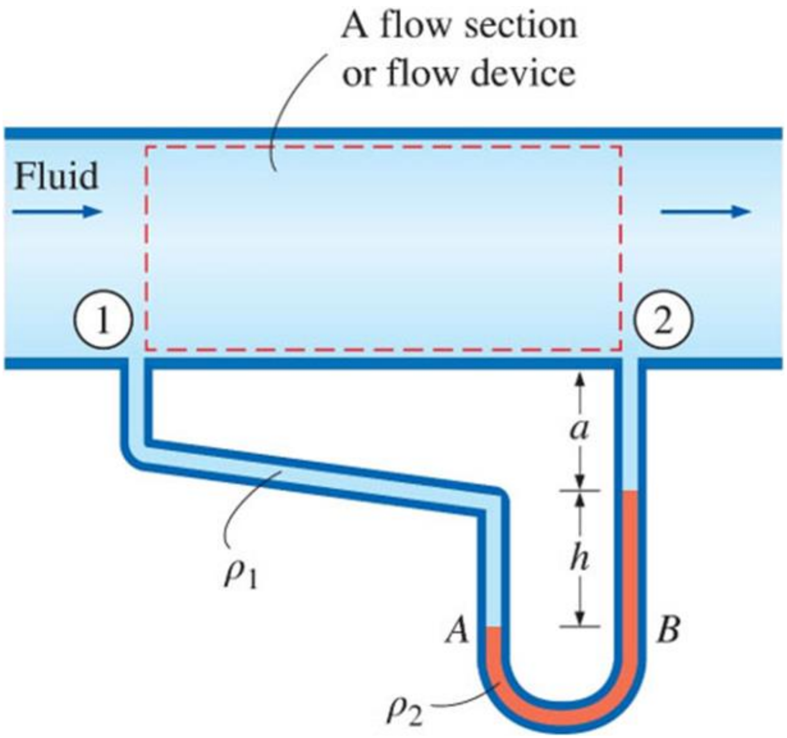
$$P_2 = P_{\text{atm}} + \rho g h$$

1-10 Pressure Measurement Devices 4

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



1-10 Pressure Measurement Devices 5



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

$$P_1 - P_2 = (\rho_2 - \rho_1)gh$$

$$\rho_2 > \rho_1$$

1-10 Pressure Measurement Devices 6

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.

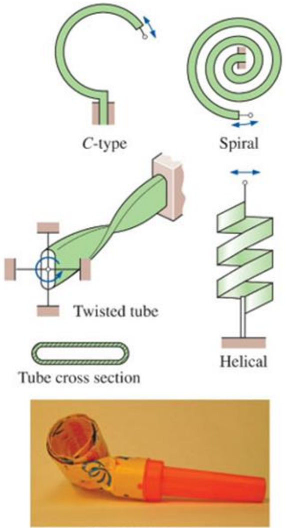
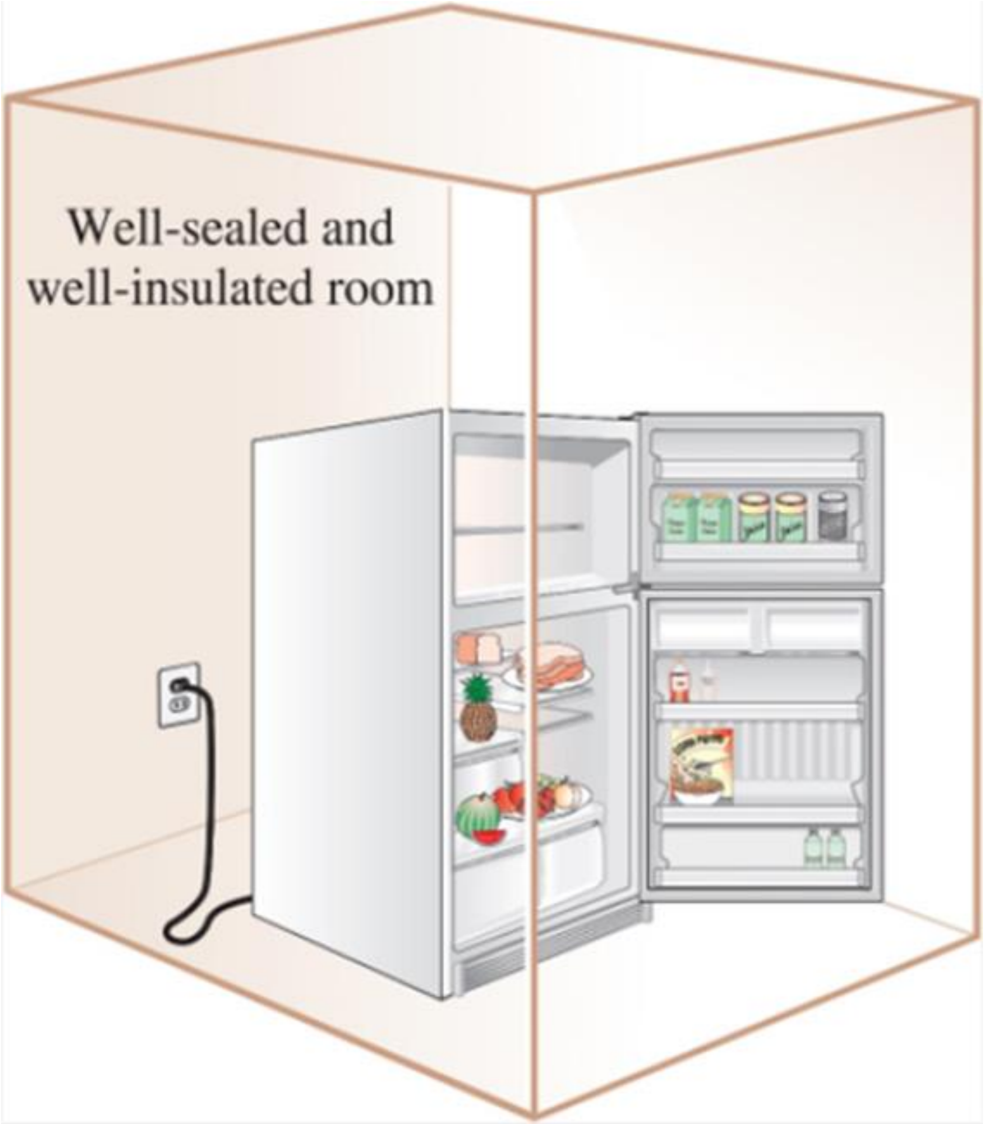


Photo: © John M. Cimbala

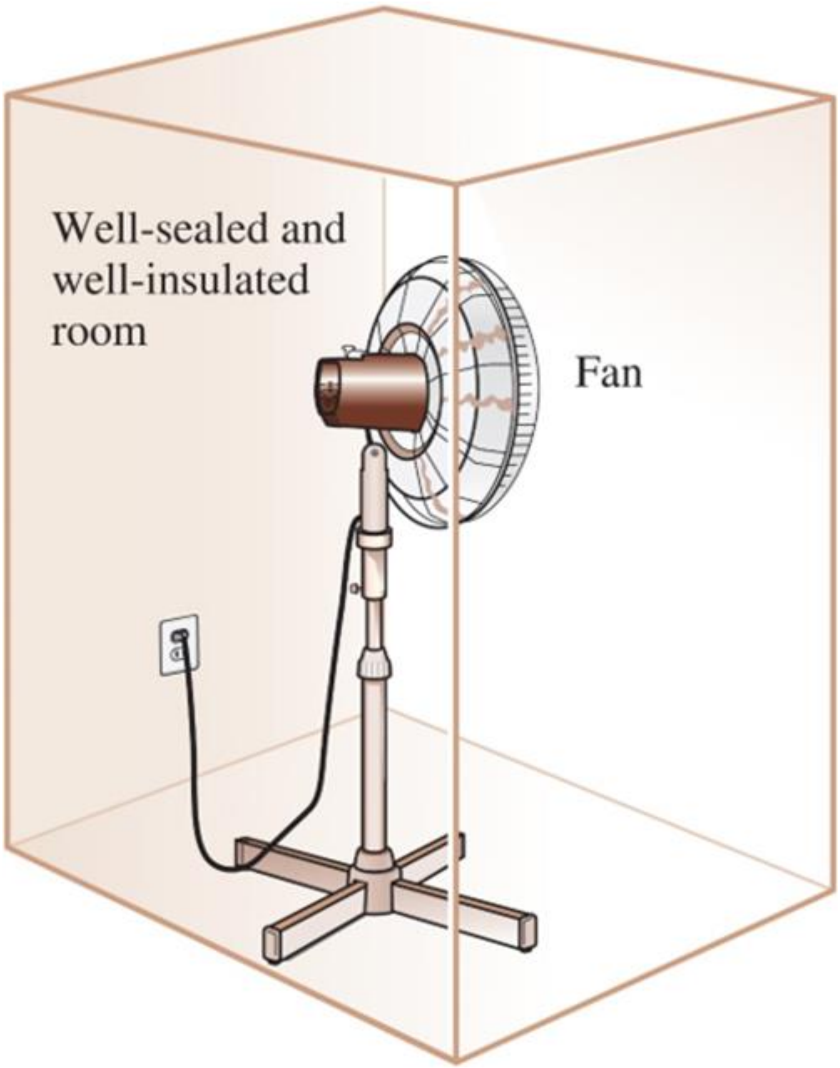
Figure 1-60

Various types of Bourdon tubes used to measure pressure. They work on the same principle as party noise-makers (bottom photo) due to the flat tube cross section.

2-1 Introduction



2-1 Introduction



2-1 Introduction

A fan is operating in an isolated a room. The fan consumes 300 W of electricity and converts 75 percent of this electricity to the kinetic energy of air. What is the heating rate of the room by the fan?

(a) 375 W

(b) 300 W

(c) 225 W

(d) 75 W

(e) 0

2-2 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.

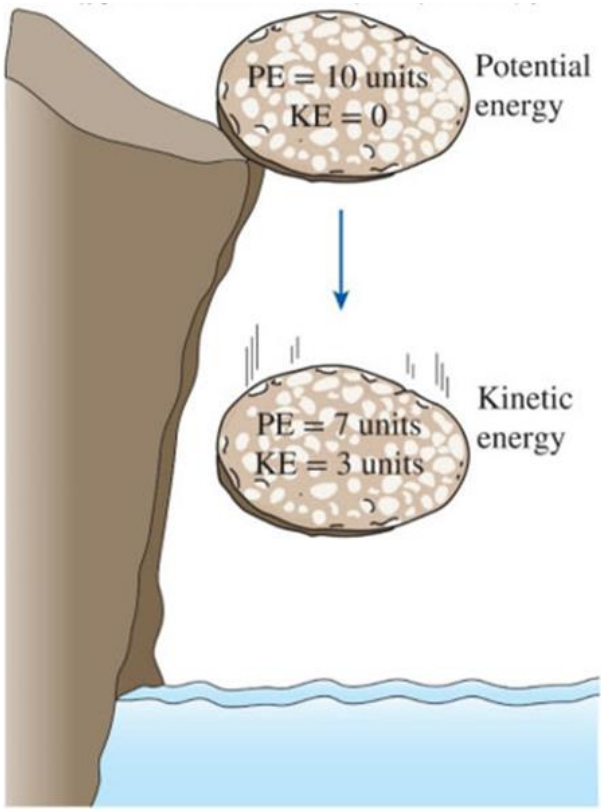
Microscopic forms of energy: Those related to the molecular structure of a system and the degree of the molecular activity.

Internal energy, *U*: The sum of all the microscopic forms of energy.

2-2 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.



2-2 Forms of Energy

$\mathrm{KE} = m\frac{V^2}{2} \quad (\mathrm{kJ})$	Kinetic energy
$\mathrm{ke} = \frac{V^2}{2} \quad (\mathrm{kJ/kg})$	Kinetic energy per unit mass
$\mathrm{PE} = mgz \quad (\mathrm{kJ})$	Potential energy
$\mathrm{pe} = gz \quad (\mathrm{kJ/kg})$	Potential energy per unit mass
$E = U + \mathrm{KE} + \mathrm{PE} = U + m\frac{V^2}{2} + mgz \quad (\mathrm{kJ})$	Total energy of a system
$e = u + \mathrm{ke} + \mathrm{pe} = u + \frac{V^2}{2} + gz \quad (\mathrm{kJ/kg})$	Energy of a system per unit mass
$\dot{E} = \dot{m}e \quad (\mathrm{kJ/s\ or\ kW})$	Energy flow rate

2-2 Forms of Energy

To what velocity do we need to accelerate a car at rest to increase its kinetic energy by 1 kJ/kg?

(a) 1 m/s

(b) 1.4 m/s

(c) 10 m/s

(d) 44.7 m/s

(e) 90 m/s

$$\mathrm{ke} = \mathrm{V}^2/2 \rightarrow 1\,\mathrm{kJ/kg} = \mathrm{V}^2/2 \rightarrow 1000\,\mathrm{m2/s2} = \mathrm{V}^2/2 \rightarrow \mathrm{V} = 44.7\,\mathrm{m/s}$$

$$1\,\mathrm{kJ/kg} = 1000\,\mathrm{m}^2/\mathrm{s}^2$$

2-2 Forms of Energy

How many meters do we need to raise a mass of 1 kg to increase its potential energy by 1 kJ?

(a) 1 m

(b) 9.8 m

(c) 49 m

(d) 98 m

(e) 102 m

PE=mgz → 1kJ = (1kg) (9.8 m/s^2)z → 1000 m^2/s^2 = (9.8 m/s^2)z → Z = 102 m

$$1\,\mathrm{kJ/kg} = 1000\,\mathrm{m^2/s^2}$$

2-2 Forms of Energy

What is the total energy of a 5-kg object with KE = 10 kJ, PE = 15 kJ, u = 20 kJ/kg?

(a) 20 kJ

(b) 25 kJ

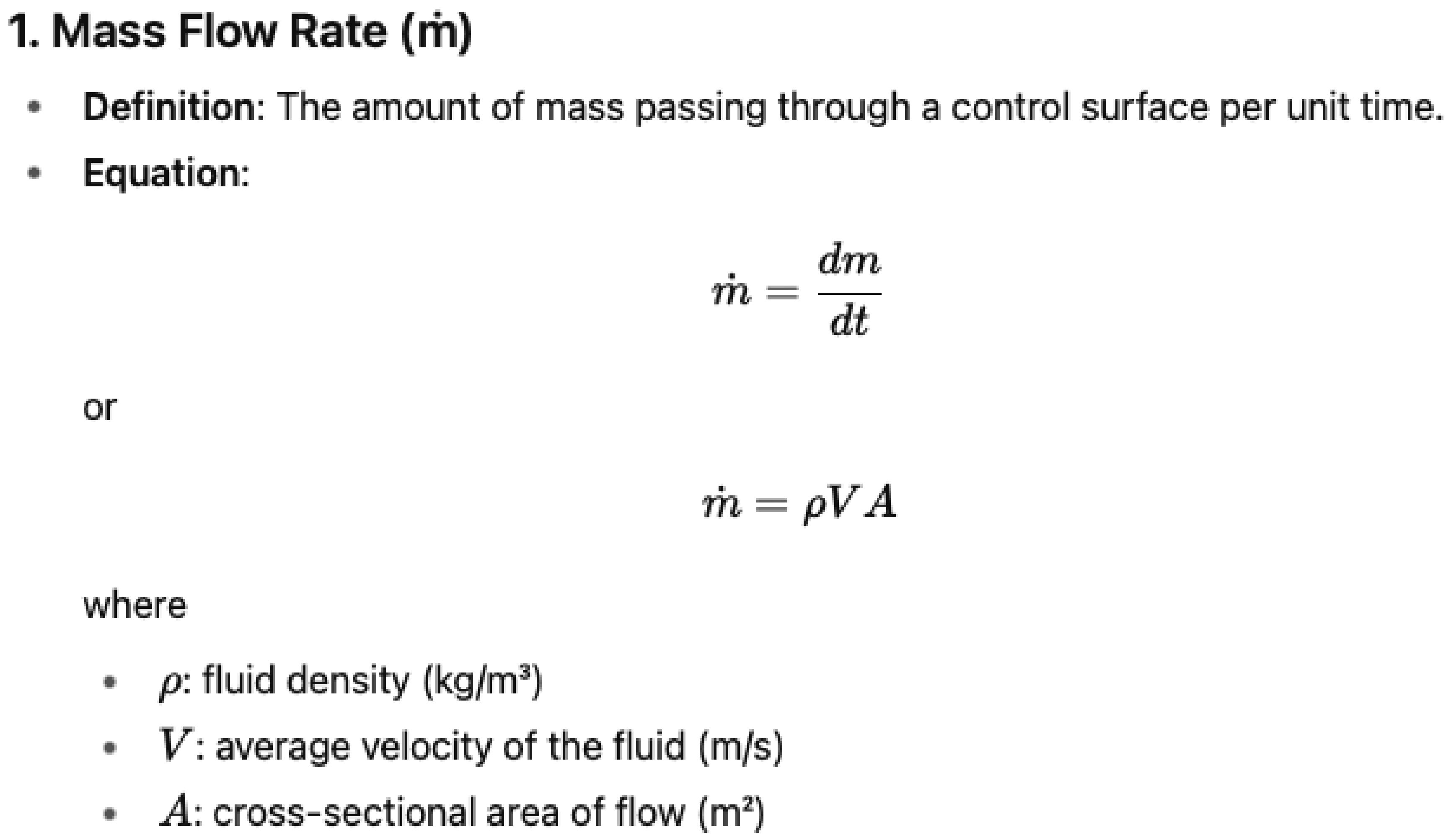
(c) 45 kJ

(d) 125 kJ

(e) 225 kJ

$$E = U + KE + PE = (5\,kg)(20\,kJ/kg) + 10\,kJ + 15\,kJ = 125\,kJ$$

2-2 Forms of Energy



1. Mass Flow Rate ($\dot{m}$)

- **Definition:** The amount of mass passing through a control surface per unit time.
- **Equation:**

$$\dot{m} = \frac{dm}{dt}$$

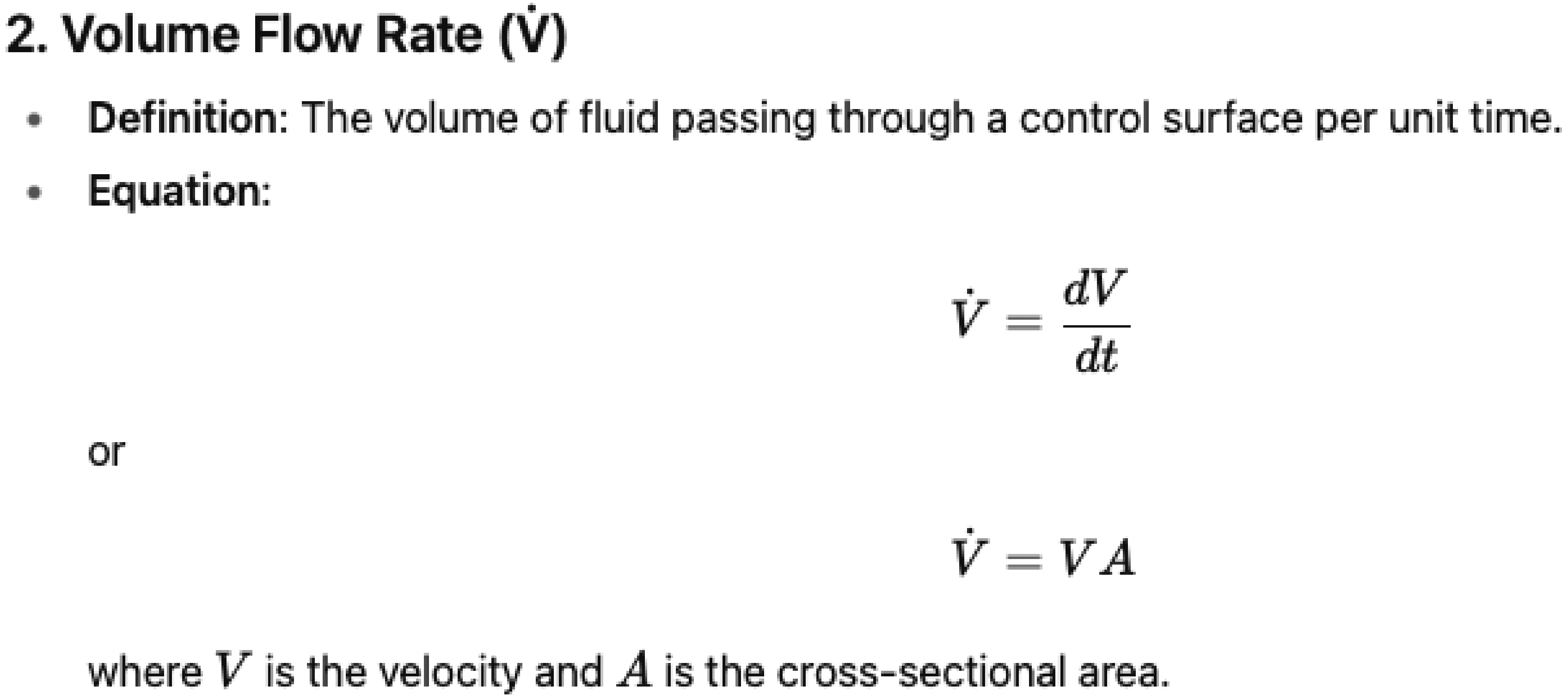
or

$$\dot{m} = \rho V A$$

where

- ρ: fluid density (kg/m³)
- V: average velocity of the fluid (m/s)
- A: cross-sectional area of flow (m²)

2-2 Forms of Energy



2. Volume Flow Rate ($\dot{V}$)

- **Definition:** The volume of fluid passing through a control surface per unit time.
- **Equation:**

$$\dot{V} = \frac{dV}{dt}$$

or

$$\dot{V} = VA$$

where V is the velocity and A is the cross-sectional area.

2-2 Forms of Energy

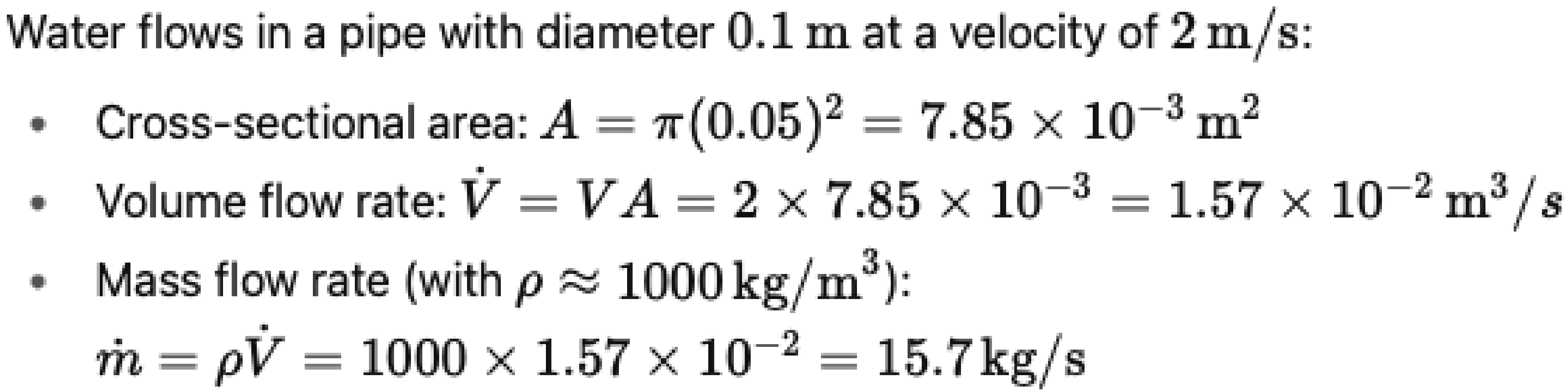
- **Volume flow rate** = “How much volume is flowing?”
- **Mass flow rate** = “How much weight (mass) is flowing?”
- They are connected by **density**.

They are directly related through density:

$$\dot{m} = \rho \dot{V}$$

- For **incompressible fluids** (e.g., water), density is constant, so mass flow rate and volume flow rate are proportional.
- For **compressible fluids** (e.g., gases), density changes with pressure and temperature, so distinguishing the two is important.

2-2 Forms of Energy



Water flows in a pipe with diameter $0.1\,\mathrm{m}$ at a velocity of $2\,\mathrm{m/s}$:

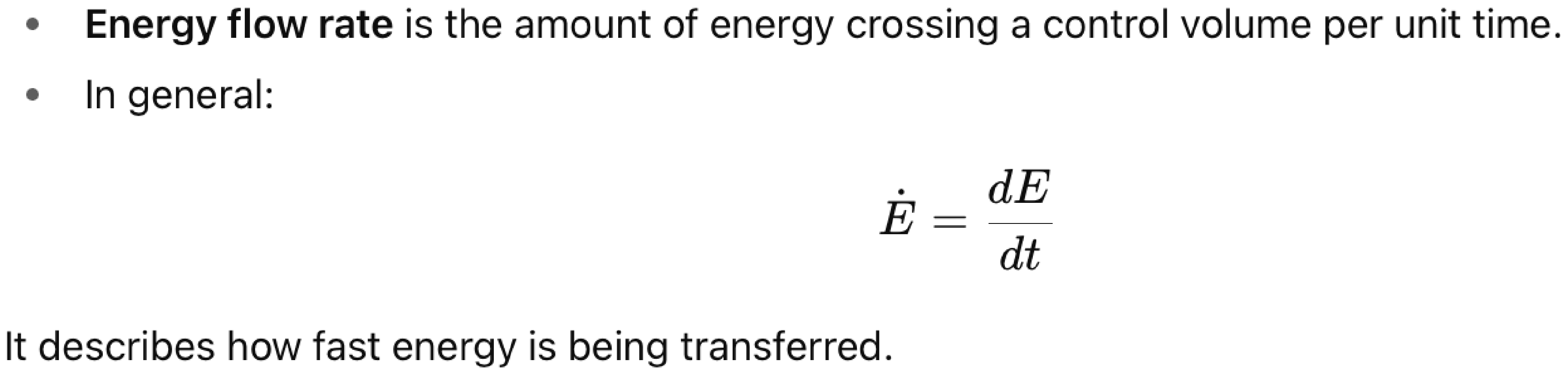
- Cross-sectional area: $A = \pi(0.05)^2 = 7.85 \times 10^{-3}\,\mathrm{m}^2$
- Volume flow rate: $\dot{V} = VA = 2 \times 7.85 \times 10^{-3} = 1.57 \times 10^{-2}\,\mathrm{m}^3/s$
- Mass flow rate (with $\rho \approx 1000\,\mathrm{kg/m^3}$):
  $\dot{m} = \rho\dot{V} = 1000 \times 1.57 \times 10^{-2} = 15.7\,\mathrm{kg/s}$

Volume flow rate?

Mass flow rate?

2-2 Forms of Energy

Energy Flow rate



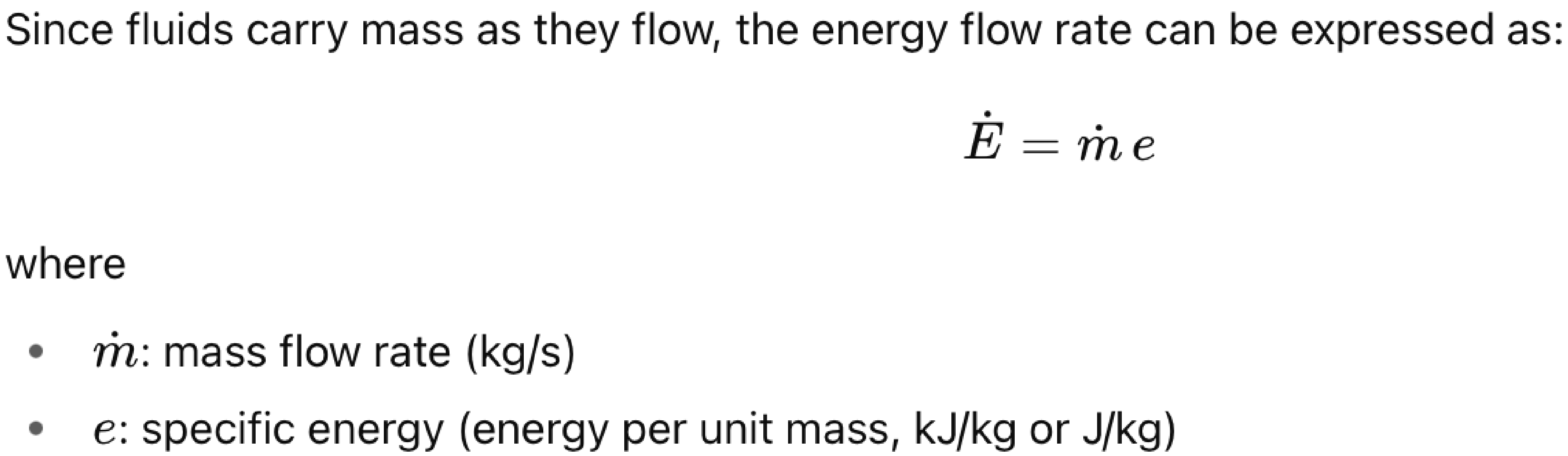
- **Energy flow rate** is the amount of energy crossing a control volume per unit time.
- In general:

$$\dot{E} = \frac{dE}{dt}$$

It describes how fast energy is being transferred.

2-2 Forms of Energy

Relation to Mass Flow Rate



Since fluids carry mass as they flow, the energy flow rate can be expressed as:

$$\dot{E} = \dot{m}\, e$$

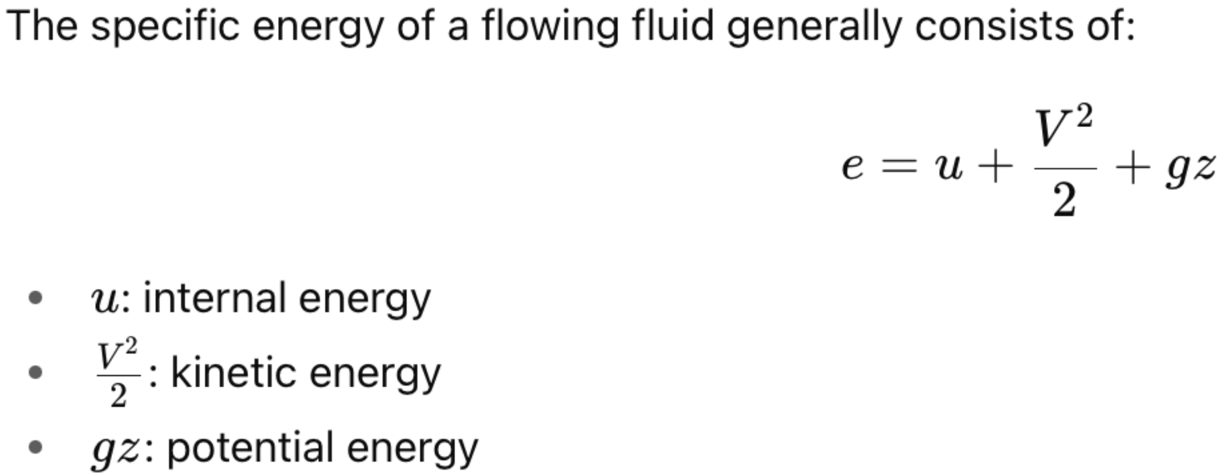
where

- $\dot{m}$: mass flow rate (kg/s)
- e: specific energy (energy per unit mass, kJ/kg or J/kg)

Energy flow rate = “how much mass flows” × “energy per unit mass.”

2-2 Forms of Energy

Components of specific energy

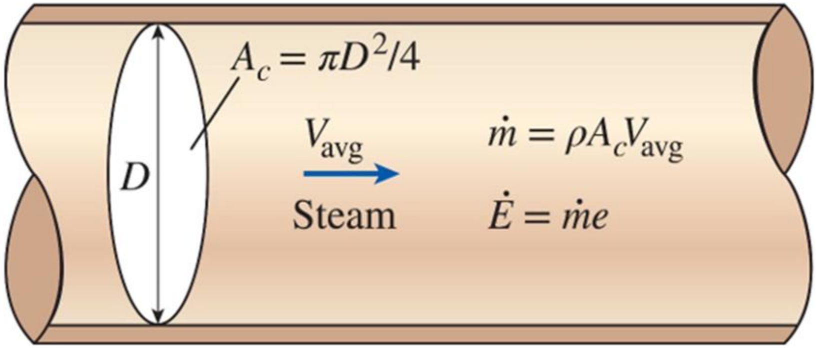


The specific energy of a flowing fluid generally consists of:

$$e = u + \frac{V^2}{2} + gz$$

- u: internal energy
- $\frac{V^2}{2}$: kinetic energy
- gz: potential energy

2-2 Forms of Energy 5



Mass and energy flow rates associated with the flow of steam in a pipe

of inner diameter *D* with an average velocity of V_{avg}.

Mass flow rate: $\dot{m} = \rho \dot{V} = \rho A_c V_{avg}$ (kg/s)

Energy flow rate: $\dot{E} = \dot{m}e$ (kJ/s or kW)

2-2 Forms of Energy

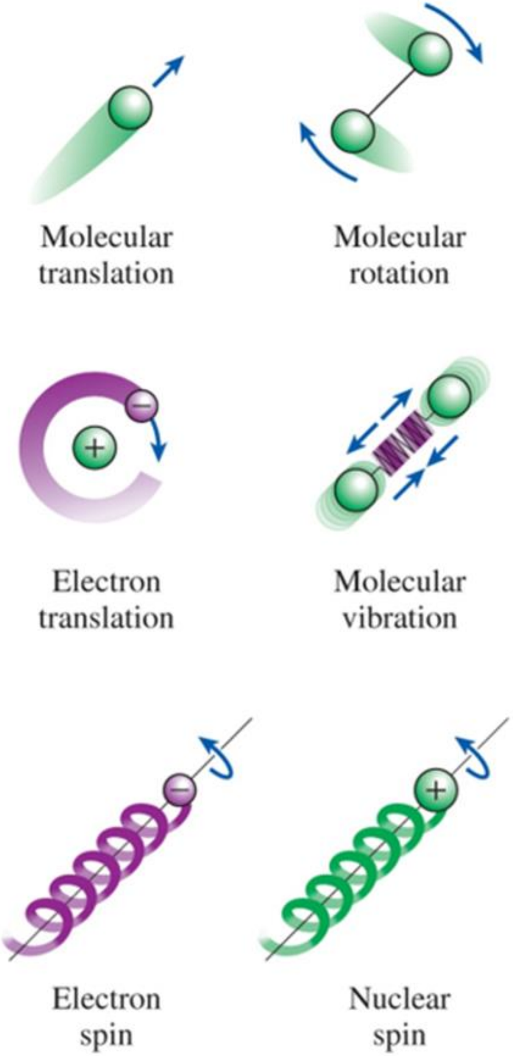
Some Physical Insight to Internal Energy

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.



2-2 Forms of Energy

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**.

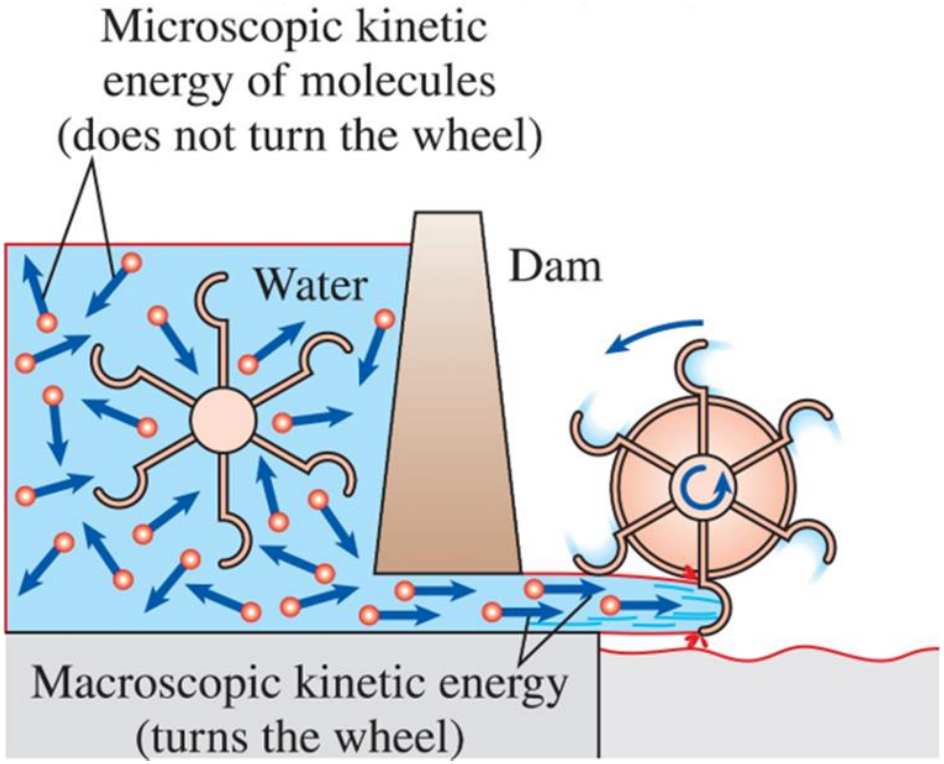
The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process.

The only two forms of energy interactions associated with a **closed system** are

- **heat transfer**
- **work**

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.

2-2 Forms of Energy



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

2-2 Forms of Energy

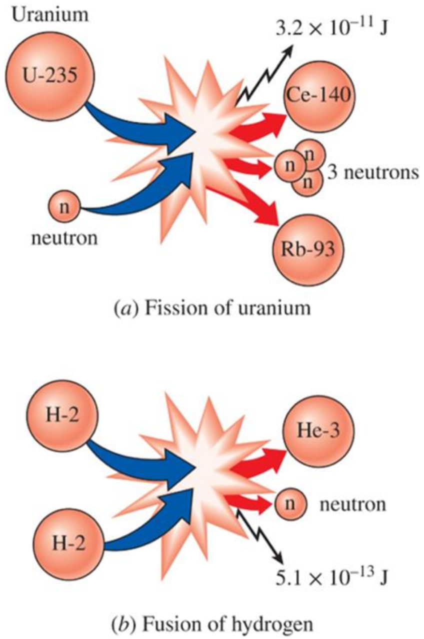
More on Nuclear Energy

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, 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.

2-2 Forms of Energy



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

2-2 Forms of Energy

Mechanical Energy

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

Flow energy

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

Mechanical energy of a flowing fluid per unit mass

2-2 Forms of Energy

Mechanical Energy

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

Rate of mechanical energy of a flowing fluid

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

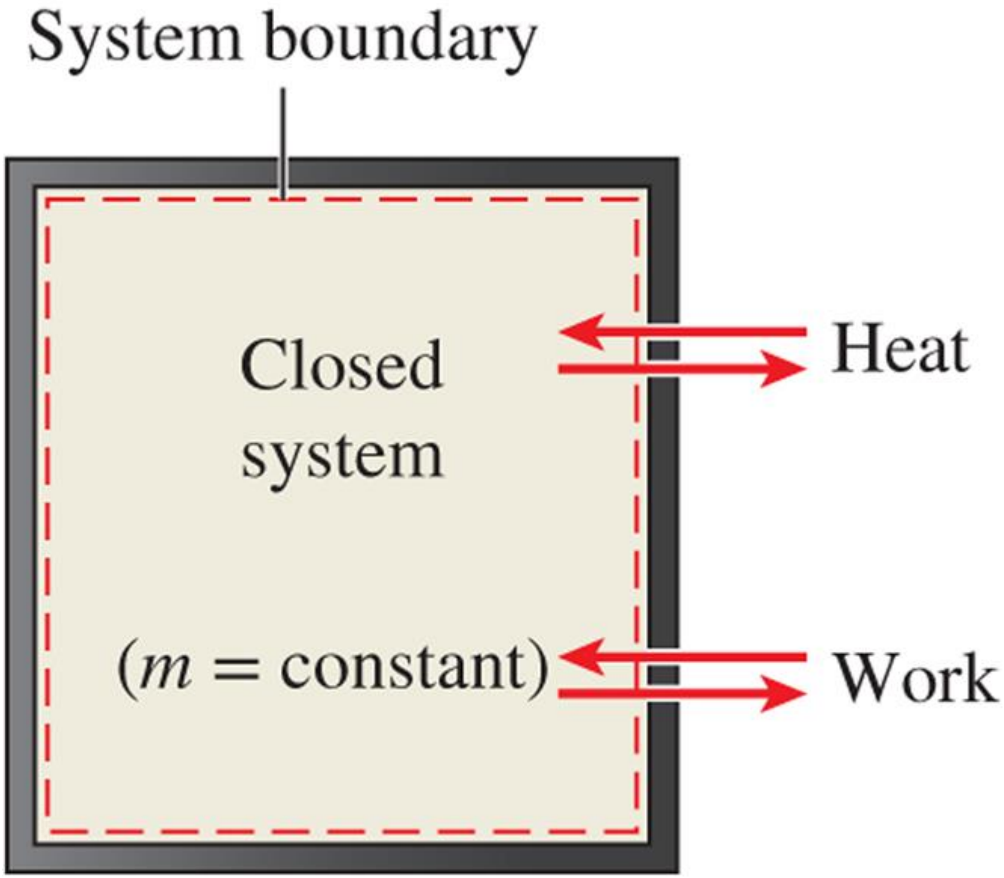
Mechanical energy change of a fluid during incompressible flow per unit mass

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

Rate of mechanical energy change of a fluid during incompressible flow

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

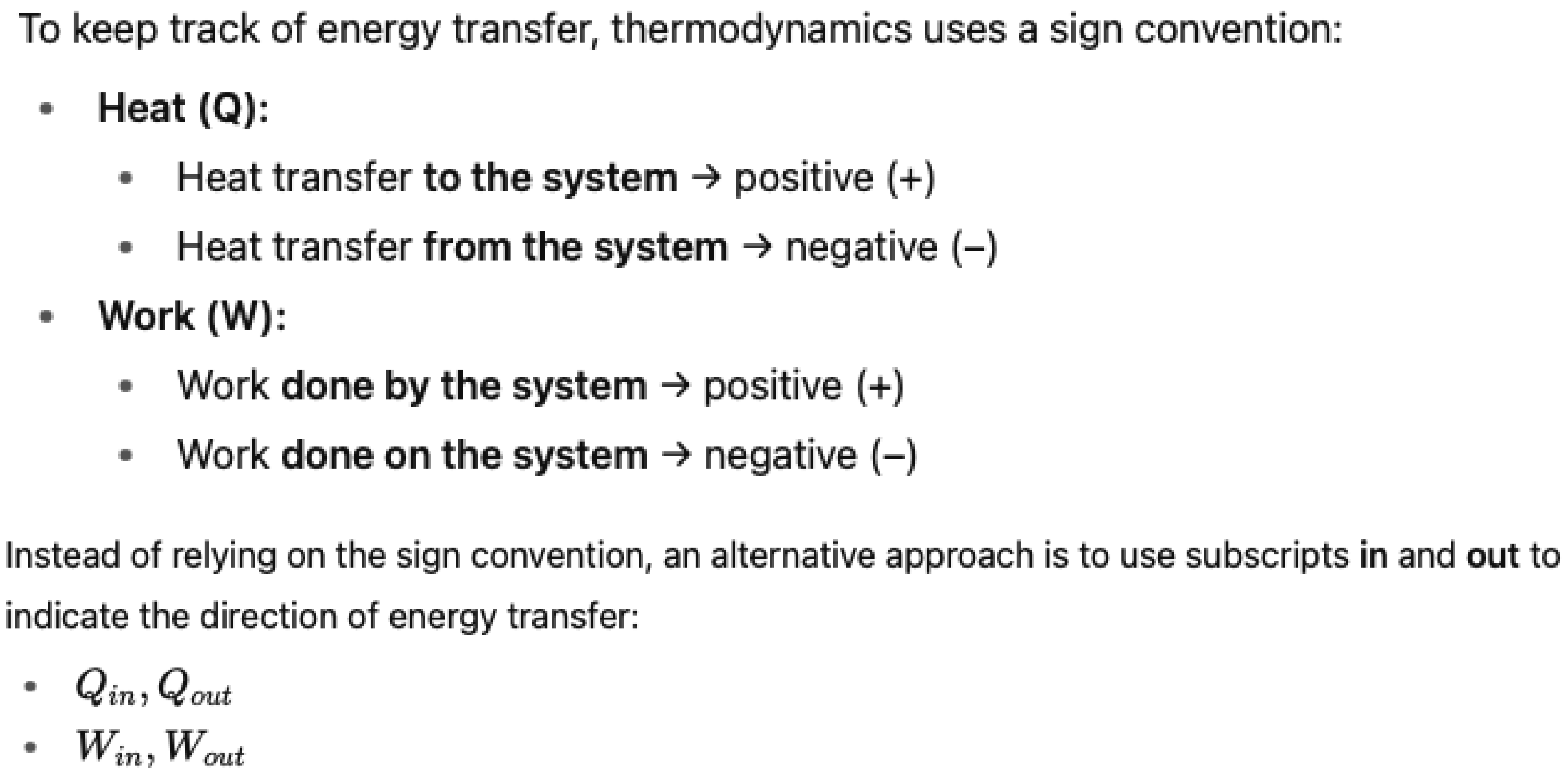
2-3 Energy Transfer by Heat



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

2-3 Energy Transfer by Heat

Formal Sign Convention



To keep track of energy transfer, thermodynamics uses a sign convention:

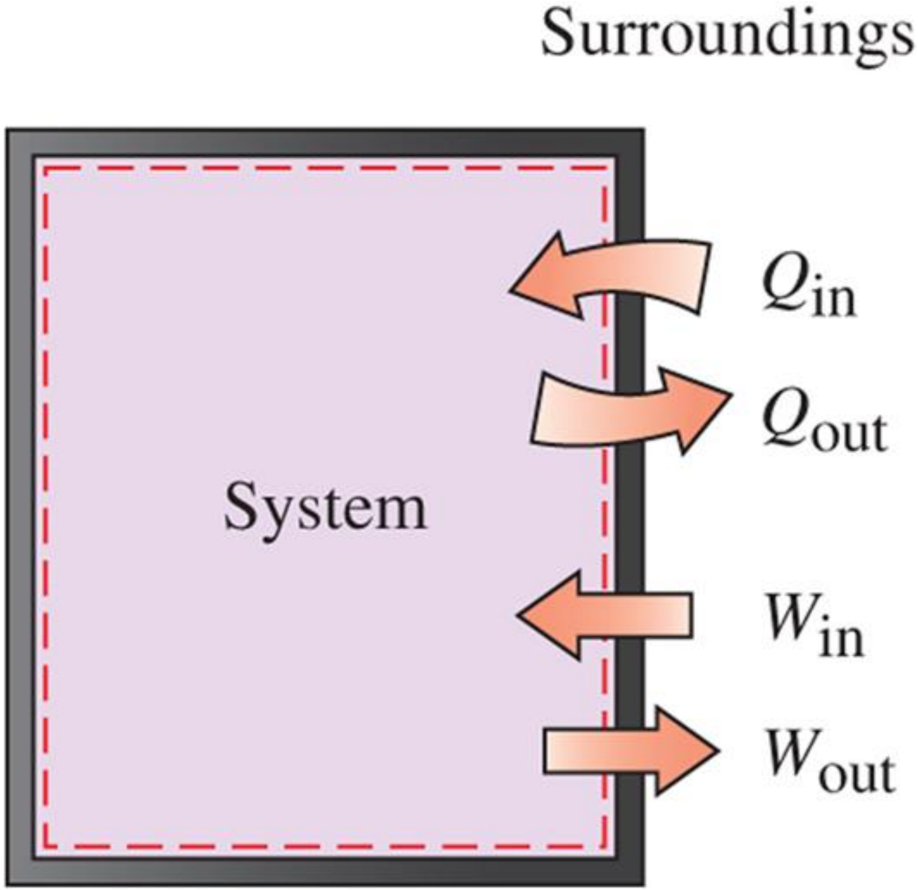
- **Heat (Q):**
  - Heat transfer **to the system** → positive (+)
  - Heat transfer **from the system** → negative (–)
- **Work (W):**
  - Work **done by the system** → positive (+)
  - Work **done on the system** → negative (–)

Instead of relying on the sign convention, an alternative approach is to use subscripts **in** and **out** to indicate the direction of energy transfer:

- Q_{in}, Q_{out}
- W_{in}, W_{out}

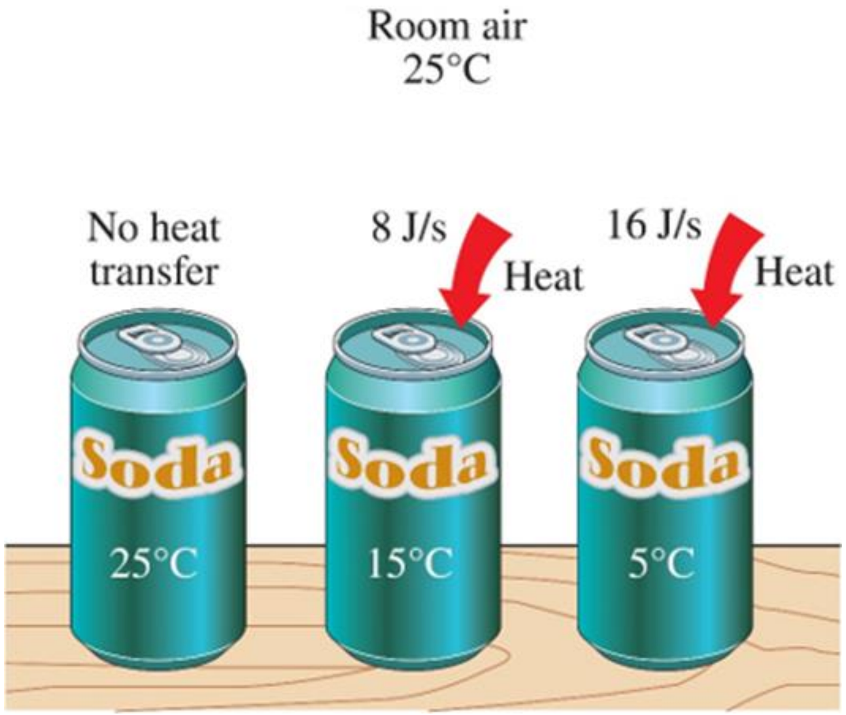
2-3 Energy Transfer by Heat

Formal Sign Convention



2-3 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.



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

2-3 Energy Transfer by Heat

Heat transfer per unit mass

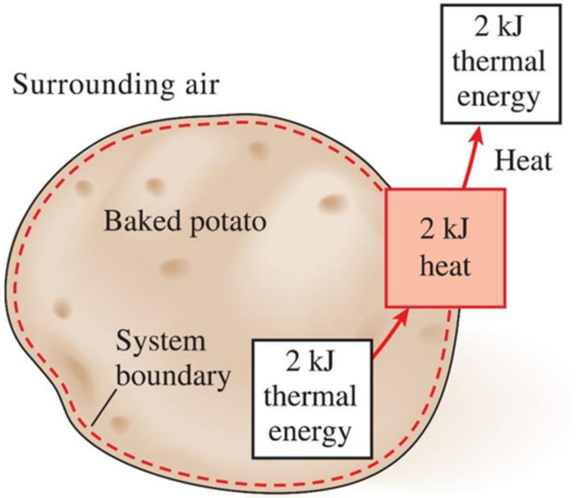
$$q = \frac{Q}{m} \quad (\text{kJ/kg})$$

Amount of heat transfer when heat transfer rate is constant

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

Amount of heat transfer when heat transfer rate changes with time

$$Q = \int_{t_1}^{t_2} \dot{Q}\, dt \qquad (\text{kJ})$$



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

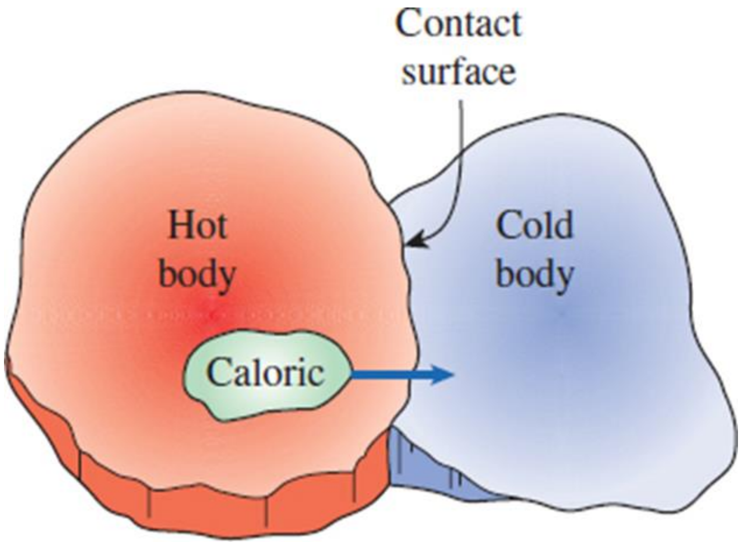
2-3 Energy Transfer by Heat

Historical Background on Heat

Caloric theory: It asserts that heat is a fluidlike substance called the **caloric** that is a massless, colorless, odorless, and tasteless substance that can be poured from one body into another

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.



In the early 19th century, heat was thought to be an invisible fluid called the caloric that flowed from warmer bodies to cooler ones.

2-3 Energy Transfer by Heat

Heat transfer mechanisms

Conduction

Definition: The transfer of energy through a solid, liquid, or gas by microscopic interactions such as collisions and vibrations of particles.

Example: When one end of a metal spoon is placed in hot water, the other end becomes hot because energetic particles transfer energy to adjacent, less energetic particles.

Key Feature: No bulk movement of the material; energy transfer occurs only through particle-to-particle interactions.

2-3 Energy Transfer by Heat

Heat transfer mechanisms

Convection

Definition: The transfer of energy between a solid surface and an adjacent fluid in motion, involving both conduction and the bulk movement of the fluid.

Example: In boiling water, hot water near the bottom rises while cooler water sinks, creating circulation that distributes heat throughout the liquid.

Key Feature: Occurs only in fluids (liquids and gases) and requires fluid motion.

2-3 Energy Transfer by Heat

Heat transfer mechanisms

Radiation

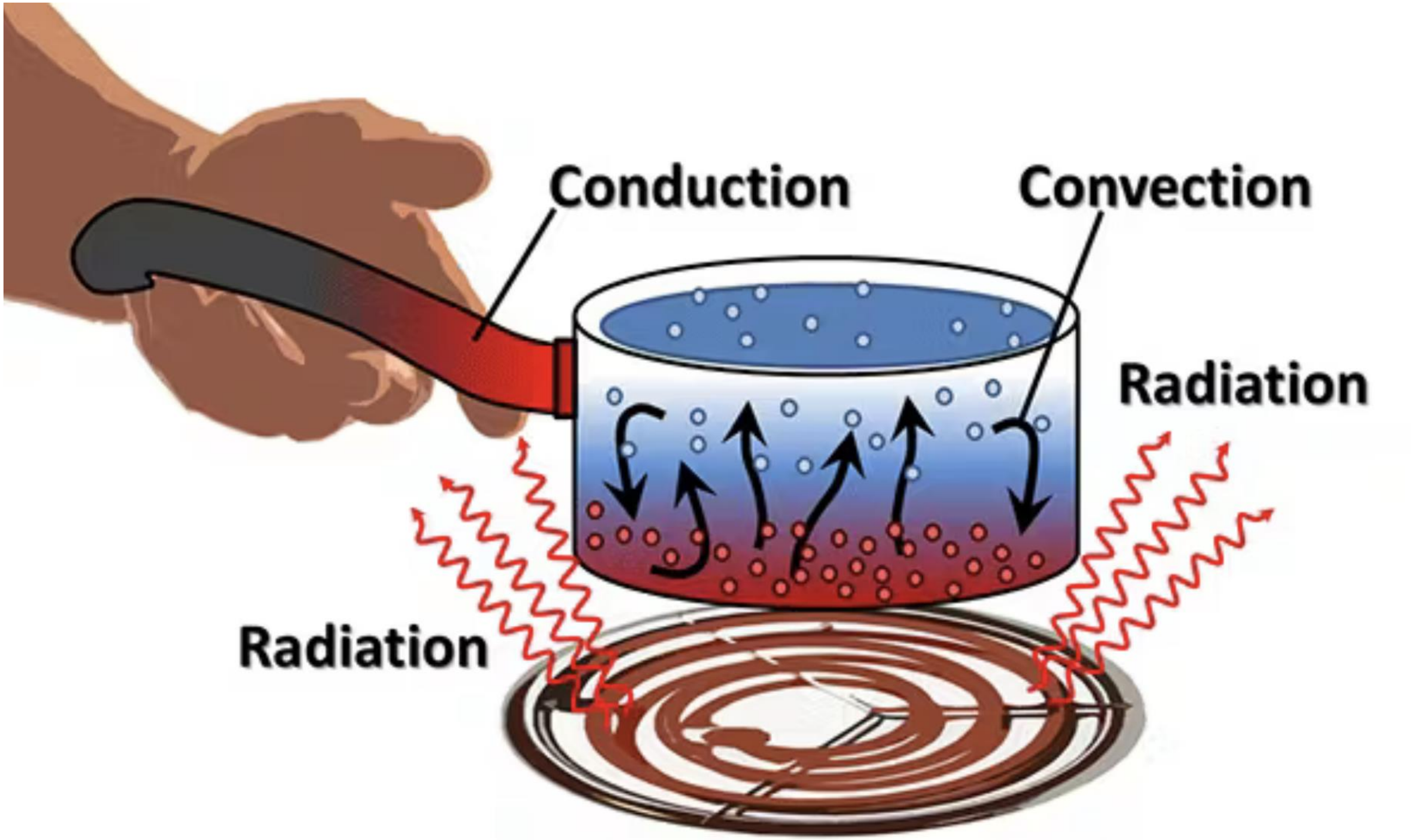
Definition: The transfer of energy in the form of electromagnetic waves (such as infrared, visible light, or ultraviolet radiation). It does not require a medium.

Example: The Sun’s energy reaches the Earth through the vacuum of space by radiation.

Key Feature: Energy transfer is possible even in empty space because it relies on electromagnetic waves.

2-3 Energy Transfer by Heat 5

Heat transfer mechanisms



2-3 Energy Transfer by Heat

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).

2-4 Energy Transfer by Work

Work is the energy transfer that occurs when a **force** acts through a **distance**. It is often expressed as the product of force and displacement in the direction of the force.

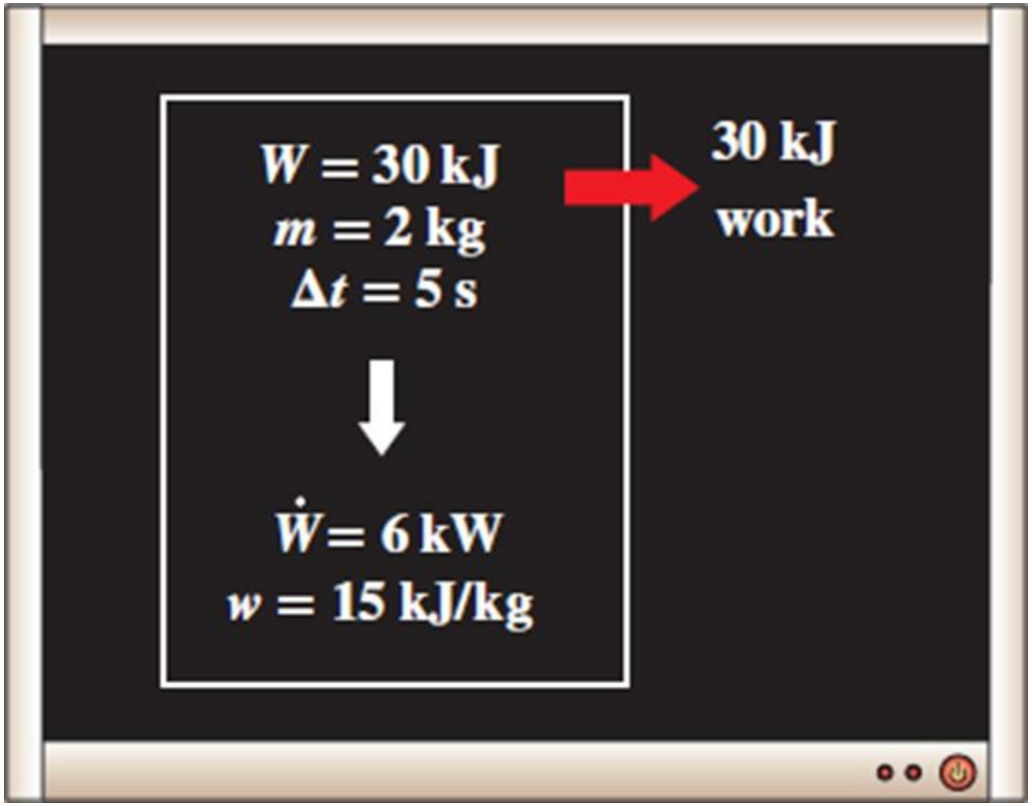
Examples:

- **Rising piston**: The expanding gas pushes the piston upward, transferring energy as boundary work.
- **Rotating shaft**: Energy is transferred across the system boundary through shaft rotation, such as in a turbine.
- **Electric wire**: Electrical work is transferred when an electric current crosses the system boundary.

2-4 Energy Transfer by Work

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

Work done per unit mass



2-4 Energy Transfer by Work

Heat v.s. 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 (that is, their magnitudes depend on the path followed during a process as well as the end states).

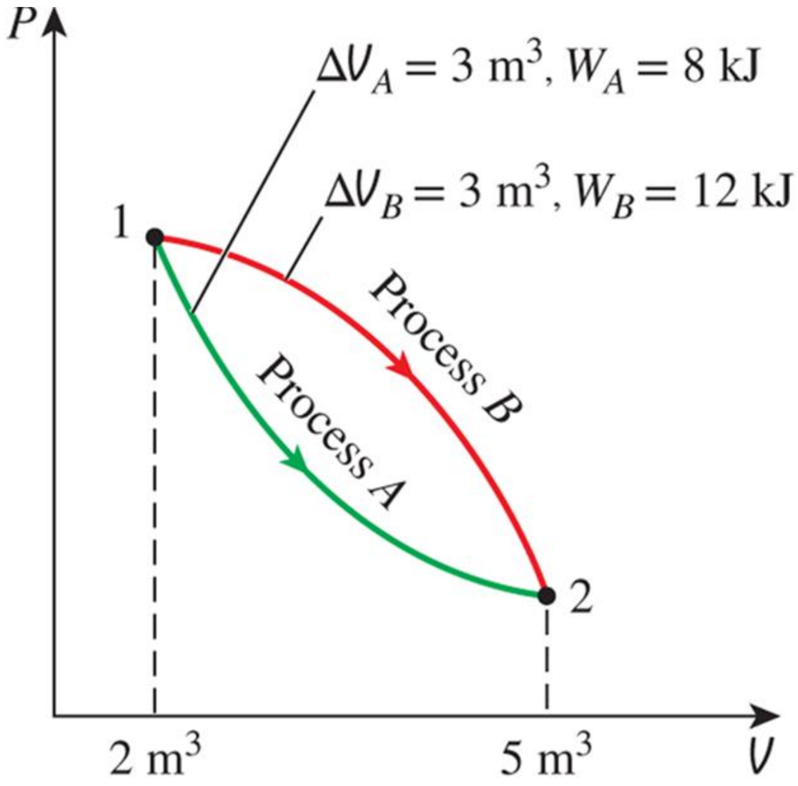
Properties are point functions have exact differentials (*d*).

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

Path functions have inexact differentials (δ)

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

2-4 Energy Transfer by Work



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

2-4 Energy Transfer by Work

Electrical Work

$W_e = \mathrm{V}N$ Electrical work

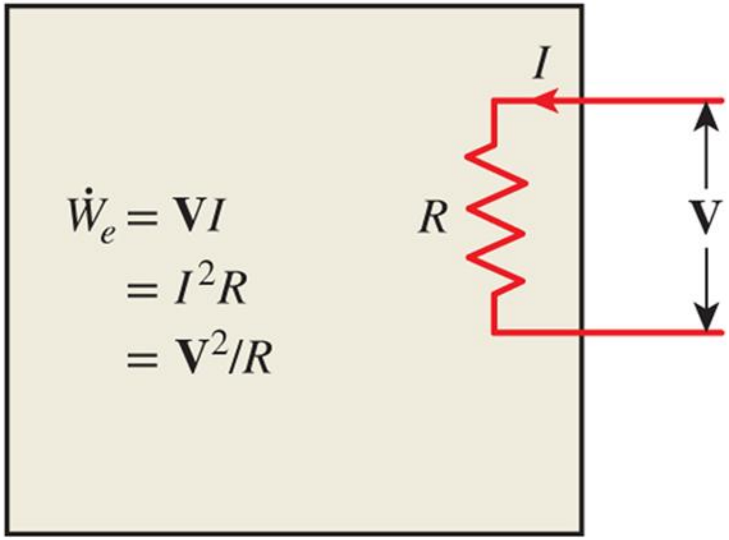
$\dot{W}_e = \mathbf{V}I$ (W) Electrical power

When potential difference and current change with time

$$W_e = \int_1^2 \mathrm{V}I \, dt \qquad (\mathrm{kJ})$$

When potential difference and current remain constant

$$W_e = \mathrm{V}I \, \Delta t \qquad (\mathrm{kJ})$$



Electrical power in terms of resistance *R*, current *I*, and potential difference **V**.

2-5 Mechanical Forms of Work

There are two requirements for a work interaction between a system and its surroundings to exist:

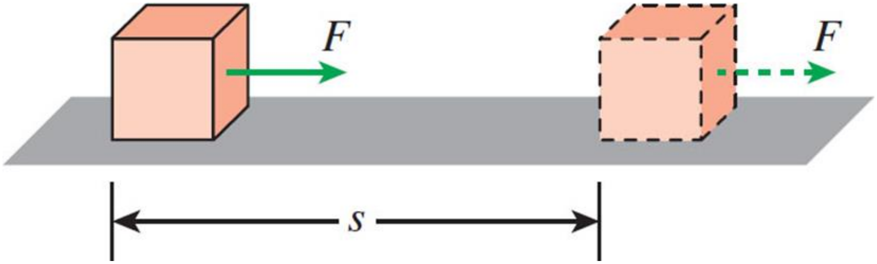
- there must be a **force** acting on the boundary.
- the boundary must **move**.

Work = Force × 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*).

2-5 Mechanical Forms of Work

Shaft Work

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

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

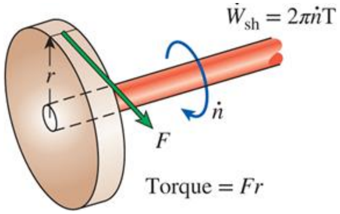
$$s = \left(2\pi r\right)n$$

This force acts through a distance *s*

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

Shaft work

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



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

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

2-5 Mechanical Forms of Work 4

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

$$\delta W_{\text{spring}} = F\,dx \quad (\text{kJ})$$

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

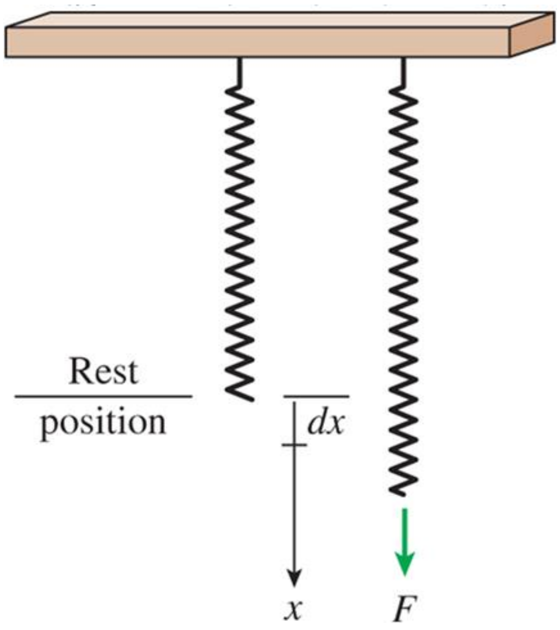
$$F = kx \quad (\text{kN})$$

k: spring constant (kN/m)

Spring work:

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

x_1 and x_2 :the initial and the final displacements

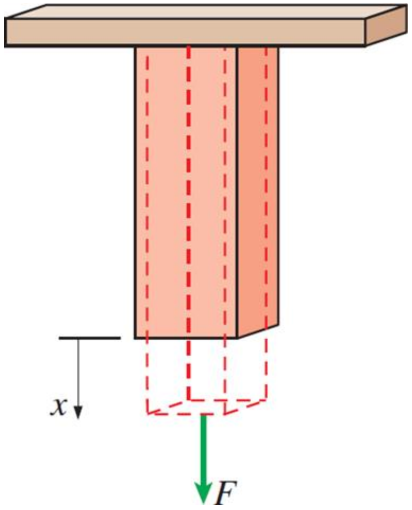


Elongation of a spring under the influence of a force.

2-5 Mechanical Forms of Work 6

Work Done on Elastic Solid Bars

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



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

2-5 Mechanical Forms of Work

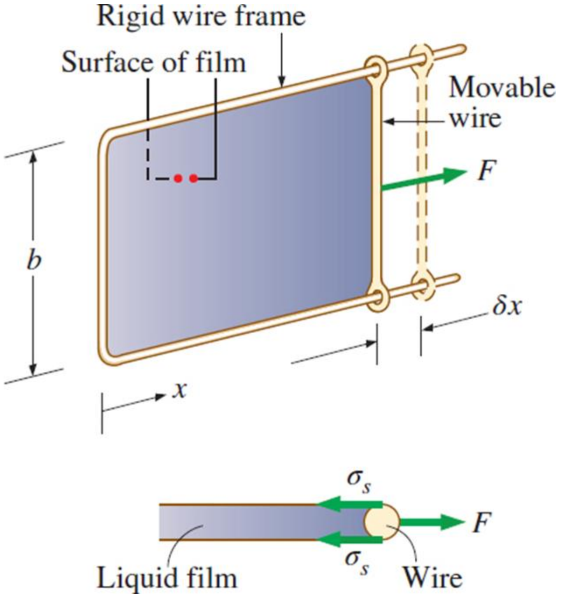
Work Associated with the Stretching of a Liquid Film

Surface tension work

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

$$dA = 2b\,dx$$

$$F = 2b\sigma_s$$



Stretching a liquid film with a U-shaped wire, and the forces acting on the movable wire of length *b.*

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Energy balance and thermodynamics

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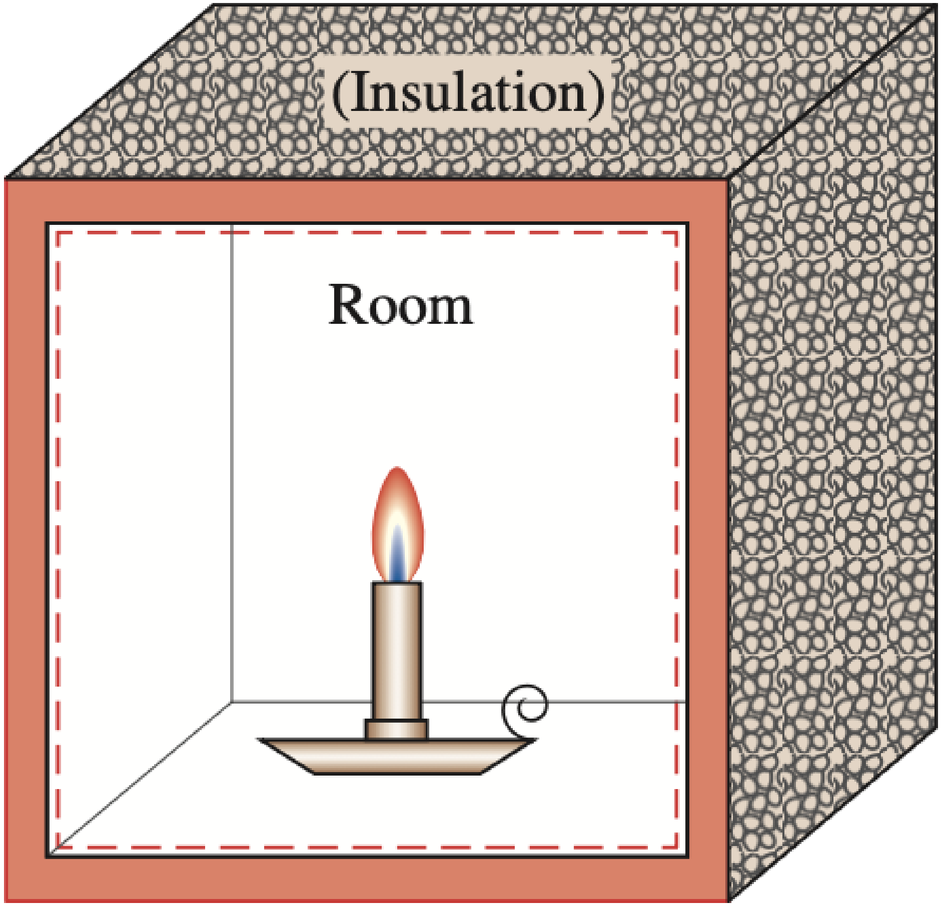
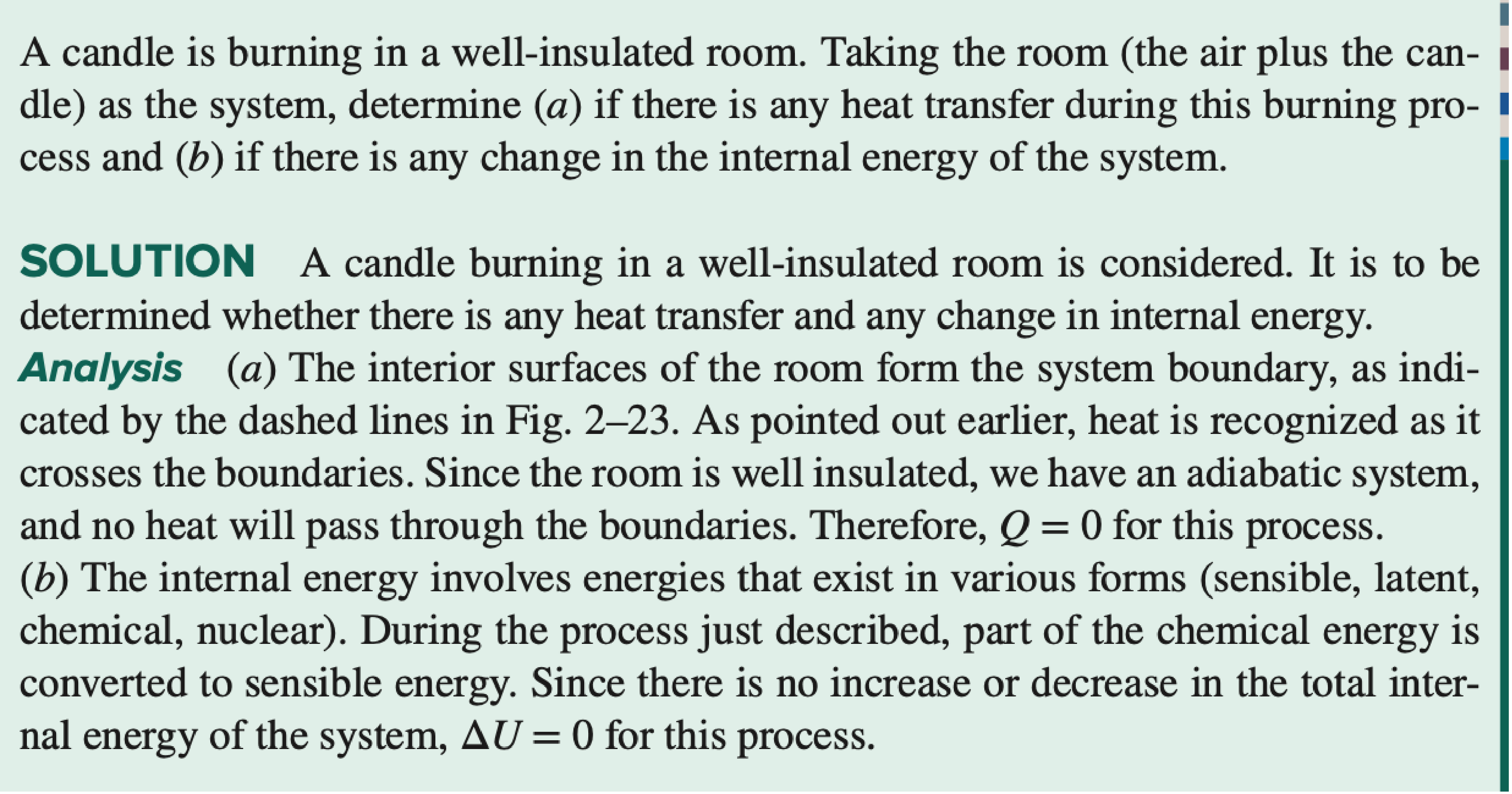
Heat and Work



Heat and Work

(a) 열전달, (b) 내부에너지 변화



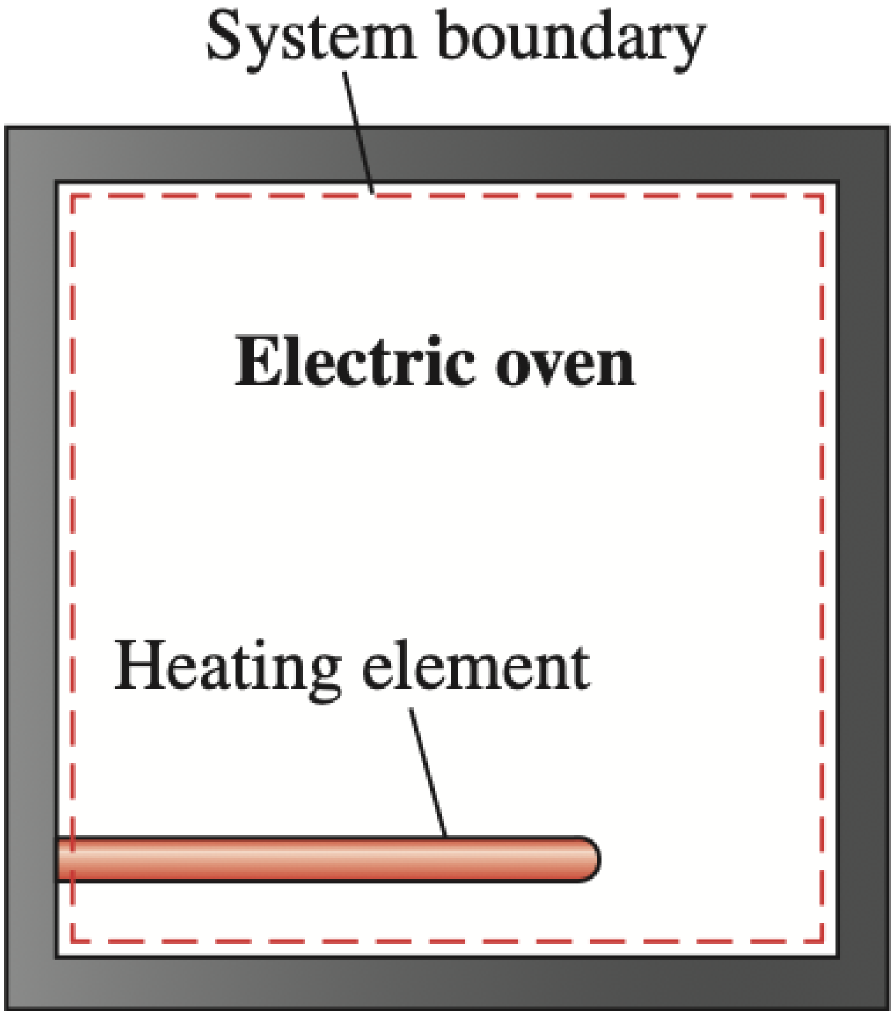
A candle is burning in a well-insulated room. Taking the room (the air plus the candle) as the system, determine (*a*) if there is any heat transfer during this burning process and (*b*) if there is any change in the internal energy of the system.

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.

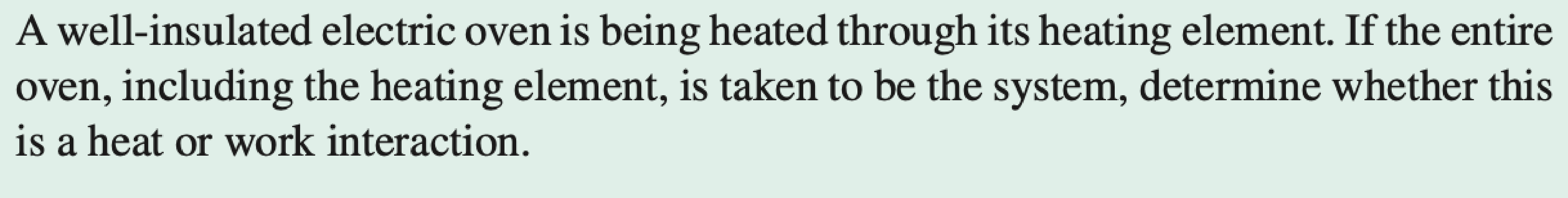
Analysis (*a*) The interior surfaces of the room form the system boundary, as indicated by the dashed lines in Fig. 2–23. As pointed out earlier, heat is recognized as it crosses the boundaries. Since the room is well insulated, we have an adiabatic system, and no heat will pass through the boundaries. 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.

Heat and Work



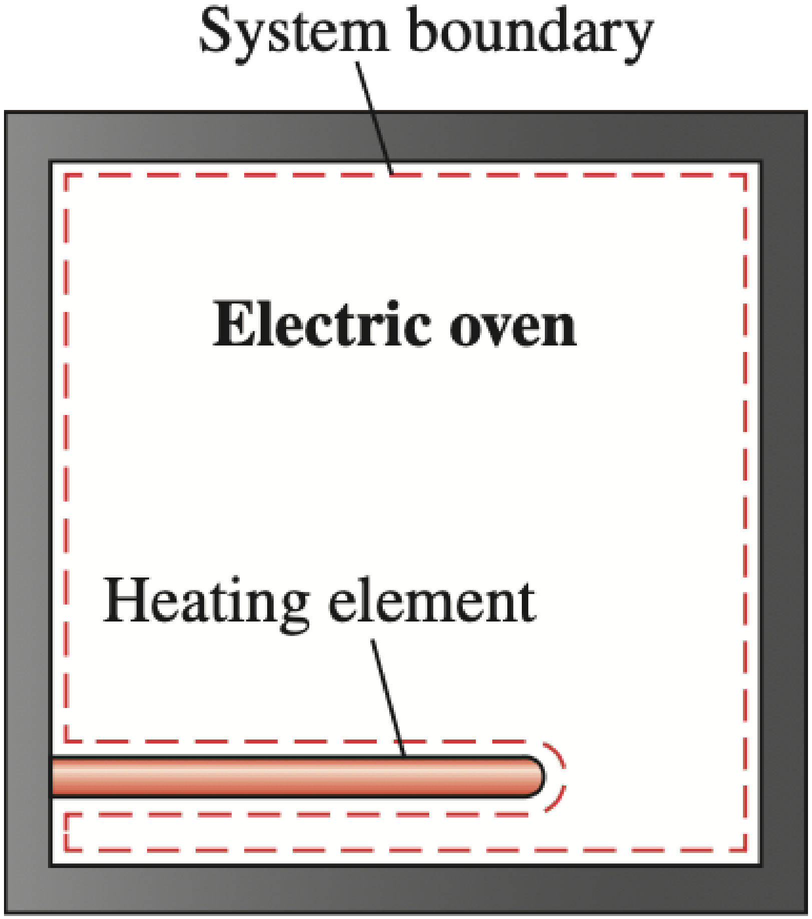
Heat and Work



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.

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.

Heat and Work



if the system is taken as only the air in the oven without the heating element.

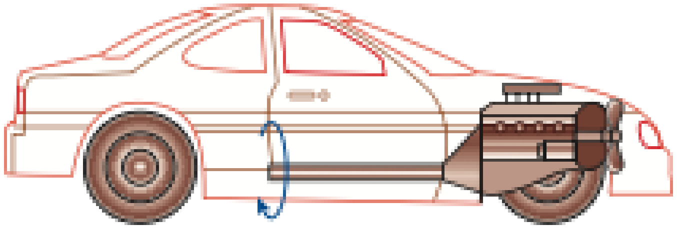
Determine the power transmitted through the shaft of a car when the torque applied is 200 N·m and the shaft rotates at a rate of 4000 revolutions per minute (rpm).

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

Analysis A sketch of the car is given in Fig. 2–31. The shaft power is determined directly from

$$\dot{W}_{sh} = 2\pi\dot{n}T = (2\pi)\left(4000\ \frac{1}{\text{min}}\right)(200\ \text{N}\cdot\text{m})\left(\frac{1\ \text{min}}{60\ \text{s}}\right)\left(\frac{1\ \text{kJ}}{1000\ \text{N}\cdot\text{m}}\right)$$

$$= \mathbf{83.8\ kW} \quad (\text{or } 112\ \text{hp})$$



$\dot{n} = 4000$ rpm

$T = 200$ N·m

2-5 Mechanical Forms of Work

Nonmechanical 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.

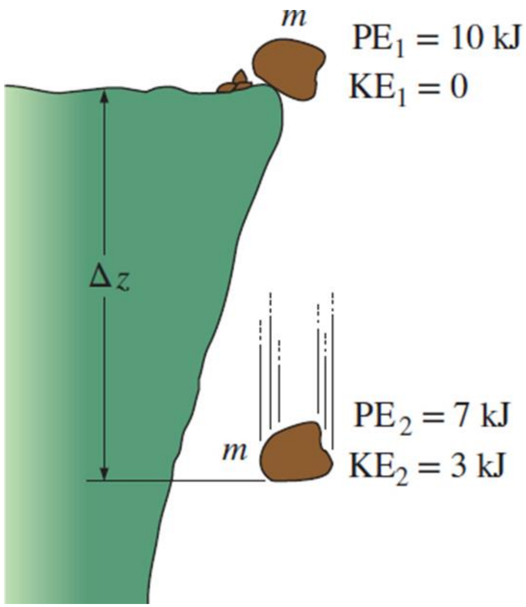
Electrical polarization work: The generalized force is the electric field strength and the generalized displacement is the polarization of the medium.

2-6 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.

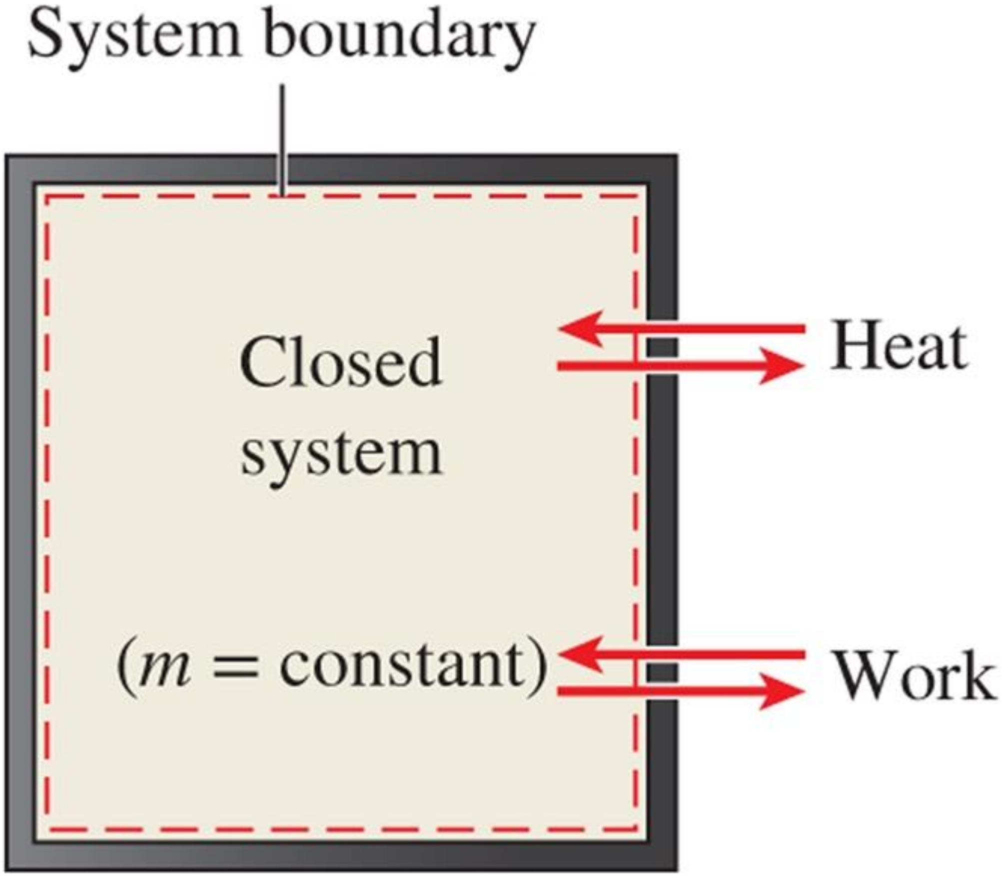
The first law states that energy can be neither created nor destroyed during a process; it can only change forms.

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.

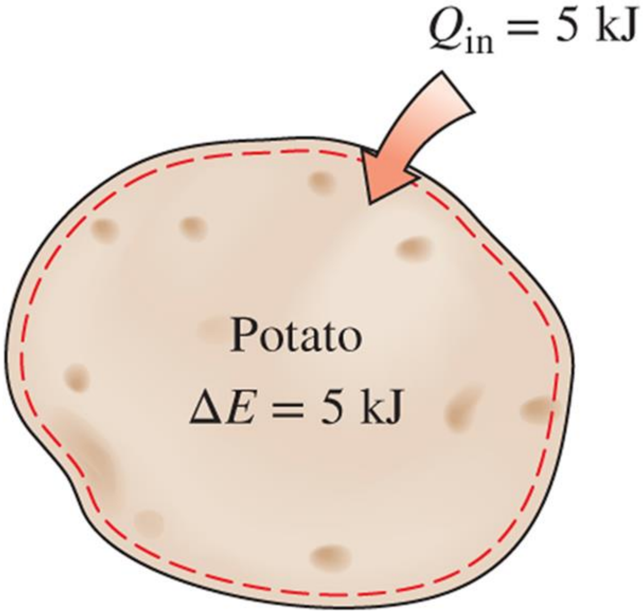


Energy cannot be created or destroyed; it can only change forms.

2-6 The First Law of Thermodynamics

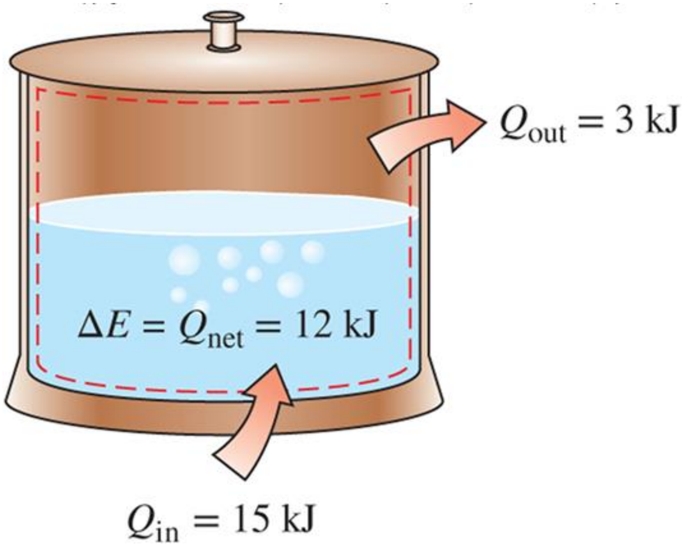


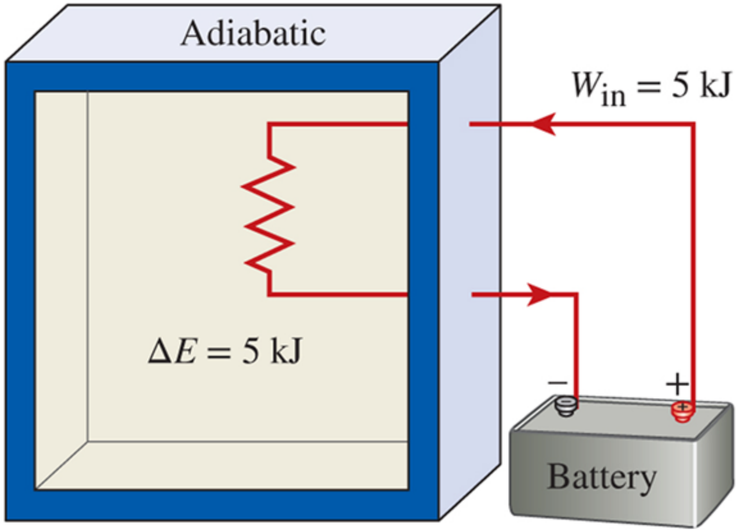
2-6 The First Law of Thermodynamics



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

2-6 The First Law of Thermodynamics

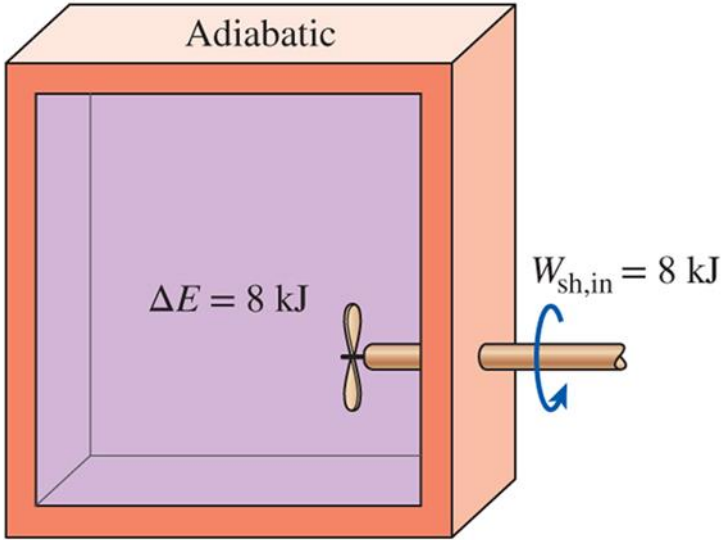




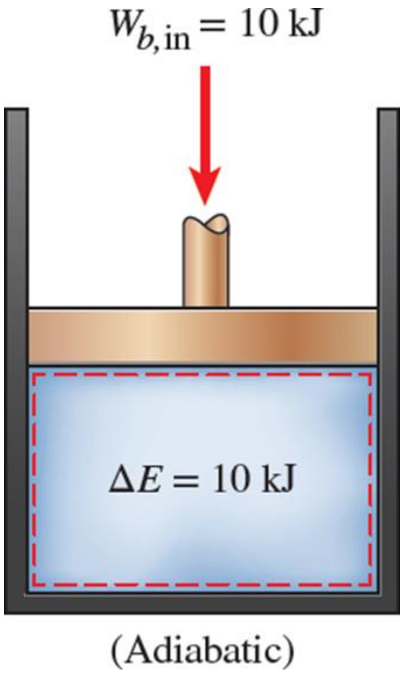
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.

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

2-6 The First Law of Thermodynamics



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



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

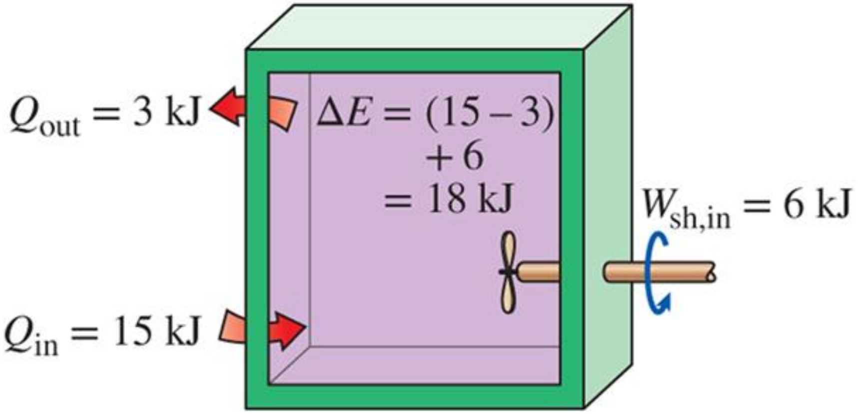
2-6 The First Law of Thermodynamics

Energy Balance

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

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

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.



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

2-6 The First Law of Thermodynamics

Energy Change of a System, ΔE_{system}

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

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

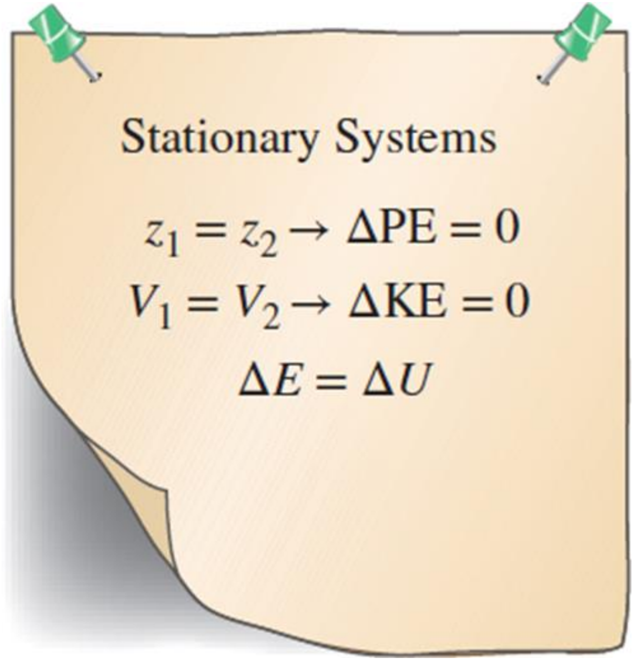
$$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

Internal, kinetic, and potential energy changes:

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

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

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



Stationary Systems

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

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

$$\Delta E = \Delta U$$

For stationary systems (고정계), $\Delta KE = \Delta PE = 0$; thus $\Delta E = \Delta U$.

2-6 The First Law of Thermodynamics

Mechanisms of Energy Transfer, E_{in} and E_{out}

Energy balance for any system undergoing any kind of process can be expressed more compactly as

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

In the **rate form**,

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

For constant rates, the total quantities during a time interval Δt are related related to the quantities per unit time as

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

2-6 The First Law of Thermodynamics

The energy balance can be expressed on a **per unit mass** basis as

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

2-6 The First Law of Thermodynamics

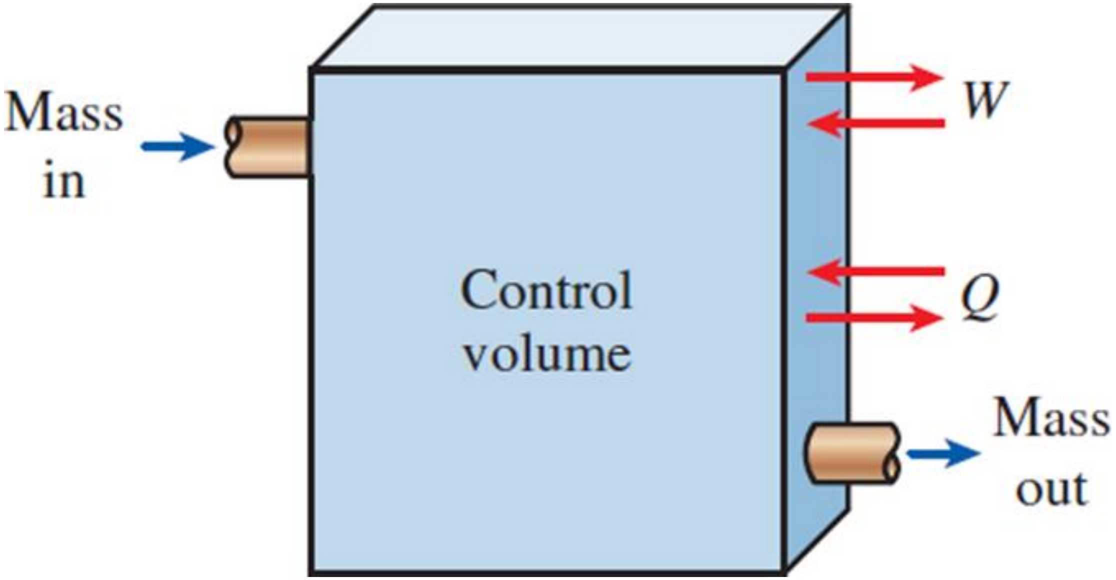
Mechanisms of energy transfer:

- Heat transfer
- Work
- Mass flow

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

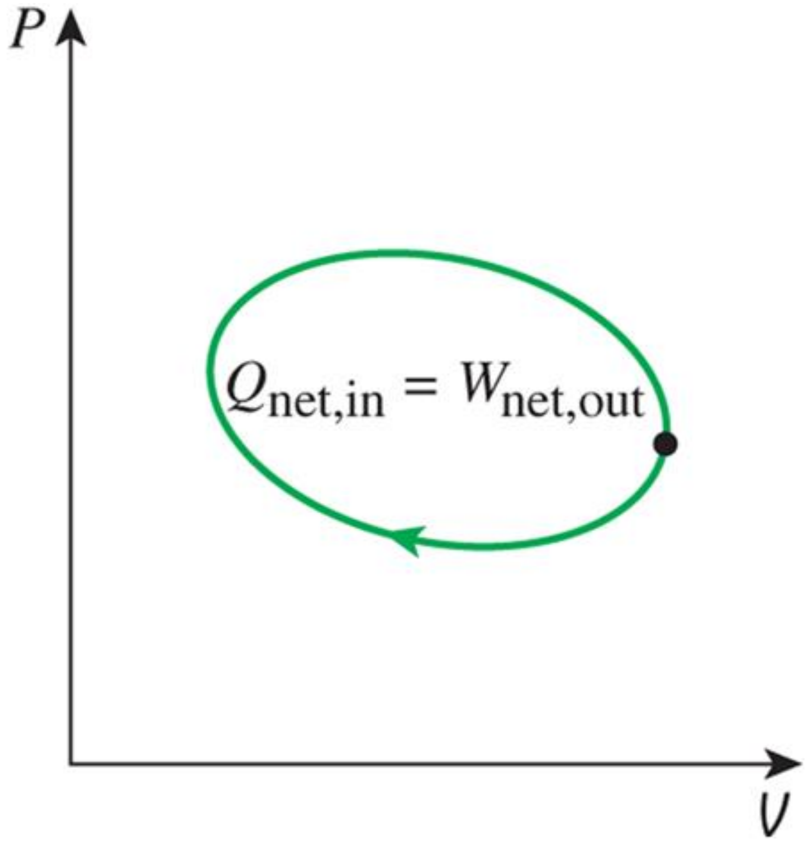
2-6 The First Law of Thermodynamics

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



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

2-6 The First Law of Thermodynamics



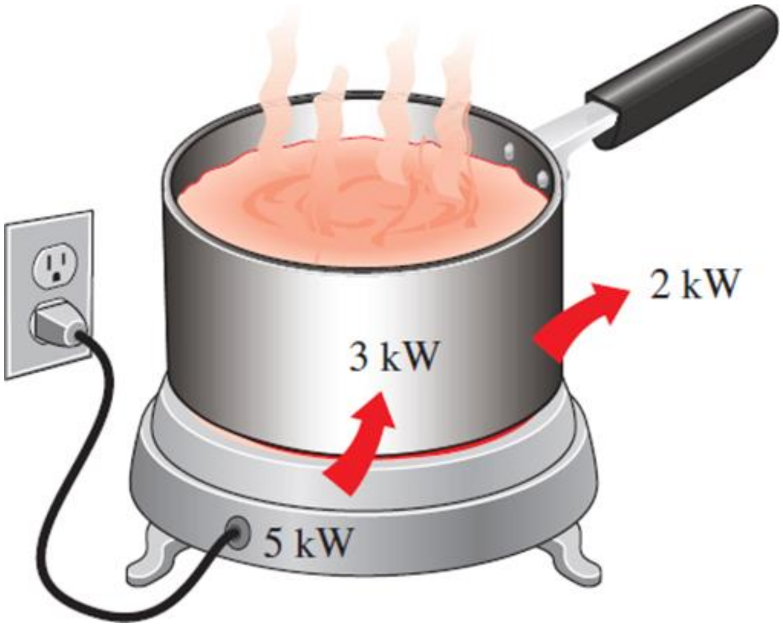
For a cycle $\Delta E = 0$, thus $Q = W$.

2-7 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.

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

2-7 Energy Conversion Efficiencies



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}} = \frac{3\text{ kWh}}{5\text{ kWh}} = 0.60$$

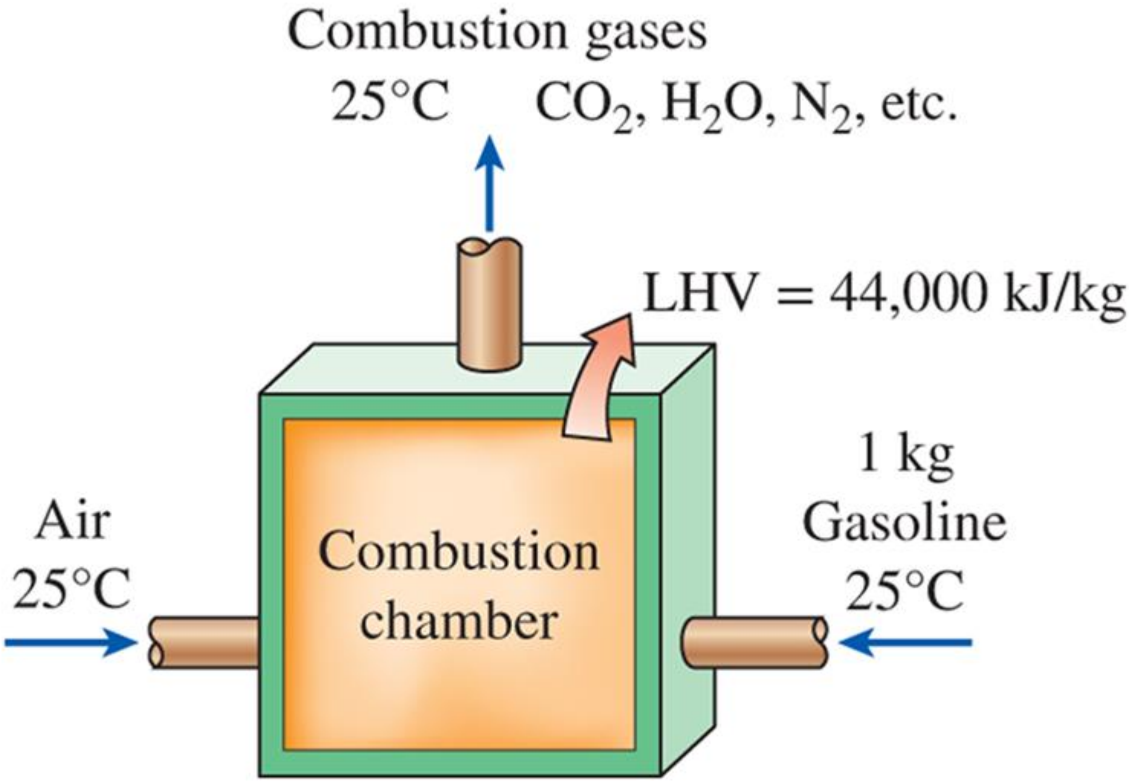
2-7 Energy Conversion Efficiencies

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 in the combustion gases is 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.

2-7 Energy Conversion Efficiencies 3



The heating value of gasoline

2-7 Energy Conversion Efficiencies

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 equipment efficiency as well as other losses such as heat losses to unheated areas and start-up and cool down losses.

The AFUE of most new heating systems is about 85 percent, although the AFUE of some old heating systems is under 60 percent.

The AFUE of some new high-efficiency furnaces exceeds 96 percent, but the high cost of such furnaces cannot be justified for locations with mild to moderate winters.

Such high efficiencies are achieved by reclaiming most of the heat in the flue gases, condensing the water vapor, and discharging the flue gases at temperatures as low as 38°C (or 100°F) instead of about 200°C (or 400°F) for the conventional models.

2-7 Energy Conversion Efficiencies

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**

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

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

2-7 Energy Conversion Efficiencies

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

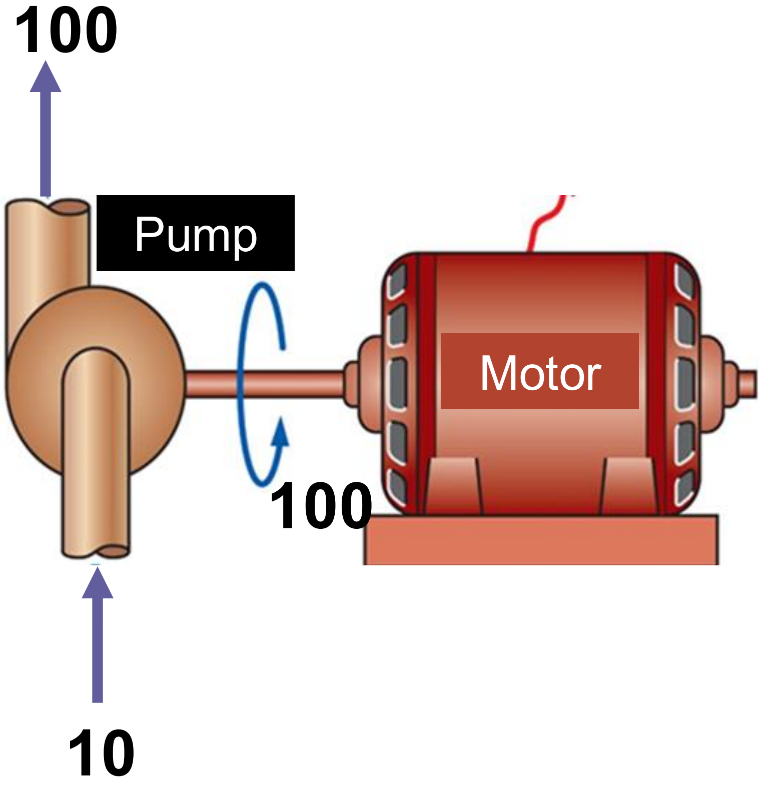
and

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

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

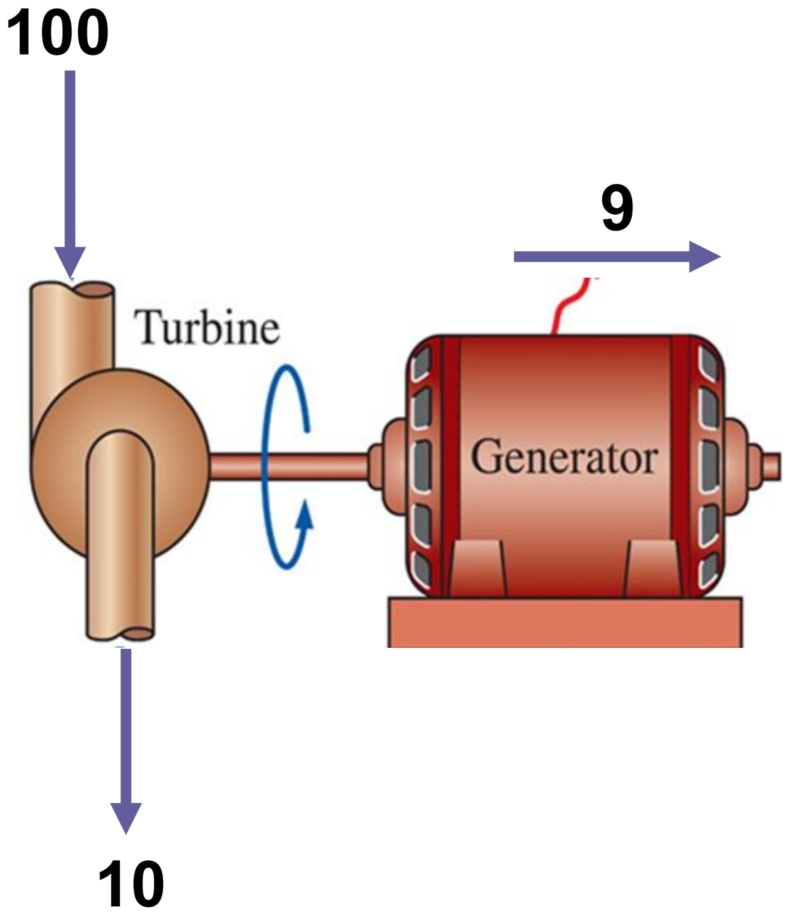
$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},e}} = \frac{\dot{W}_{\text{elect,out}}}{\left|\Delta\dot{E}_{\text{mech,fluid}}\right|}$$

2-7 Energy Conversion Efficiencies



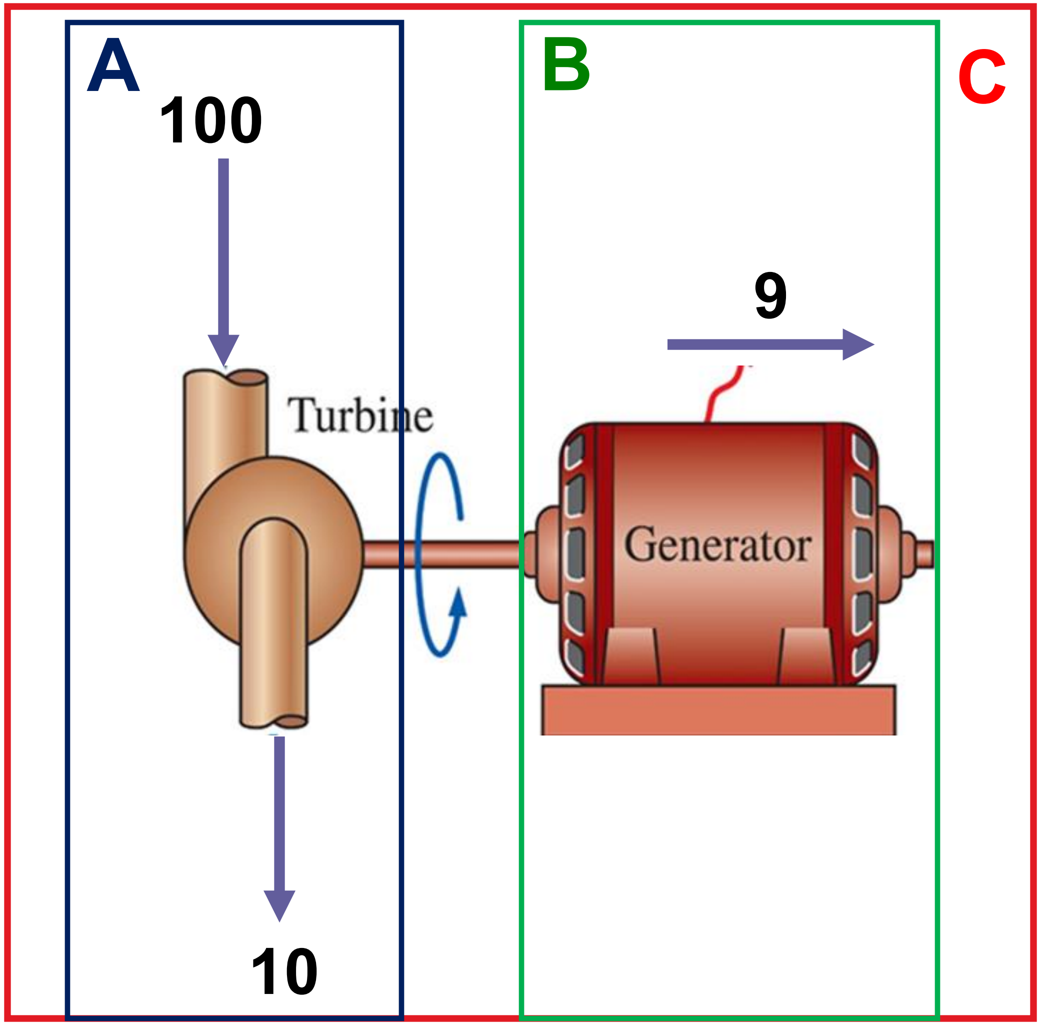
$E_{ff} = 90\%$

2-7 Energy Conversion Efficiencies



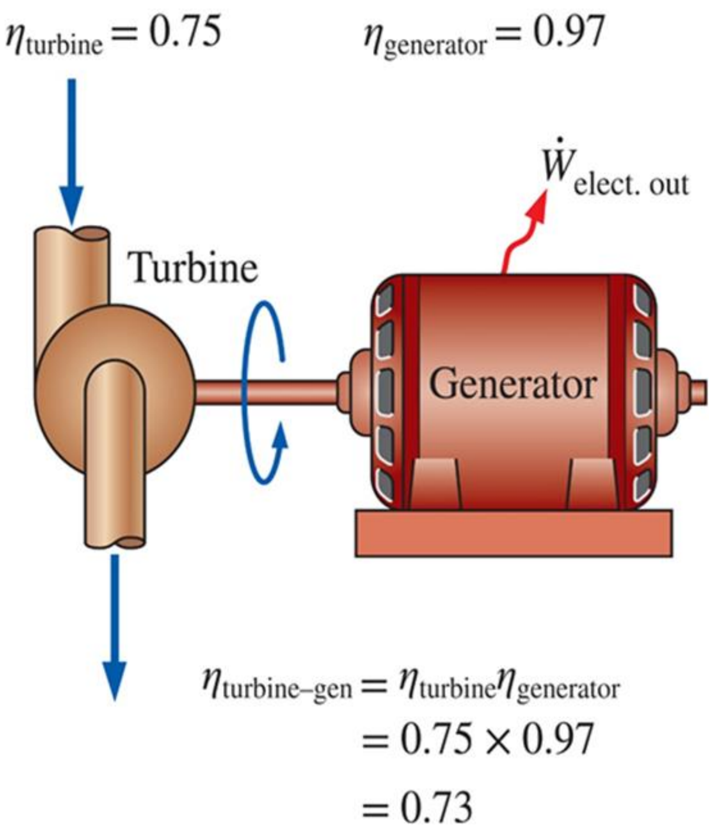
$E_{ff} = 10\%$

2-7 Energy Conversion Efficiencies



Eff_A * Eff_B = Eff_C

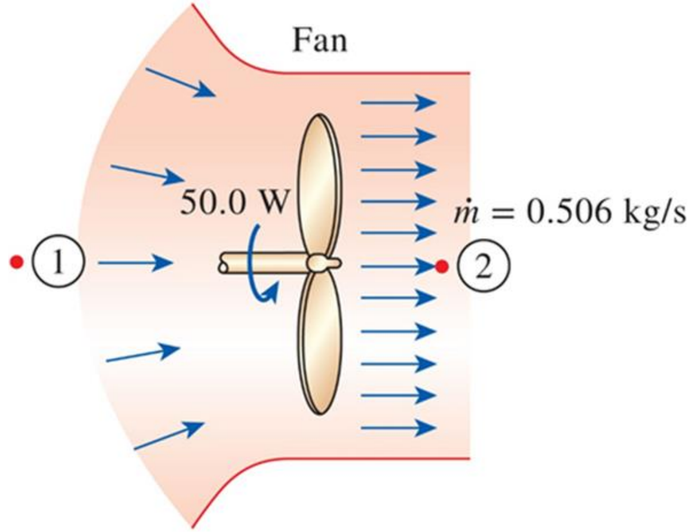
2-7 Energy Conversion Efficiencies



$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = 0.75 \times 0.97 = 0.73$$

The overall efficiency of a turbine– generator is the product of the efficiency of the turbine and the efficiency of the generator, and it represents the fraction of the mechanical power of the fluid converted to electrical power.

2-7 Energy Conversion Efficiencies



The mechanical efficiency of a fan

$$V_1 \approx 0$$

$$V_2 = 12.1 \text{m/s}$$

$$z_1 = z_2$$

$$P_1 \approx P_{atm} \text{ and } P_2 \approx P_{atm}$$

$$\eta_{\text{mech,fan}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{m}V_2^2/2}{\dot{W}_{\text{shaft,in}}}$$

$$= \frac{(0.506 \text{ kg/s})(12.1 \text{ m/s})^2/2}{50.0 \text{ W}}$$

$$= 0.741$$

2-8 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**.

2-8 Energy and Environment

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 (VO Cs) 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.

2-8 Energy and Environment

Acid Rain

The sulfur in the fuel reacts with oxygen to form sulfur dioxide (SO_2), which is an air pollutant.

The main source of SO_2 is the electric power plants that burn high-sulfur coal. Motor vehicles also contribute to SO_2 emissions since gasoline and diesel fuel also contain small amounts of sulfur.

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.

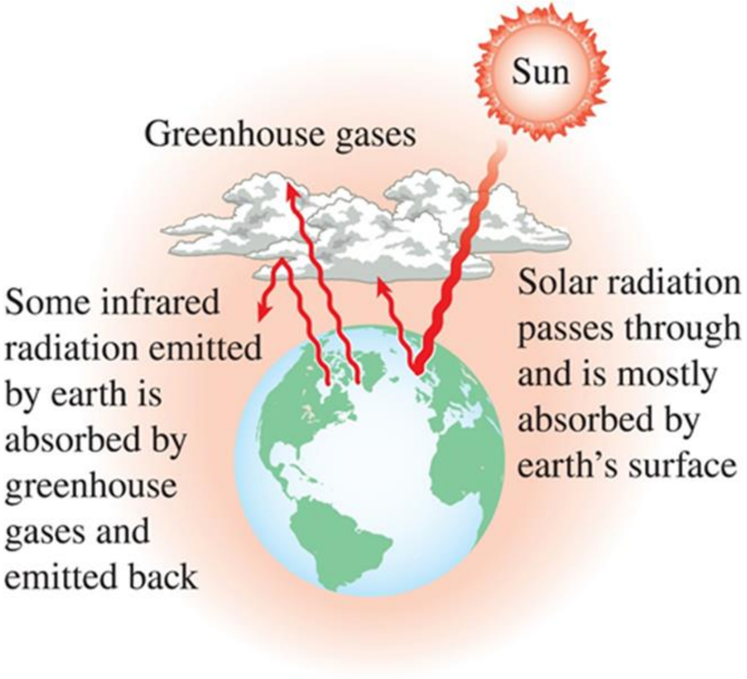
These acid-laden droplets, which can be as acidic as lemon juice, are washed from the air on to the soil by rain or snow. This is known as **acid rain**.

2-8 Energy and Environment

The Greenhouse Effect: Global Warming and Climate Change

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 (that is, 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.



2-8 Energy and Environment

Carbon dioxide $(\mathrm{CO_2})$, 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 $\mathrm{CO_2}$ being the primary component.

$\mathrm{CO_2}$ is produced by the burning of fossil fuels such as coal, oil, and natural gas.

2-8 Energy and Environment

A 1995 report: The earth has already warmed about **0.5°C** during the last century, and they estimate that the earth's temperature will rise another **2°C** by the year 2100.

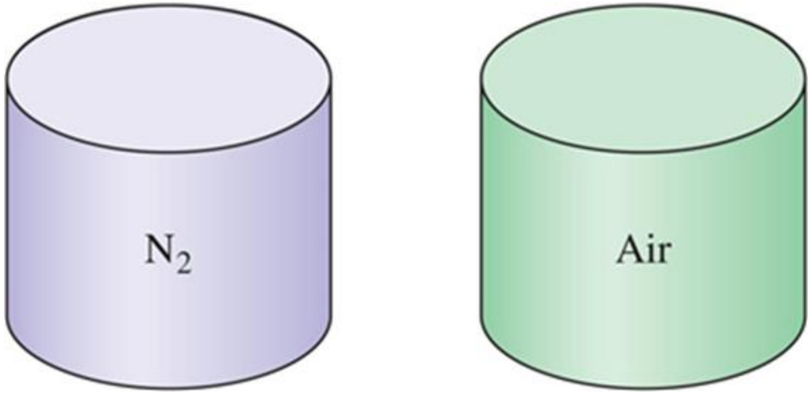
A rise of this magnitude can cause **severe changes in weather patterns** with storms and heavy rains and flooding at some parts and drought in others, major floods due to the melting of ice at the poles, loss of wetlands and coastal areas due to rising sea levels, and other negative results.

How to minimize global warming?

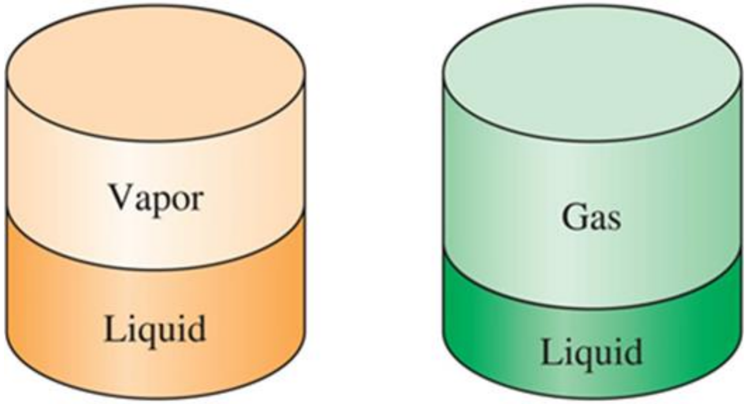
- Improved energy efficiency
- energy conservation
- using renewable energy sources

3–1 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.



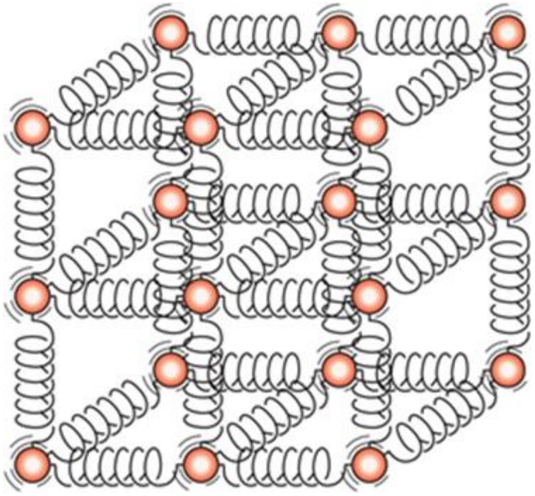
Nitrogen and gaseous air are pure substances.



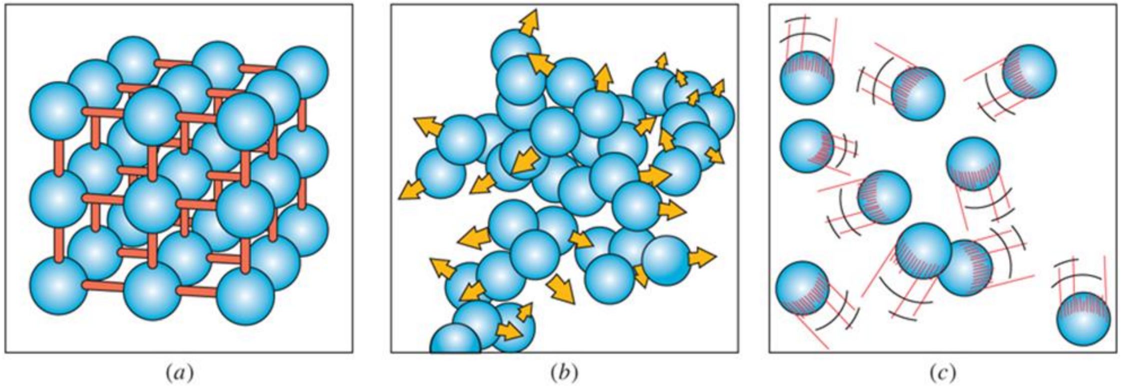
(*a*) H_2O (*b*) Air

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

3–2 Phases of a Pure Substance



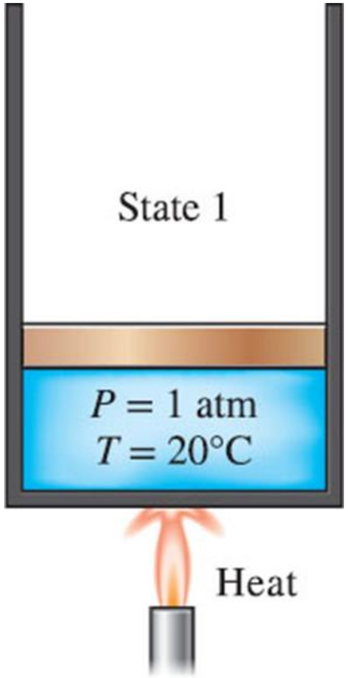
The molecules in a solid are kept at their positions by the large springlike intermolecular forces.



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..

3–3 Phase-Change Processes of Pure Substances

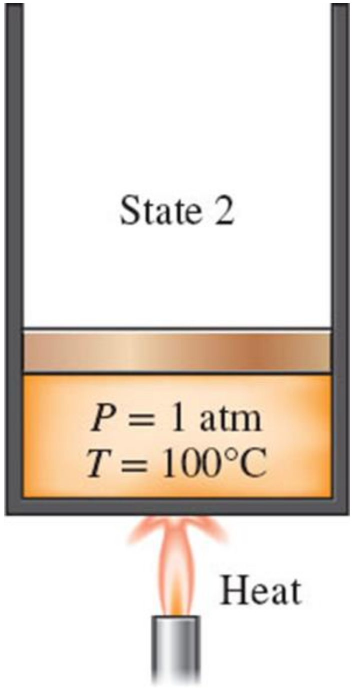
Compressed liquid (subcooled liquid): A substance that it is not about to vaporize



At 1 atm and 20°C, water exists in the liquid phase (compressed or subcooled liquid).

3–3 Phase-Change Processes of Pure Substances

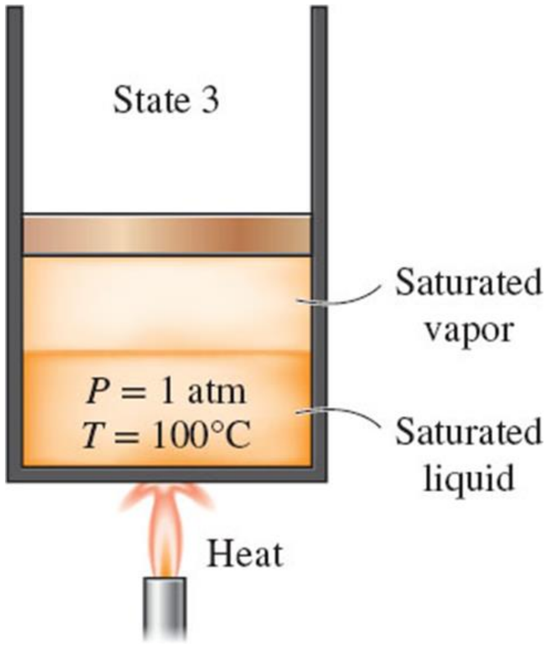
Saturated liquid: A liquid that is about to vaporize



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

3–3 Phase-Change Processes of Pure Substances

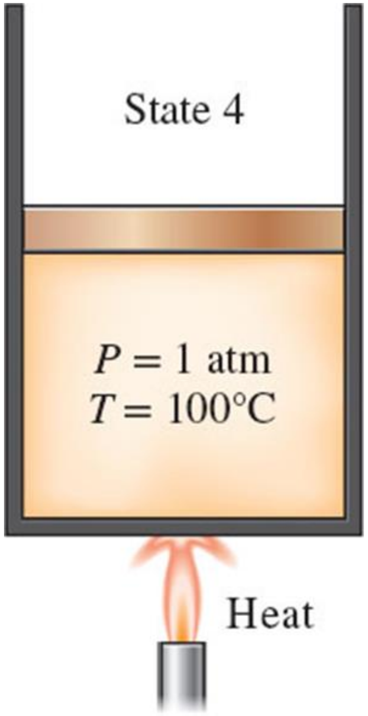
Saturated liquid–vapor mixture: The state at which the liquid and vapor phases coexist in equilibrium



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

3–3 Phase-Change Processes of Pure Substances

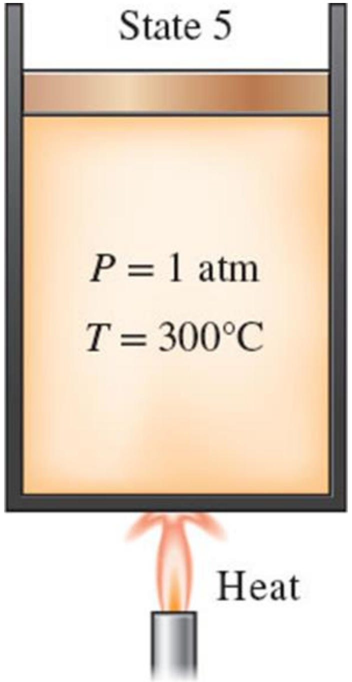
Saturated vapor: A vapor that is about to condense



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

3–3 Phase-Change Processes of Pure Substances 5

Superheated vapor: A vapor that is not about to condense (that is not a saturated vapor).



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

3–3 Phase-Change Processes of Pure Substances

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.

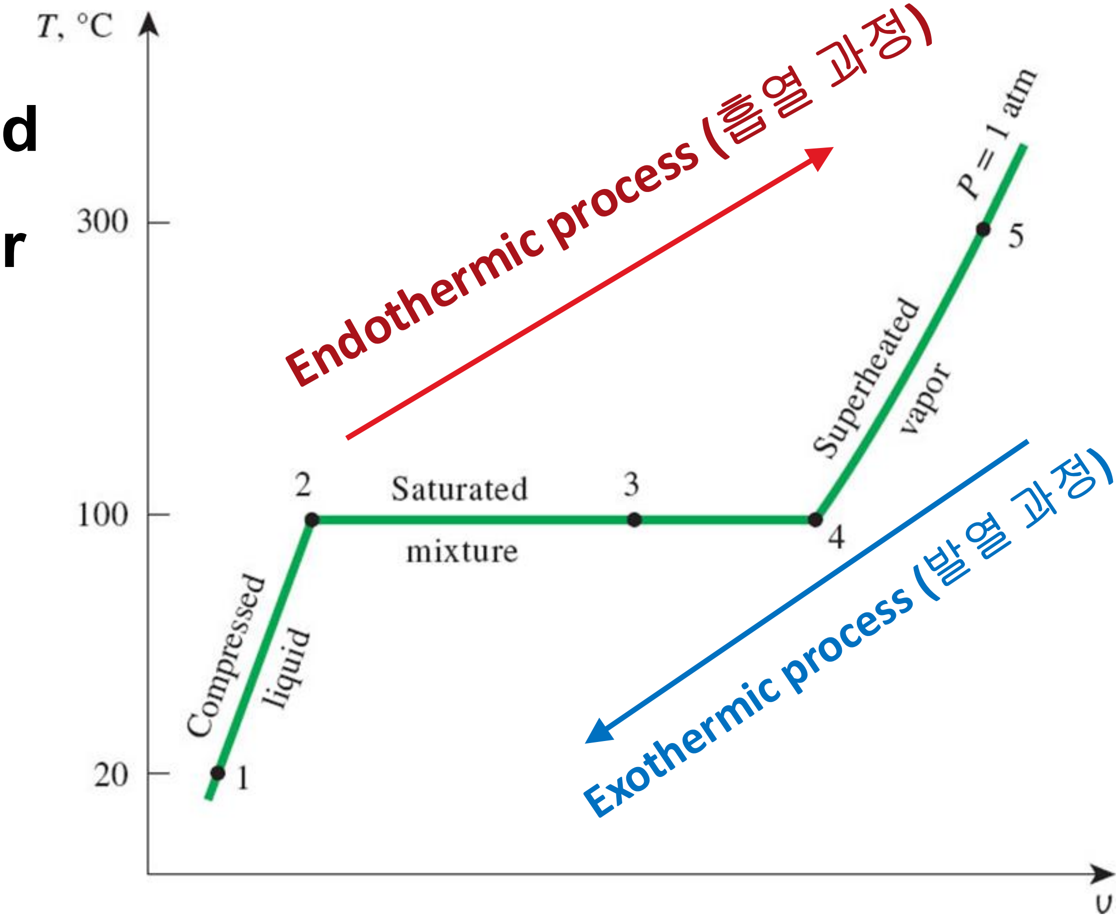
At 1 atm pressure, the latent heat of fusion of water is 334 kJ/kg and the latent heat of vaporization is 2257 kJ/kg.

The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.

3–3 Phase-Change Processes of Pure Substances

Point 2 : Saturated liquid

Point 4: Saturated vapor



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

3–3 Phase-Change Processes of Pure Substances

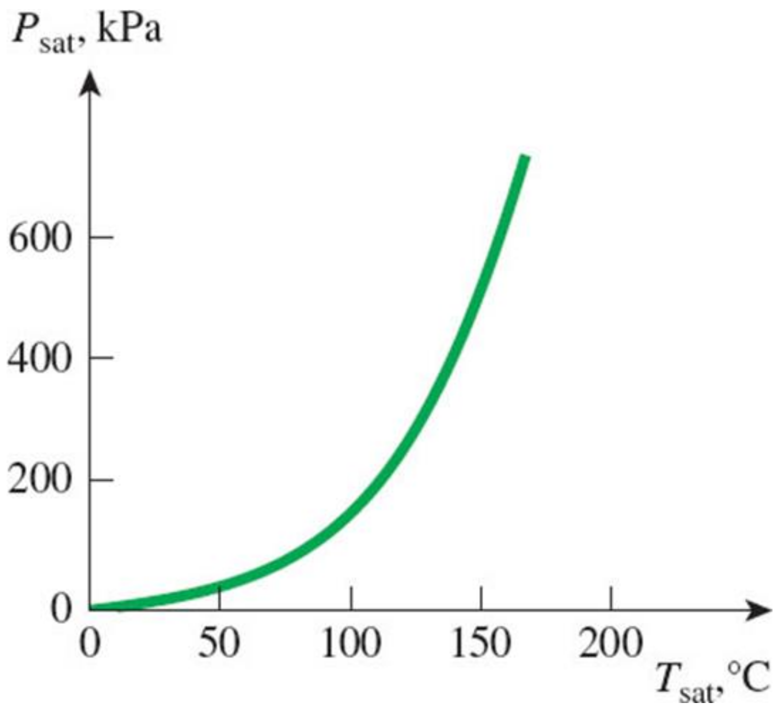
Saturation Temperature and Saturation Pressure

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_{sat} : The temperature at which a pure substance changes phase at a given pressure.

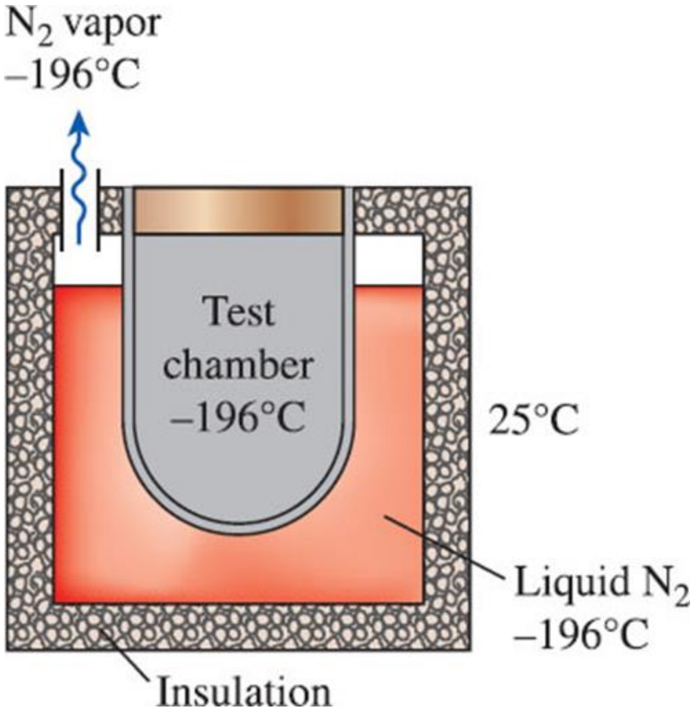
Saturation pressure pressure at which a pure substance changes phase at a given temperature.



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

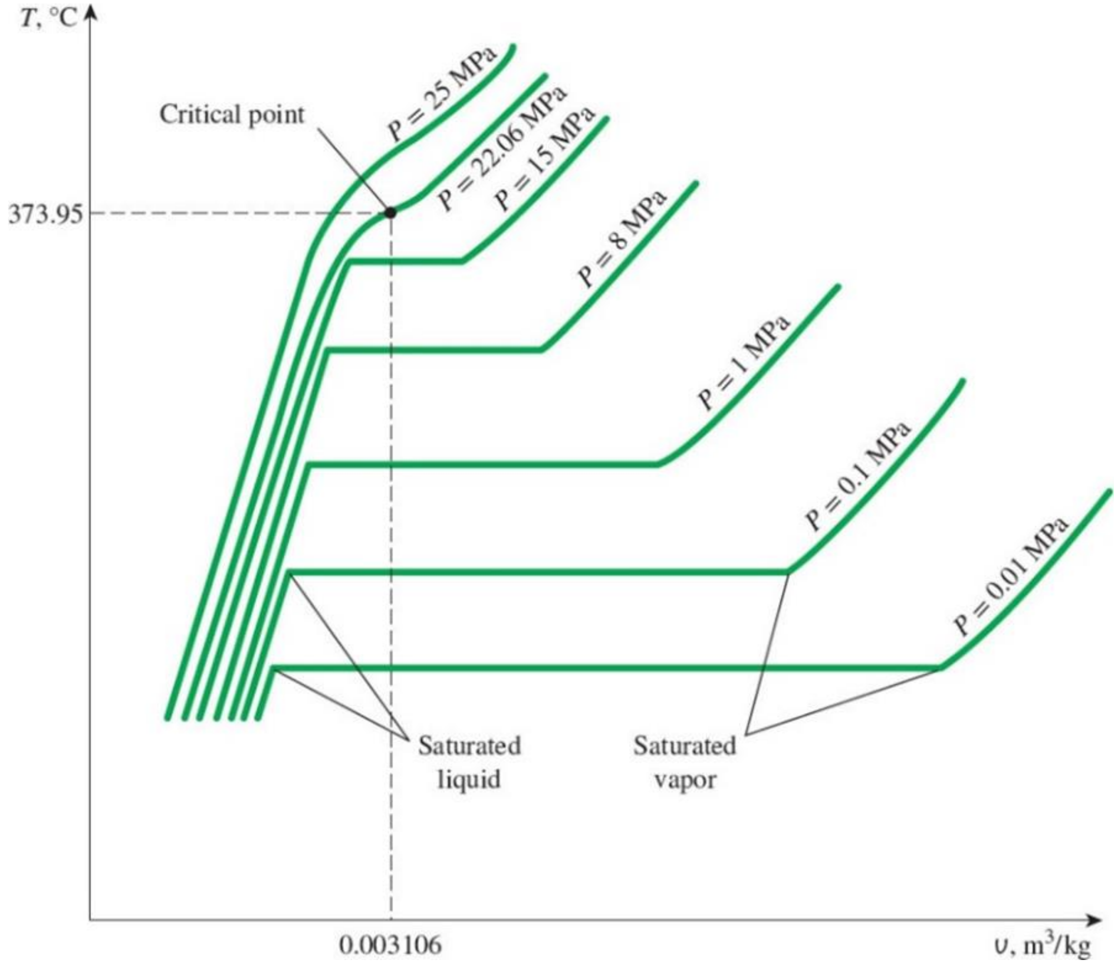
3–3 Phase-Change Processes of Pure Substances

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



The temperature of liquid nitrogen exposed to the atmosphere remains constant at −196°C, and thus it maintains the test chamber at −196°C.

3–4 Property Diagrams for Phase-Change Processes



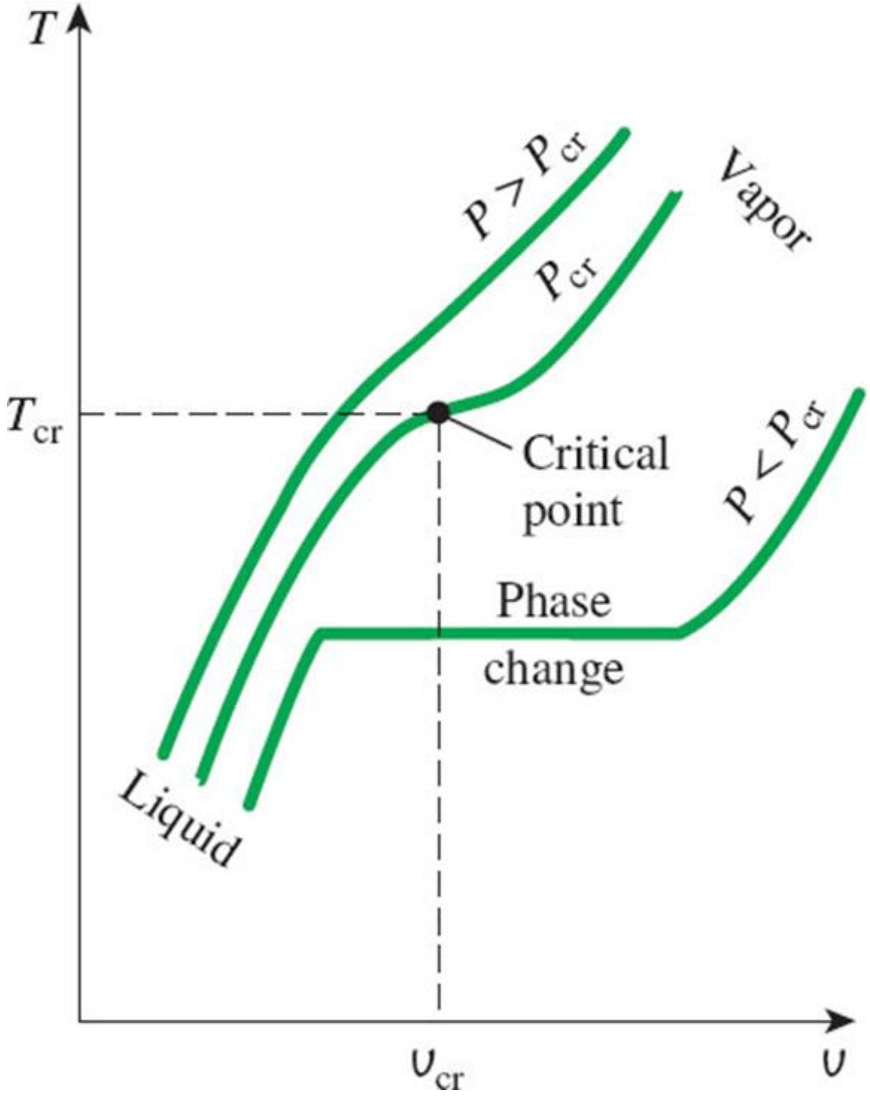
T-v diagram of **constant-pressure** phase-change processes of a pure substance at various pressures (numerical values are for water).

3–4 Property Diagrams for Phase-Change Processes

Critical point:

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

There is no distinct phase-change (boiling) process.



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Energy balance and thermodynamics

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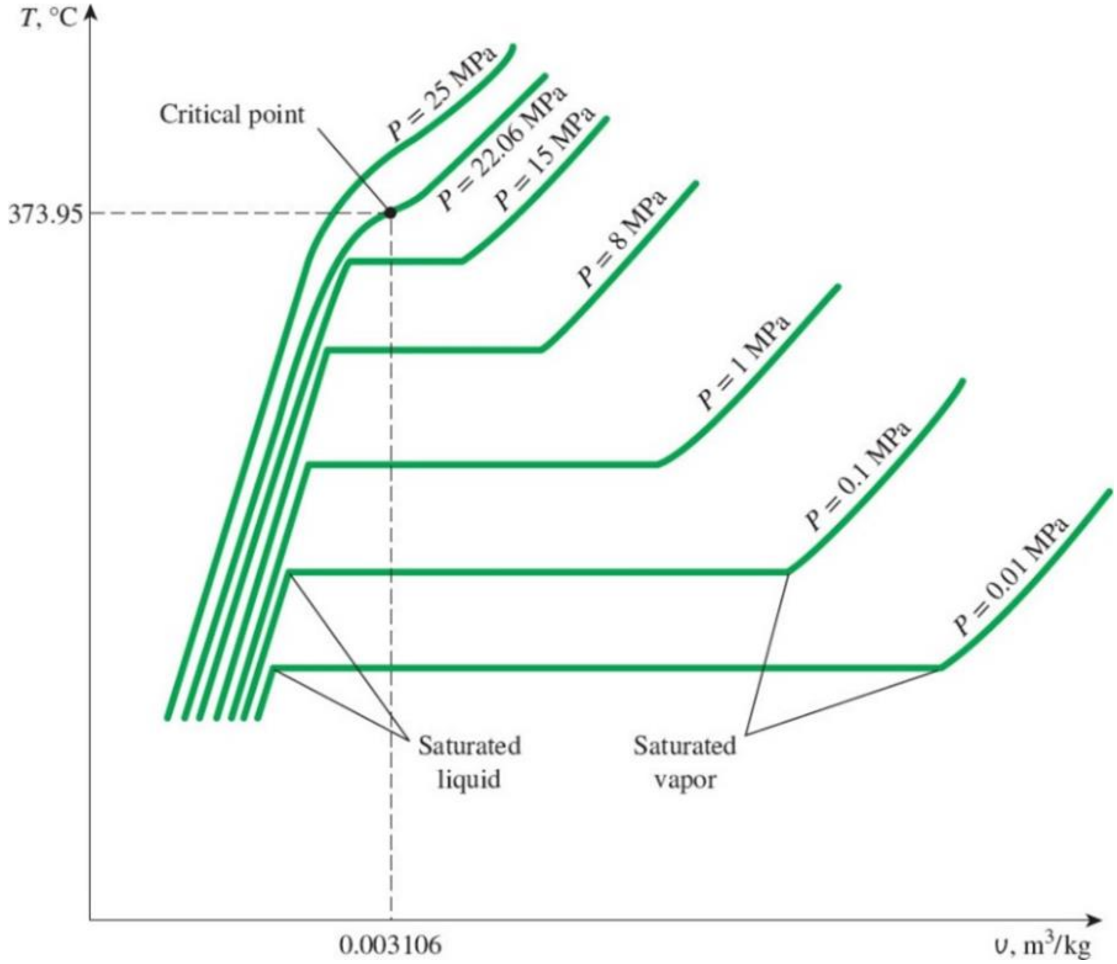
Dept. of Energy and Environmental Engineering

3–4 Property Diagrams for Phase-Change Processes



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

3–4 Property Diagrams for Phase-Change Processes

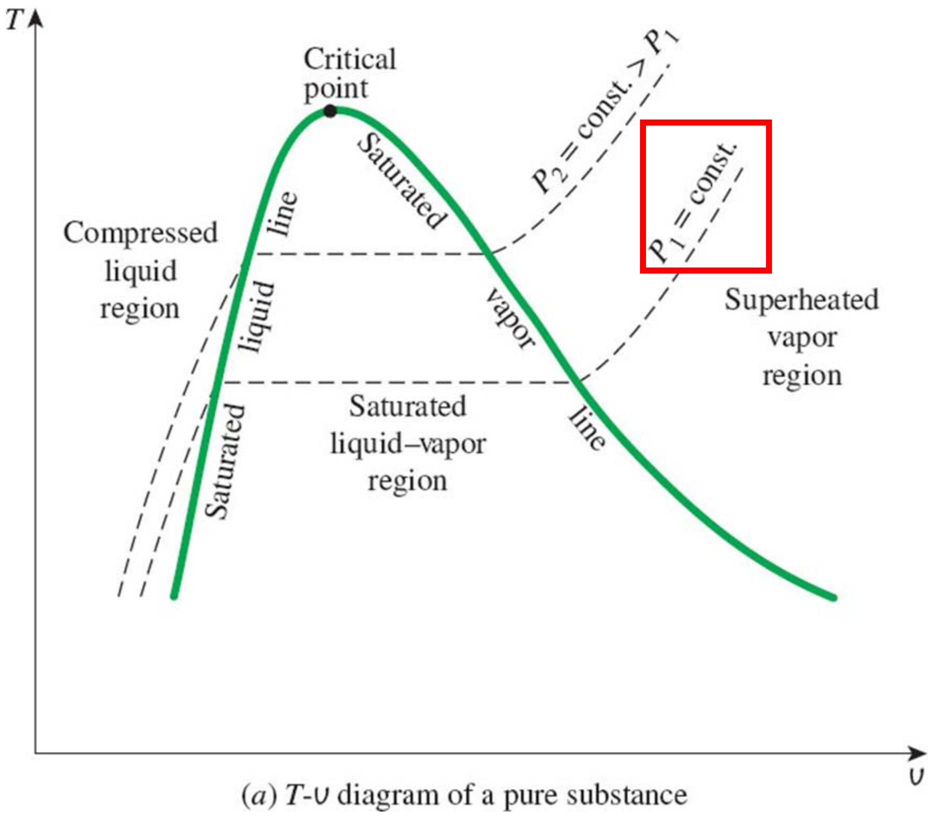
Saturated liquid line

Saturated vapor line

Compressed liquid region

Saturated liquid–vapor mixture region (wet region)

Superheated vapor region

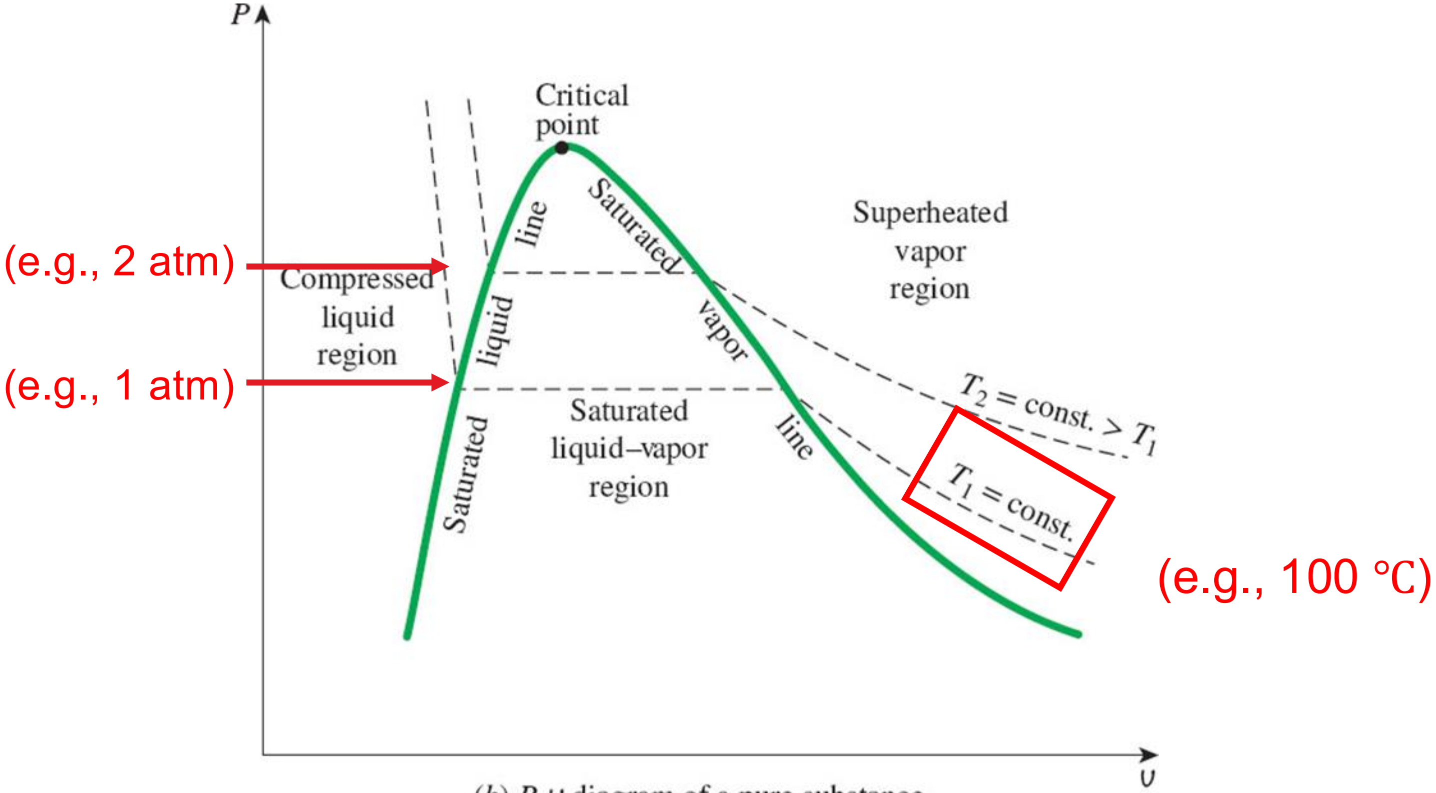


(a) T-υ diagram of a pure substance

Property diagrams of a pure substance.

T-v

3–4 Property Diagrams for Phase-Change Processes



(e.g., 2 atm)

(e.g., 1 atm)

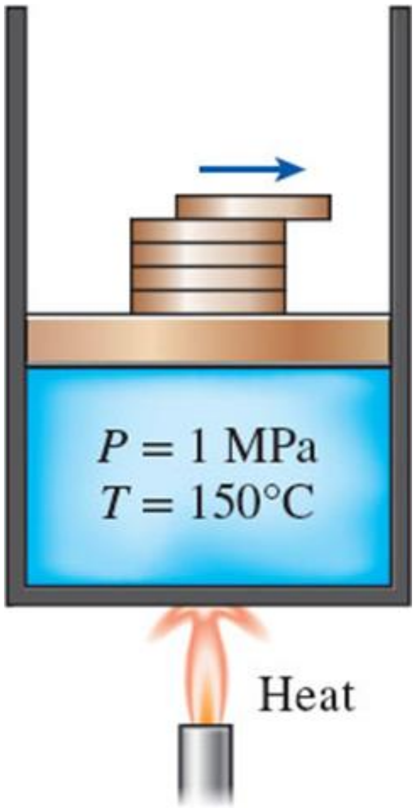
(e.g., 100 ℃)

(*b*) *P*-υ diagram of a pure substance

Property diagrams of a pure substance.

P-v

3–4 Property Diagrams for Phase-Change Processes



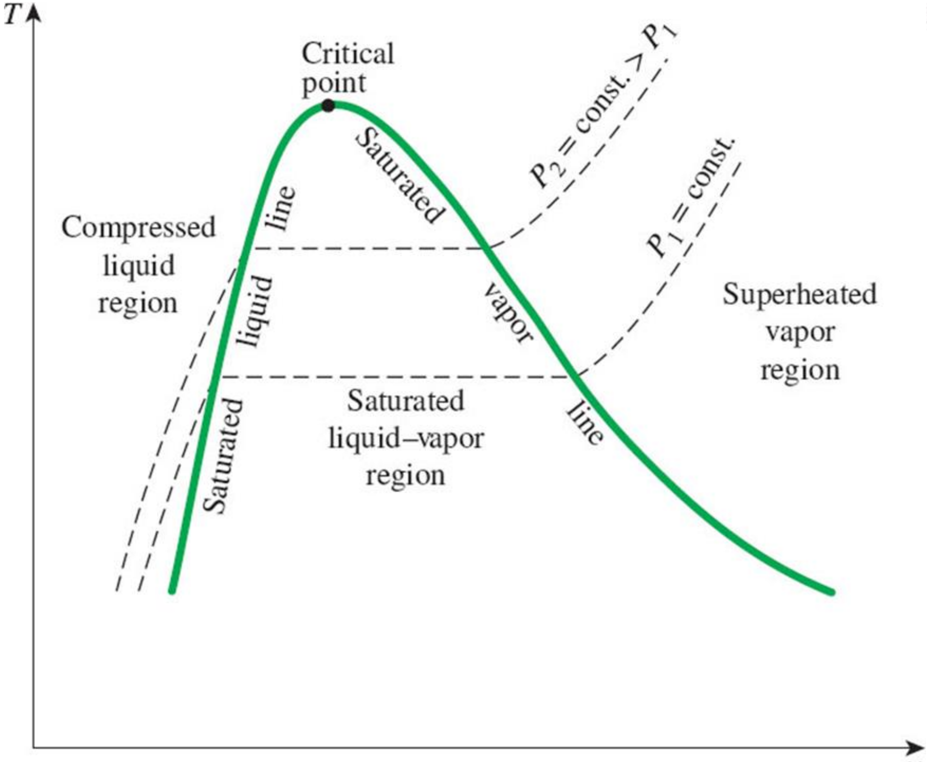
If weights are removed one by one from the piston (assuming heat exchange with the surroundings is allowed and the water temperature remains constant):

1. As the pressure decreases, the volume of the water increases slightly.

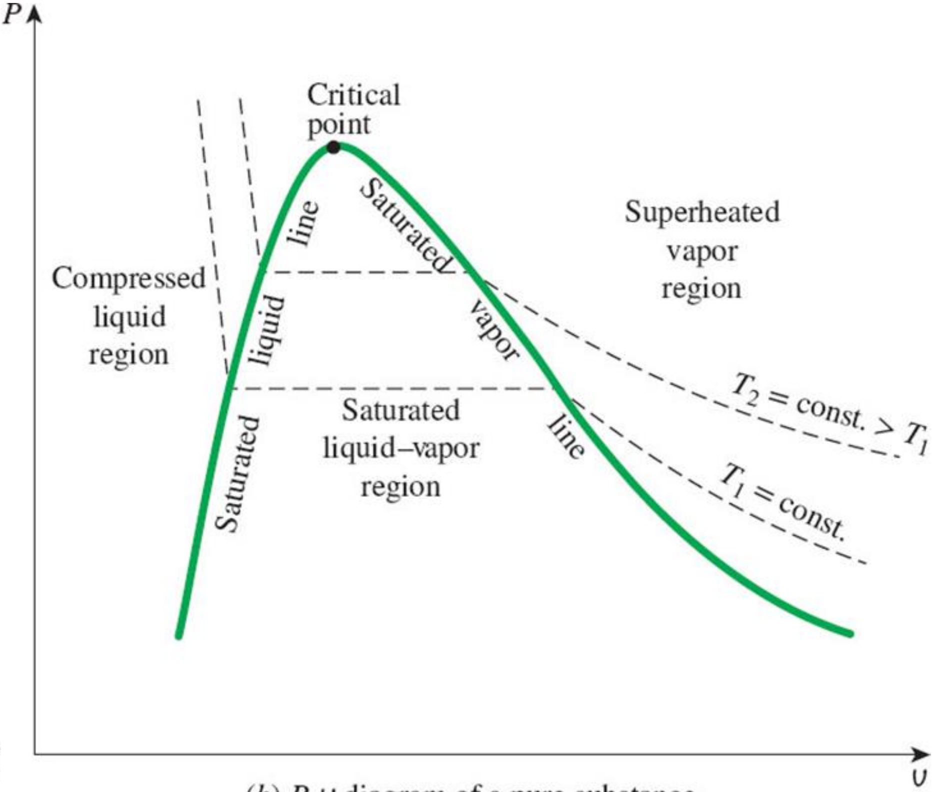
2. When the pressure reaches the saturation pressure at 150 °C (0.476 MPa), the water begins to boil → During the vaporization process, *both temperature and pressure remain constant, but the specific volume increases.*

3. After complete vaporization, further decreases in pressure cause the specific volume to increase.

3–4 Property Diagrams for Phase-Change Processes



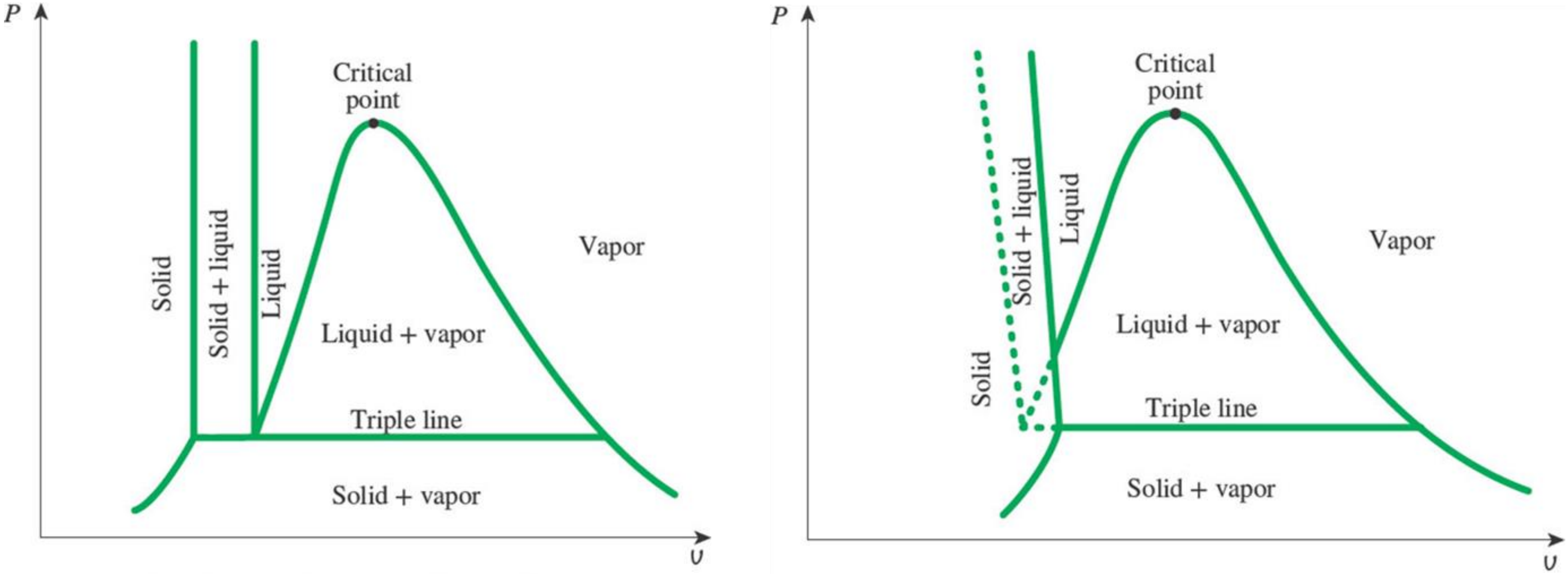
(a) T-υ diagram of a pure substance



(b) P-υ diagram of a pure substance

3–4 Property Diagrams for Phase-Change Processes

Extending the Diagrams to Include the Solid Phase



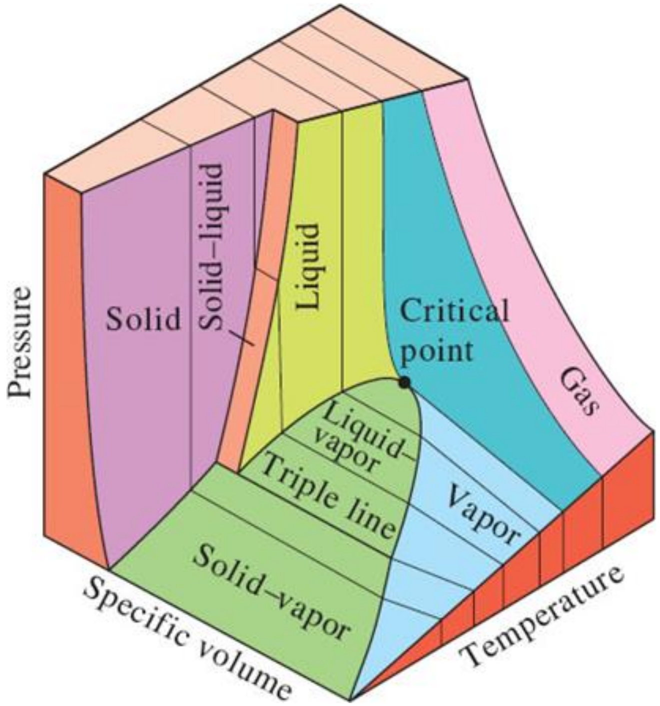
(*a*) *P*-*υ* diagram of a substance that contracts on freezing

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

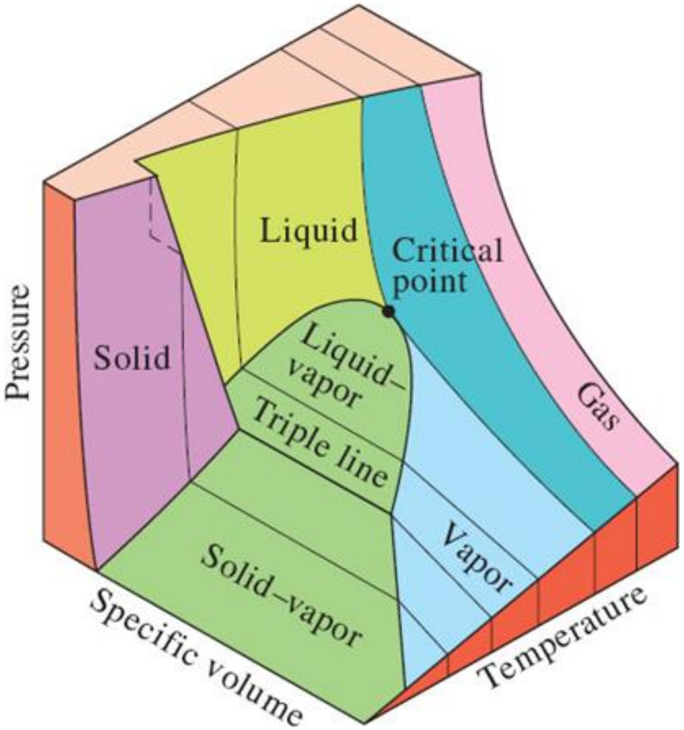
P-*v* diagrams of different substances.

3–4 Property Diagrams for Phase-Change Processes

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.



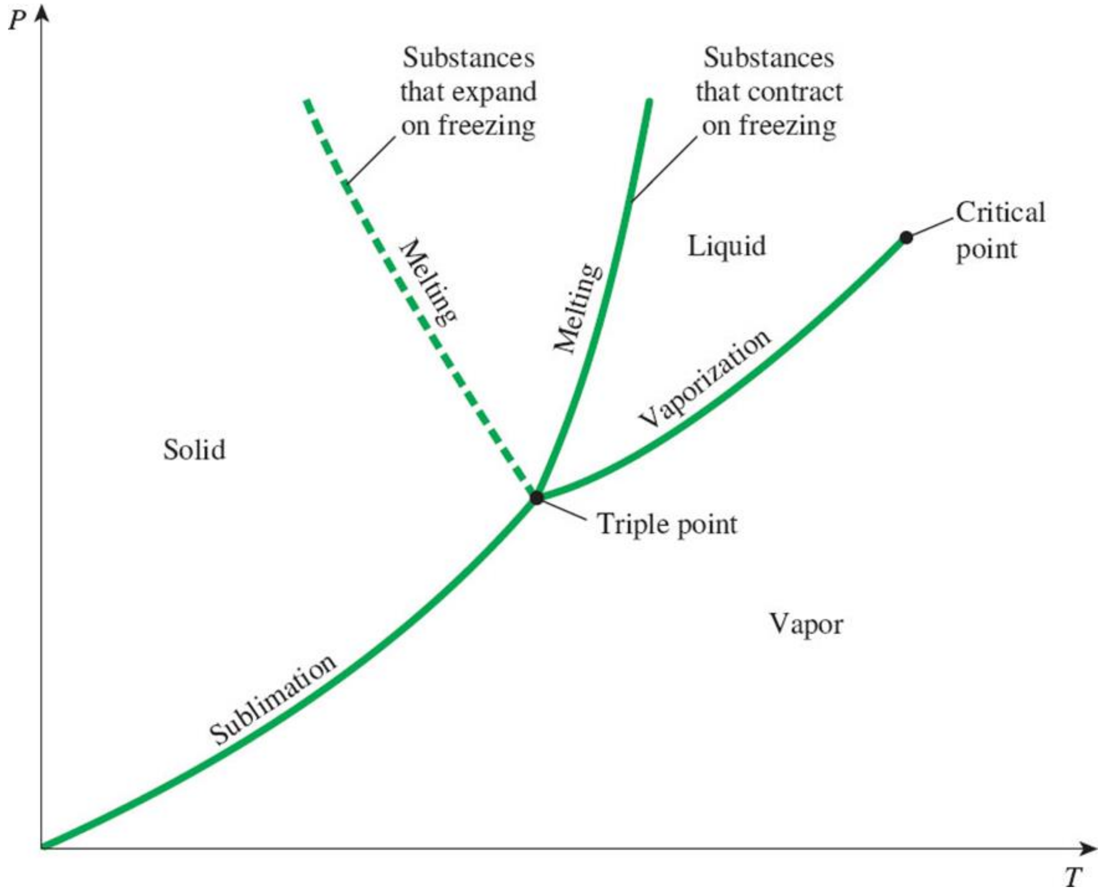
P-v-T surface of a substance that contracts on freezing.



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

3–4 Property Diagrams for Phase-Change Processes 8

Phase diagram



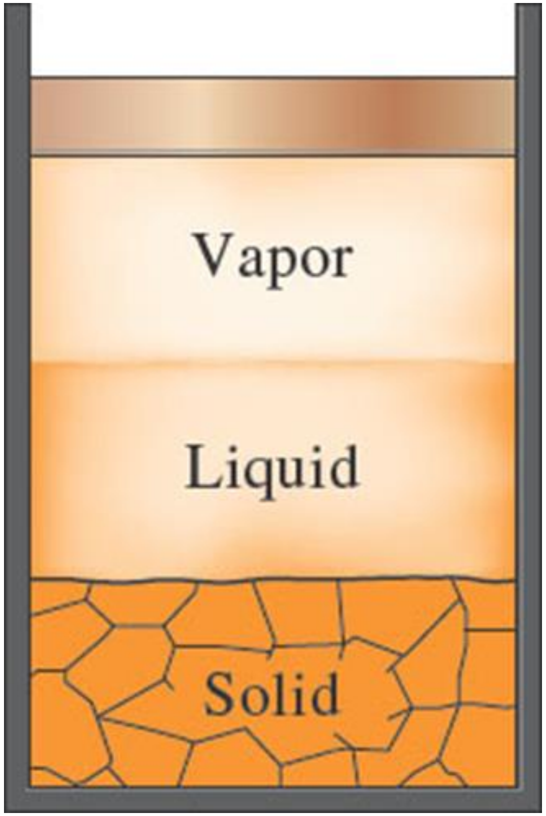
P-*T* diagram of pure substances.

3–4 Property Diagrams for Phase-Change Processes

For water,

$$T_{tp} = 0.01°C$$

$$P_{tp} = 0.6117\ kPa$$



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

3–4 Property Diagrams for Phase-Change Processes

Sublimation (승화): Passing from the solid phase directly into the vapor phase.

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

3–5 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.

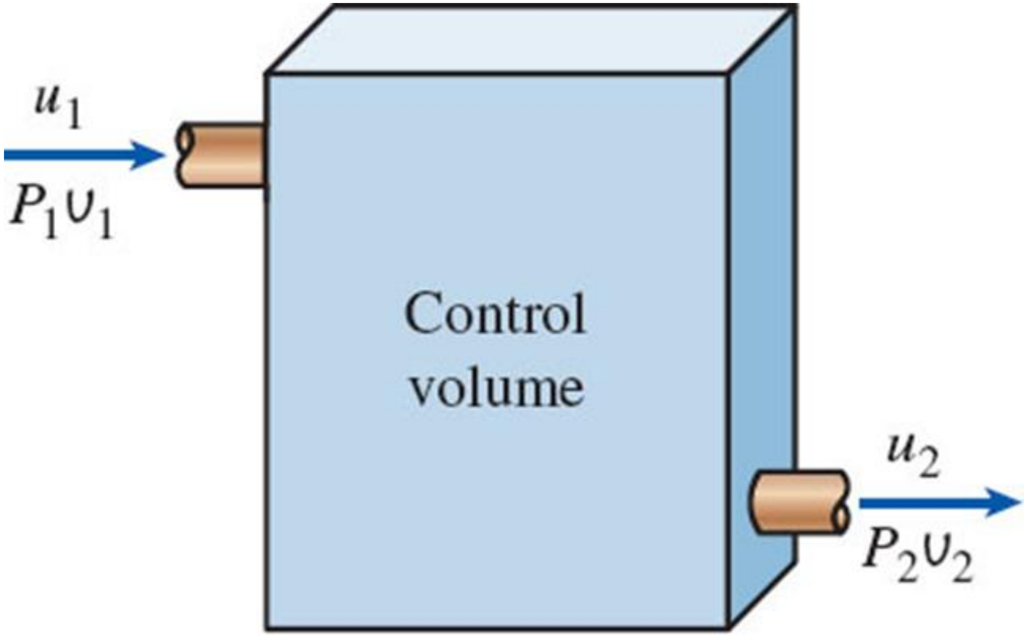
The results of these measurements and calculations are presented in tables in a convenient format.

3–5 Property Tables

Enthalpy—A Combination Property

$$h = u + Pv \quad (kJ/kg)$$

$$H = U + PV \quad (kJ)$$



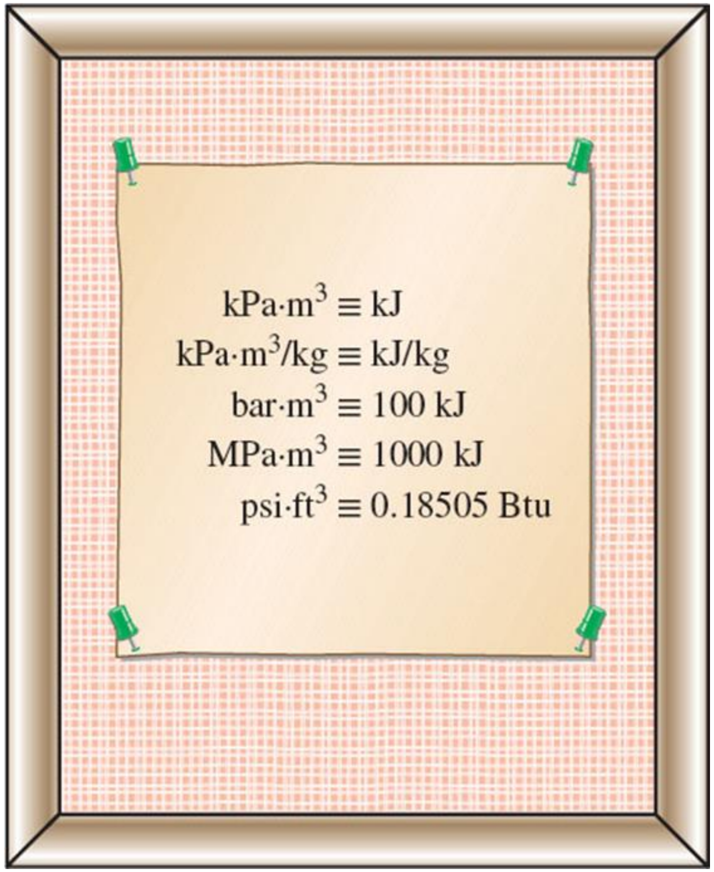
The combination *u* + *Pv* is often encountered in the analysis of control volumes.

3–5 Property Tables

Enthalpy—A Combination Property

$$h = u + Pv \quad (kJ/kg)$$

$$H = U + PV \quad (kJ)$$



$$\mathrm{kPa\cdot m^3} \equiv \mathrm{kJ}$$

$$\mathrm{kPa\cdot m^3/kg} \equiv \mathrm{kJ/kg}$$

$$\mathrm{bar\cdot m^3} \equiv 100\ \mathrm{kJ}$$

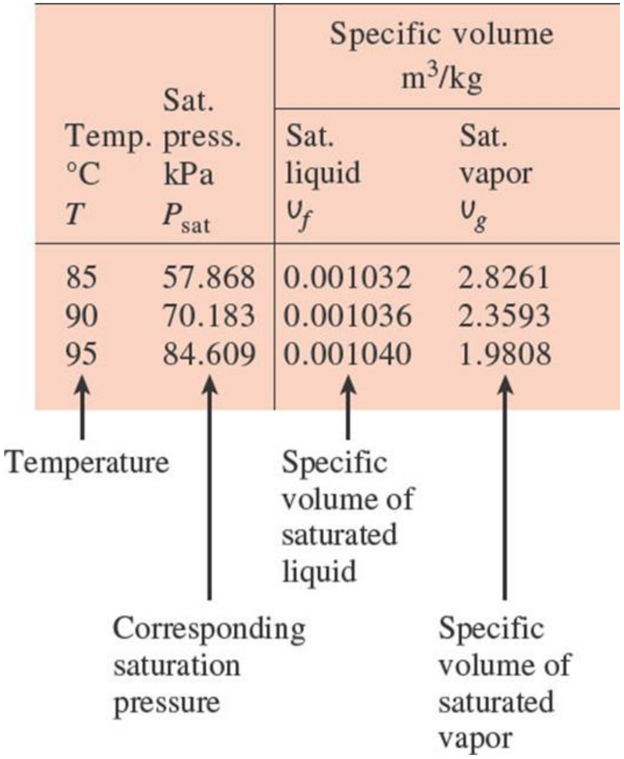
$$\mathrm{MPa\cdot m^3} \equiv 1000\ \mathrm{kJ}$$

$$\mathrm{psi\cdot ft^3} \equiv 0.18505\ \mathrm{Btu}$$

The product *pressure* × *volume* has energy units.

3–5 Property Tables

Saturated Liquid and Saturated Vapor States



Temp. °C T	Sat. press. kPa P_{sat}	Specific volume m^3/kg Sat. liquid v_f	 Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

A partial list of Table A–4.

v_f = specific volume of saturated liquid

v_g = specific volume of saturated vapor

$$\mathrm{v}_{fg} = \mathrm{v}_g - \mathrm{v}_f$$

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

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

3–5 Property Tables

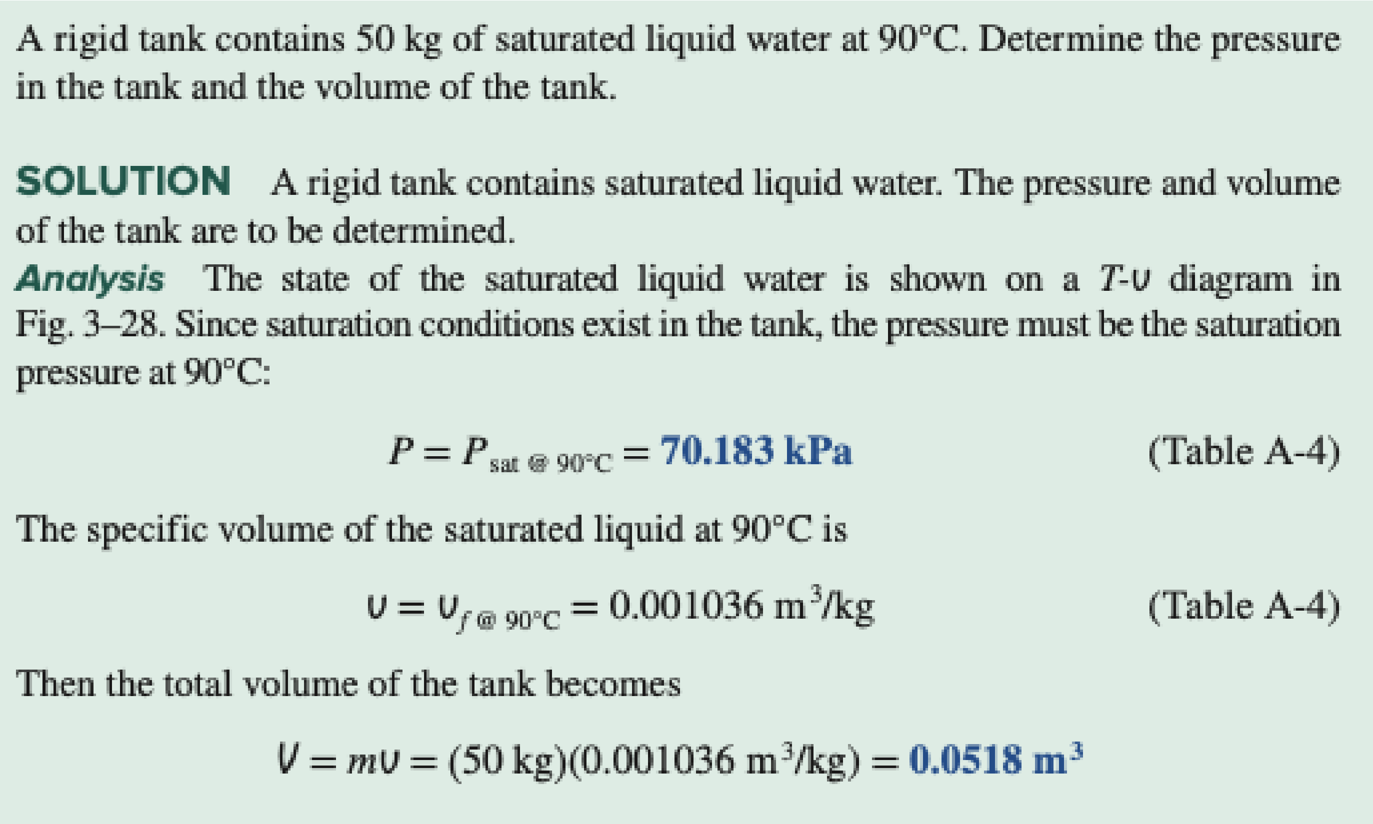
Enthalpy of vaporization, (Latent heat of vaporization) h_{fg}

The amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.

It represents the amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.

It decreases as the temperature or pressure increases and becomes zero at the critical point.

3–5 Property Tables



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.

Analysis The state of the saturated liquid water is shown on a T-v diagram in Fig. 3–28. Since saturation conditions exist in the tank, the pressure must be the saturation pressure at 90°C:

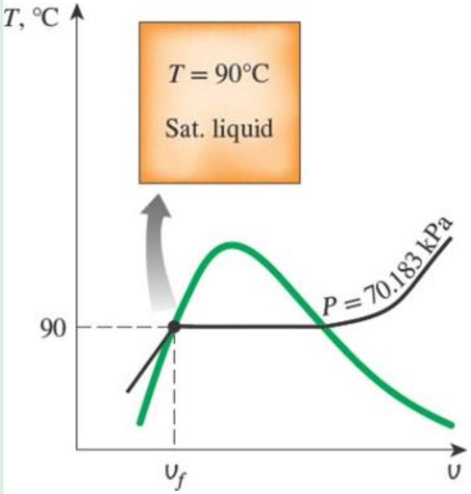
$$P = P_{\text{sat @ 90°C}} = \mathbf{70.183\ kPa} \qquad \text{(Table A-4)}$$

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

$$v = v_{f\,@\,90°\text{C}} = 0.001036\ \text{m}^3/\text{kg} \qquad \text{(Table A-4)}$$

Then the total volume of the tank becomes

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



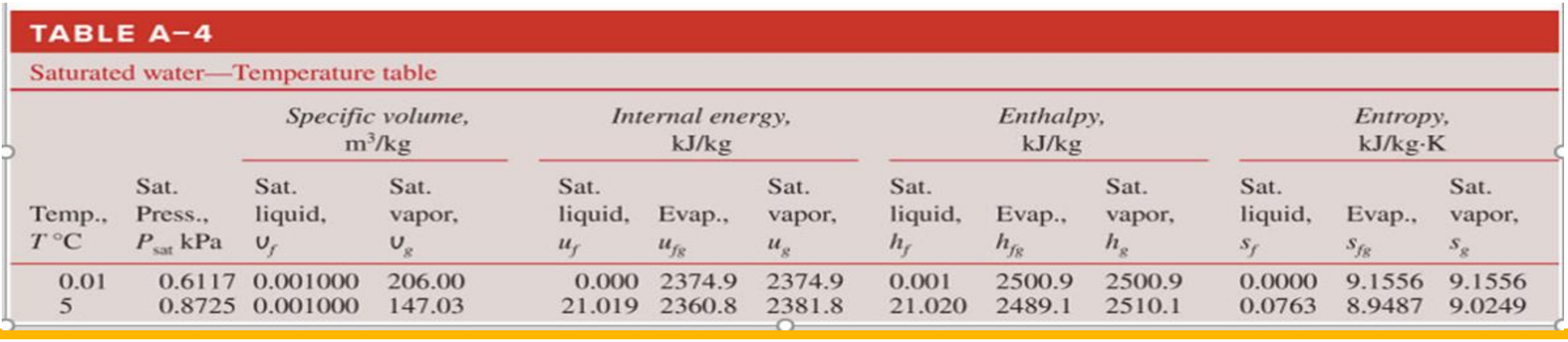


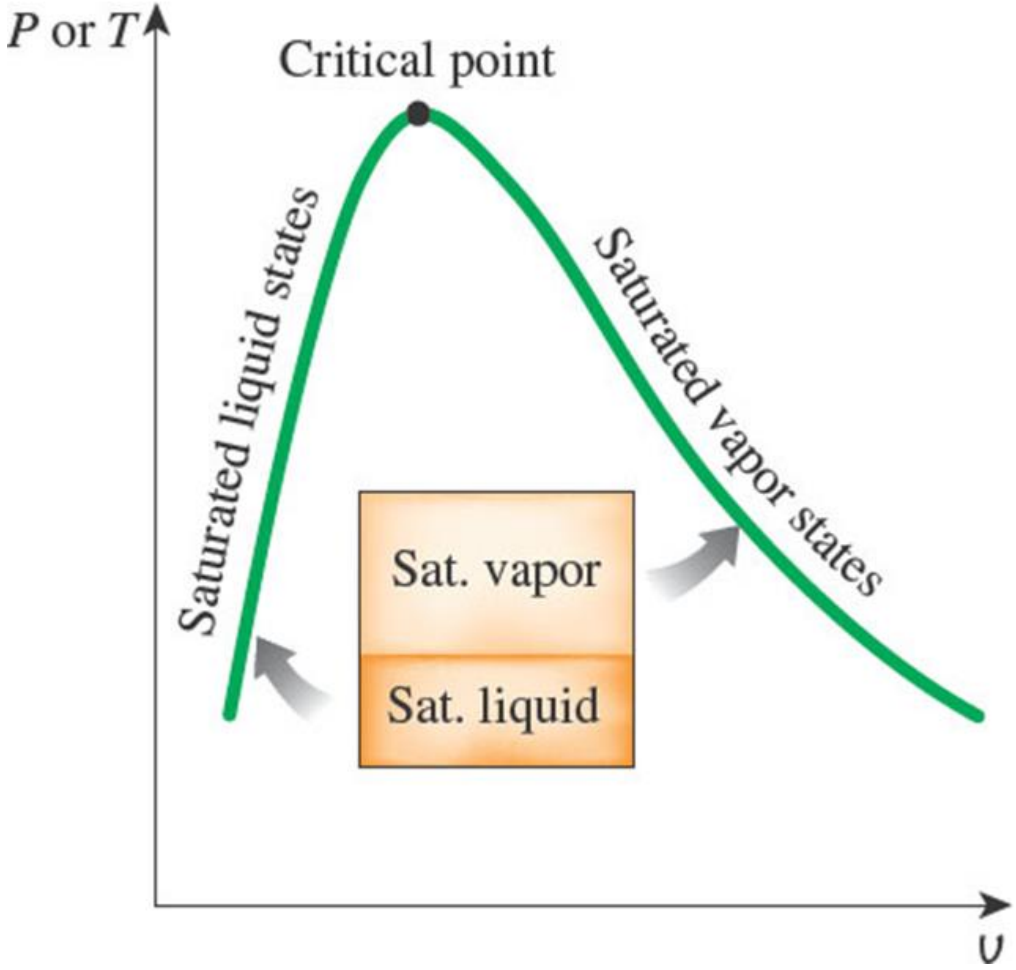
TABLE A–4

Saturated water—Temperature table

		Specific volume, m³/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg·K		
Temp., T °C	Sat. Press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249

3–5 Property Tables

Saturated Liquid–Vapor Mixture



3–5 Property Tables

Saturated Liquid–Vapor Mixture

Quality (건도), *x*: The ratio of the mass of vapor to the total mass of the mixture.

Quality is between 0 and 1.

- $x = 0$ saturated liquid
- $x = 1$ saturated vapor

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

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

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

3–5 Property Tables

$$V = V_f + V_g$$

$$V = mv \longrightarrow m_t v_{\text{avg}} = m_f v_f + m_g v_g$$

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

Dividing by m_t yields

$$v_{\text{avg}} = (1 - x) v_f + x v_g$$

since $x = m_g/m_t$. This relation can also be expressed as

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

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

$$\boldsymbol{= v_f + x(v_g - v_f) = v_f + x v_{fg}}$$

where $v_{fg} = v_g - v_f$. Solving for quality, we obtain

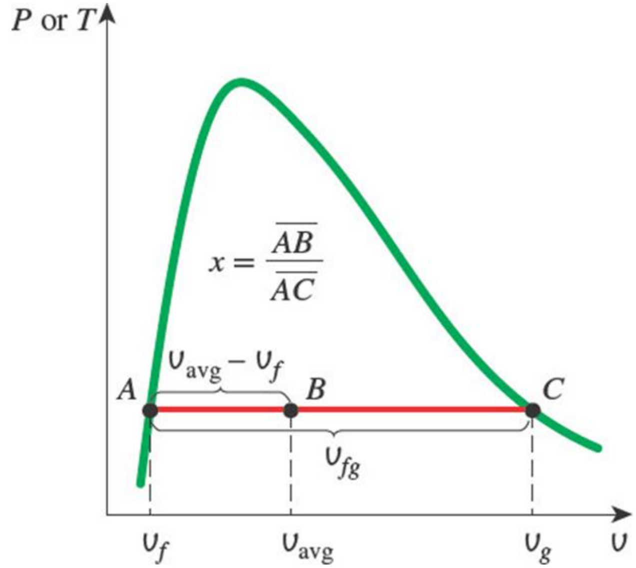
$$x = \frac{v_{\text{avg}} - v_f}{v_{fg}}$$

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

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

$$y_{\text{avg}} = y_f + x y_{fg} \qquad y \rightarrow v,\ u,\ \text{or } h$$

$$y_f \le y_{\text{avg}} \le y_g$$



3–5 Property Tables

Superheated Vapor

Compared to saturated vapor, superheated vapor is characterized by

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

Higher temperatures $\left(T > T_{\text{sat}} \text{ at a given } P\right)$

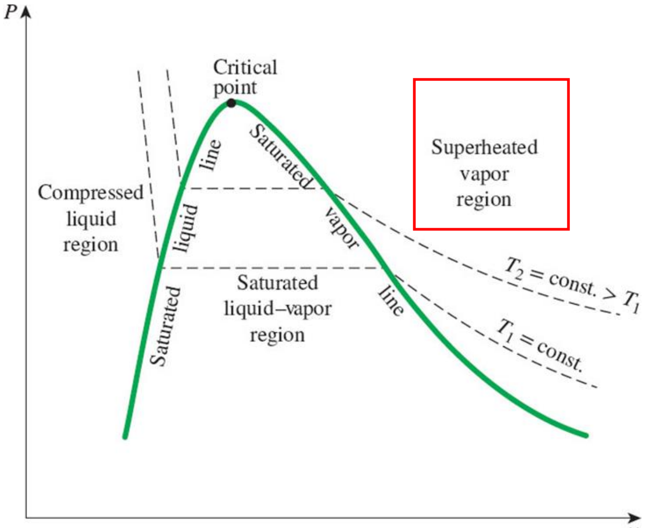
Higher specific volumes $\left(v > v_g \text{ at a given } P \text{ or } T\right)$

Higher internal energies $\left(u > u_g \text{ at a given } P \text{ or } T\right)$

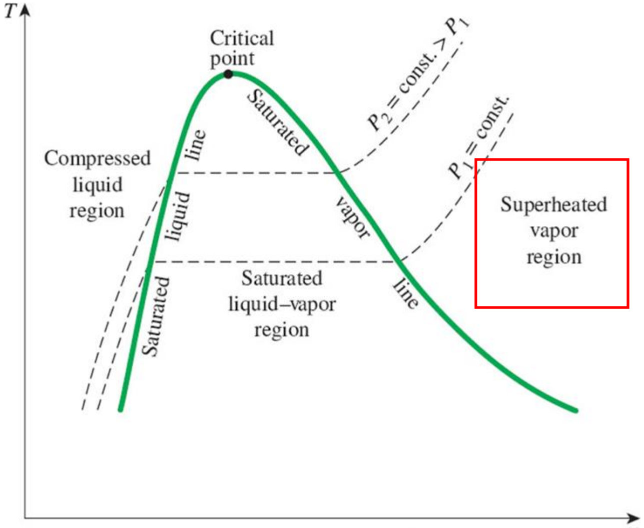
Higher enthalpies $\left(h > h_g \text{ at a given } P \text{ or } T\right)$

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.

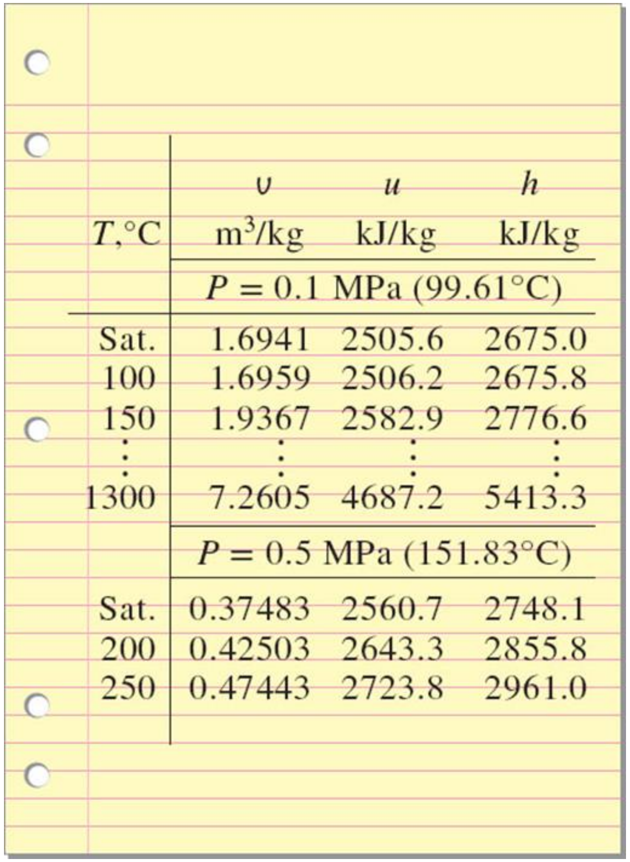


(b) P-υ diagram of a pure substance



(a) T-υ diagram of a pure substance

3–5 Property Tables



T,°C	v m^3/kg	u kJ/kg	h kJ/kg
	$P = 0.1$ MPa (99.61°C)		
Sat.	1.6941	2505.6	2675.0
100	1.6959	2506.2	2675.8
150	1.9367	2582.9	2776.6
⋮	⋮	⋮	⋮
1300	7.2605	4687.2	5413.3
	$P = 0.5$ MPa (151.83°C)		
Sat.	0.37483	2560.7	2748.1
200	0.42503	2643.3	2855.8
250	0.47443	2723.8	2961.0

A partial listing of Table A–6.

3–5 Property Tables

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

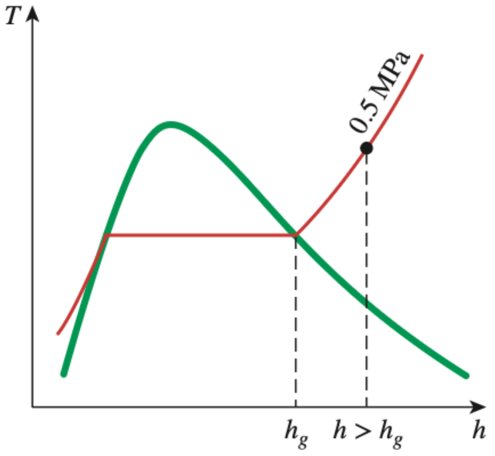
SOLUTION The temperature of water at a specified state is to be determined.

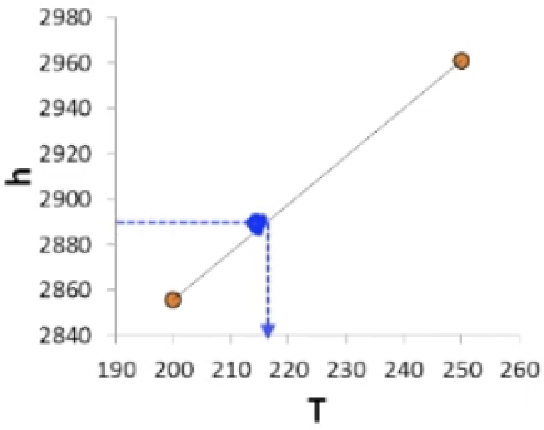
Analysis At 0.5 MPa, the enthalpy of saturated water vapor is $h_g = 2748.1$ kJ/kg. Since $h > h_g$, as shown in Fig. 3–39, we again have superheated vapor. Under 0.5 MPa in Table A–6 we read

T, °C	h, kJ/kg
200	2855.8
250	2961.0

Obviously, the temperature is between 200 and 250°C. By linear interpolation it is determined to be

$$T = 216.3°\text{C}$$





$$\boxed{\left[\frac{\Delta h}{\Delta T}\right]_1 = \frac{(2961.0 - 2855.8)}{(250 - 200)}} = \boxed{\left[\frac{\Delta h}{\Delta T}\right]_2 = \frac{(2961.0 - 2890)}{(250 - T)}}$$

3–5 Property Tables

Compressed Liquid

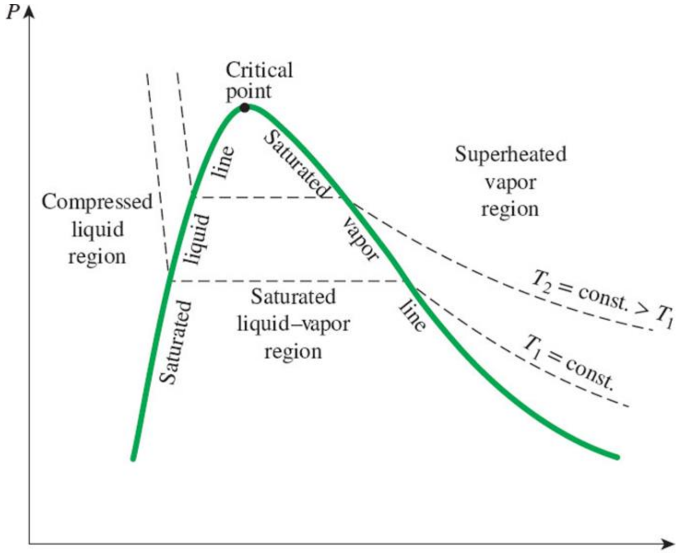
Higher pressures $\left(P > P_{\text{sat}} \text{ at a given } T\right)$

Lower temperatures $\left(T < T_{\text{sat}} \text{ at a given } P\right)$

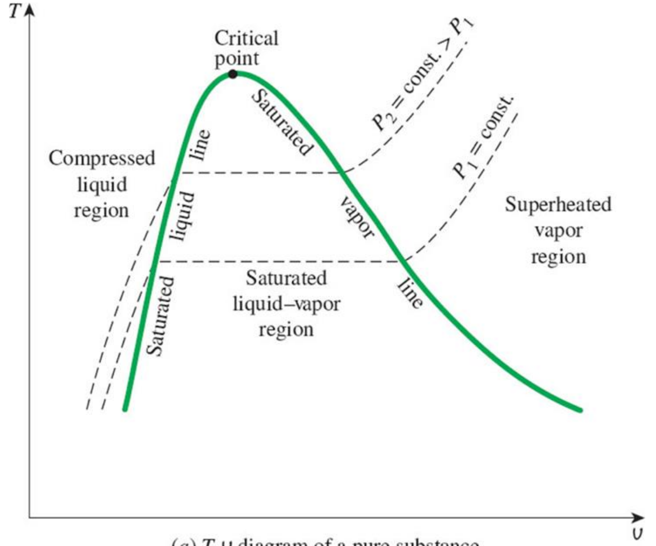
Lower specific volumes $\left(\text{v} < \text{v}_f \text{ at a given } P \text{ or } T\right)$

Lower internal energies $\left(u < u_f \text{ at a given P or } T\right)$

Lower enthalpies $\left(h < h_f \text{ at a given P or } T\right)$



(*b*) *P*-v diagram of a pure substance

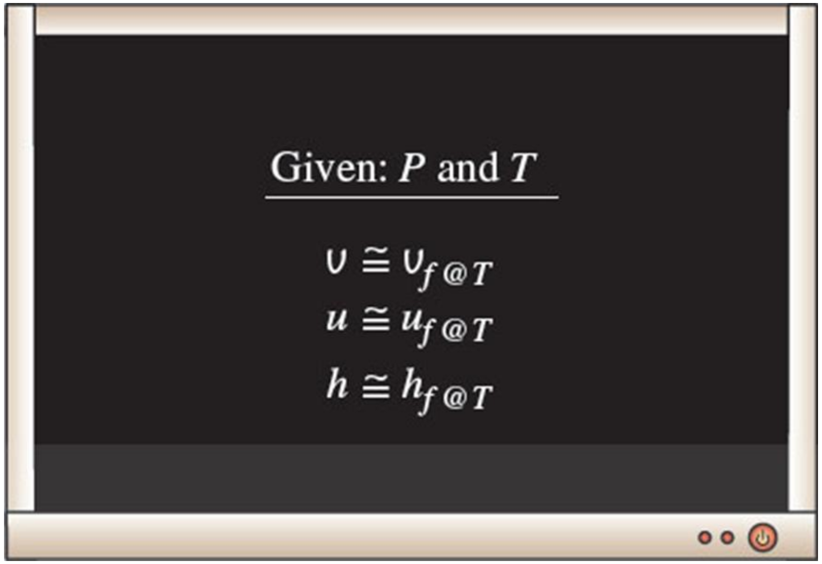


(*a*) *T*-v diagram of a pure substance

3–5 Property Tables

Compressed Liquid

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



Given: P and T

$$v \cong v_{f@T}$$
$$u \cong u_{f@T}$$
$$h \cong h_{f@T}$$

If compressed liquid data are not available, the compressed liquid is approximated as a saturated liquid at the given temperature.

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

A more accurate relation for *h*

$$h \cong h_{f@T} + \mathrm{v}_{f@T}\left(P - P_{\text{sat}@T}\right)$$

3–5 Property Tables

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°C and for R-134a is −40°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.

3–5 Property Tables

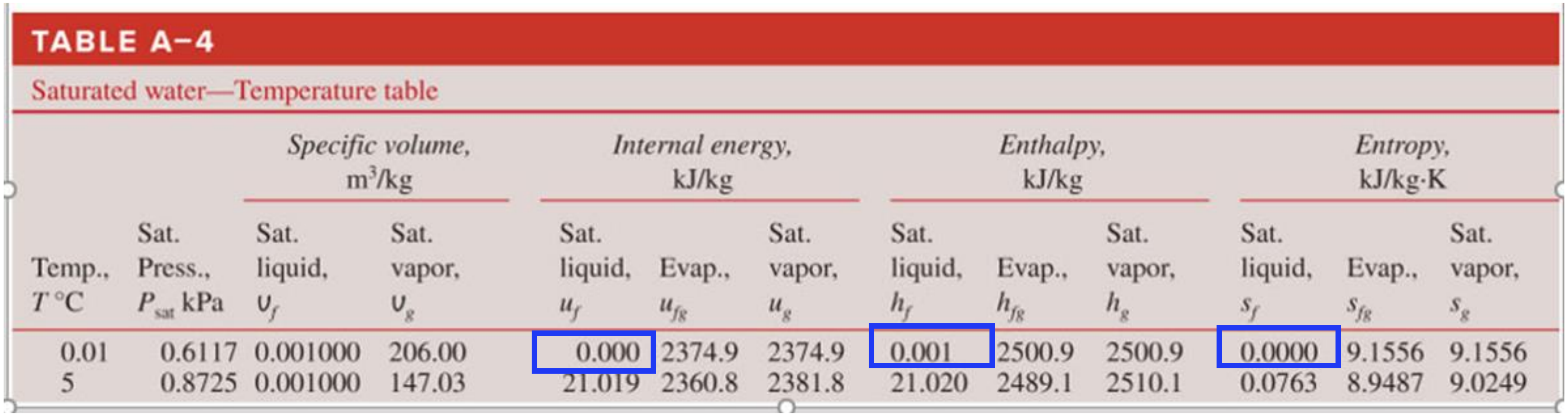


TABLE A–4

Saturated water—Temperature table

		Specific volume, m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg·K		
Temp., T °C	Sat. Press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249

$$h = u + Pv \quad (kJ/kg)$$

3–6 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.

$$Pv = RT$$

Ideal gas equation of state

$$PV = NR_uT$$

3–6 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.

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

$$Pv = RT$$ Ideal gas equation of state

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

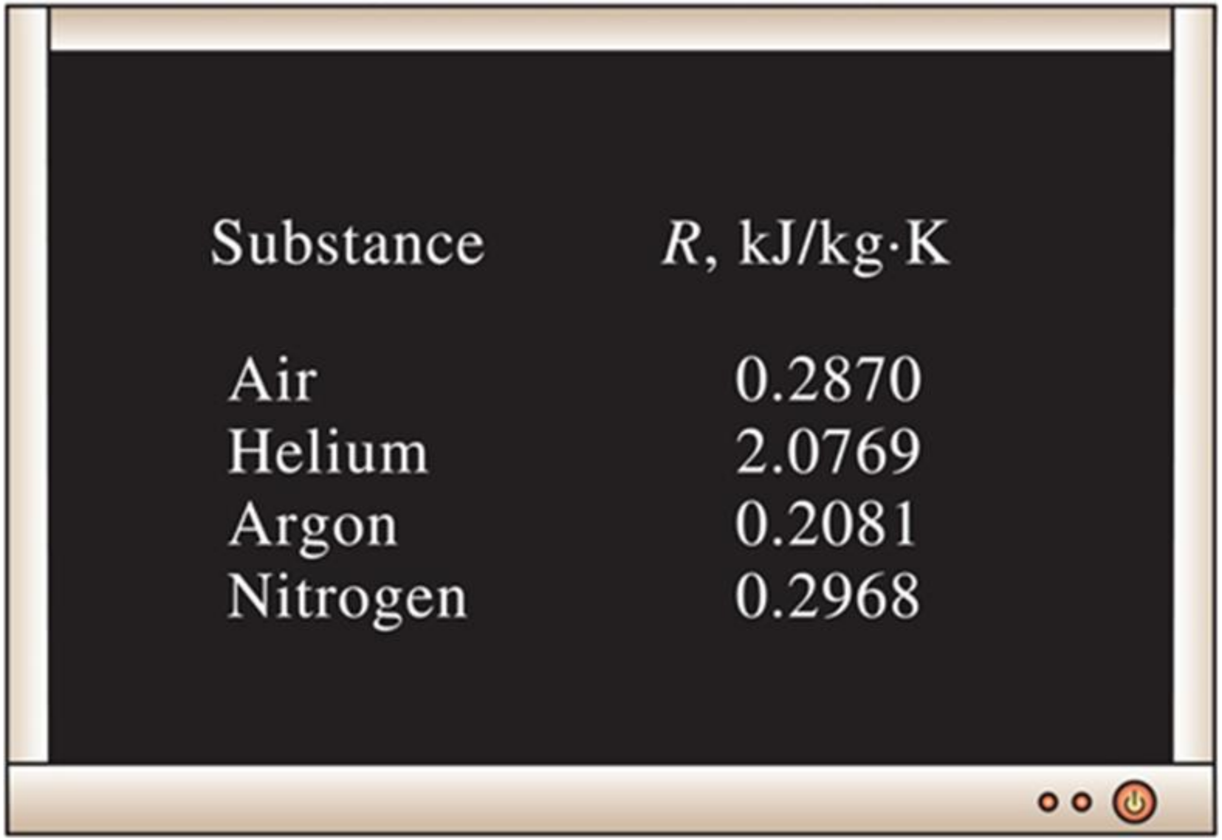
R gas constant

M molar mass (kg/kmol)

R_u universalgas constant

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

3–6 The Ideal-Gas Equation of State



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

Different substances have different gas constants.

3–6 The Ideal-Gas Equation of State

Mass = Molar mass × Mole number

$$m = MN \quad (kg)$$

Various expressions of ideal gas equation

$$\mathrm{V} = m\mathrm{v} \rightarrow P\mathrm{V} = mRT$$

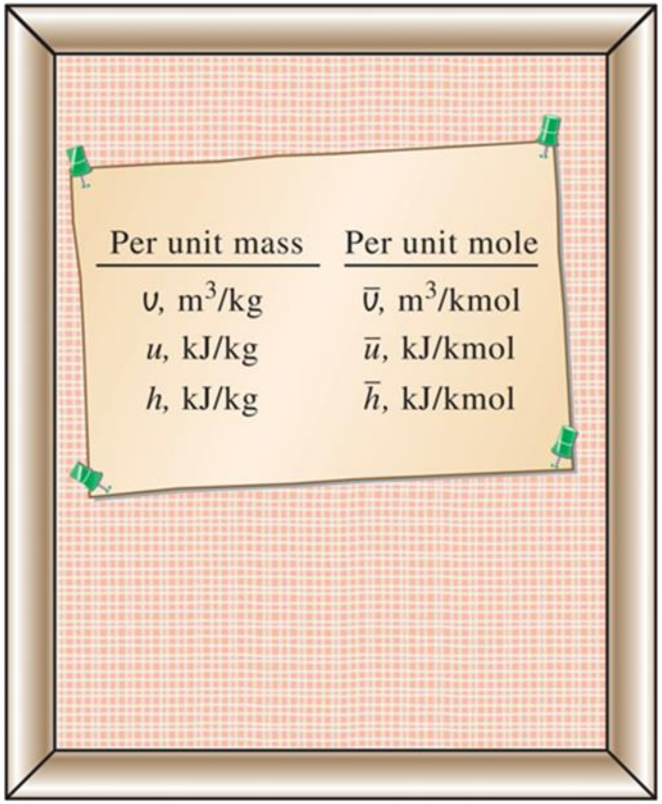
$$mR = (MN)R = NR_u \rightarrow P\mathrm{V} = NR_uT$$

$$\mathrm{V} = N\overline{\mathrm{v}} \rightarrow P\overline{\mathrm{v}} = R_uT$$

$$\frac{P_1\mathrm{V}_1}{T_1} = \frac{P_2\mathrm{V}_2}{T_2}$$

Ideal gas equation at two states for a fixed mass

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



Per unit mass	Per unit mole
v, m^3/kg	$\overline{v}$, m^3/kmol
u, kJ/kg	$\overline{u}$, kJ/kmol
h, kJ/kg	$\overline{h}$, kJ/kmol

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

$\overline{v}$ is the molar specific volume, that is, the volume per unit mole

3–6 The Ideal-Gas Equation of State

Is Water Vapor an Ideal Gas?

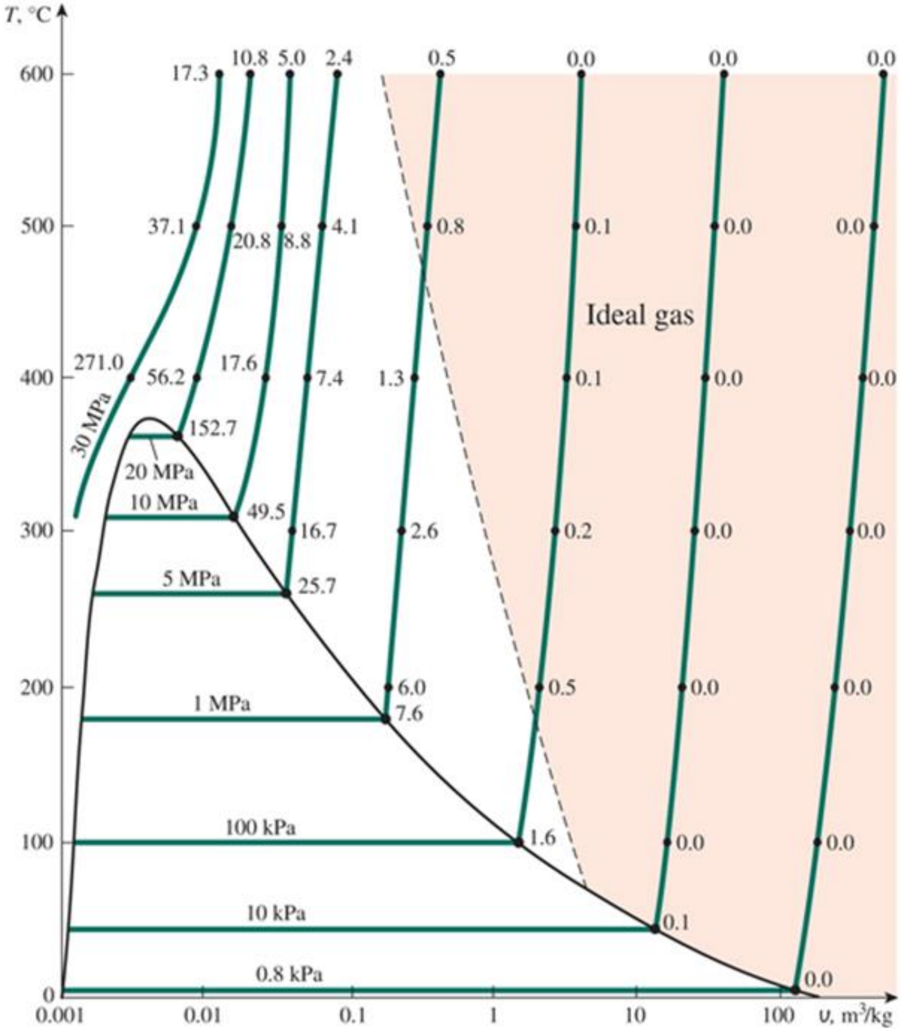
At pressures below 10 kPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent).

At higher pressures, 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.

In steam power plant applications, the pressures involved are usually very high; therefore, ideal-gas relations should not be used.

3–6 The Ideal-Gas Equation of State



Percentage error

$$\left(\left[\frac{\left|V_{\text{table}}-V_{\text{ideal}}\right|}{V_{\text{table}}}\right]\times 100\right)$$

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.

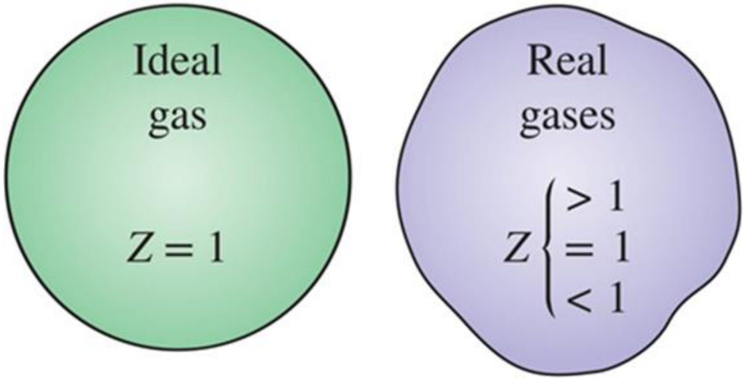
3–7 Compressibility Factor—A Measure of Deviation from Ideal-Gas Behavior

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

$$Z = \frac{PV}{RT}$$

$$PV = ZRT$$

$$Z = \frac{V_{\text{actual}}}{V_{\text{ideal}}}$$



The compressibility factor is unity for ideal gases.

$$V_{\text{ideal}} = \frac{RT}{P}$$

Z = 1 for ideal gases

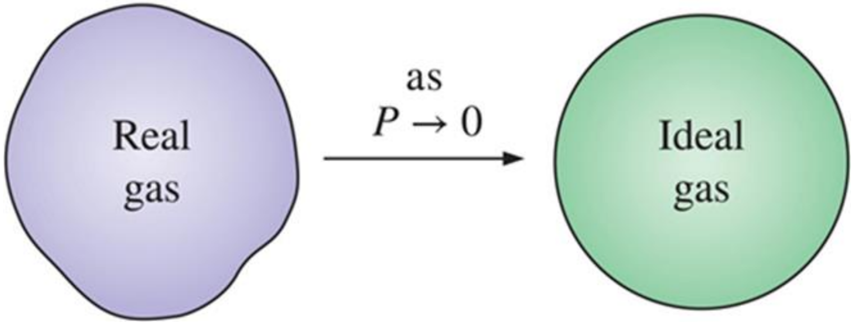
3–7 Compressibility Factor—A Measure of Deviation from Ideal-Gas Behavior

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 (that is low pressure, high temperature).

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

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



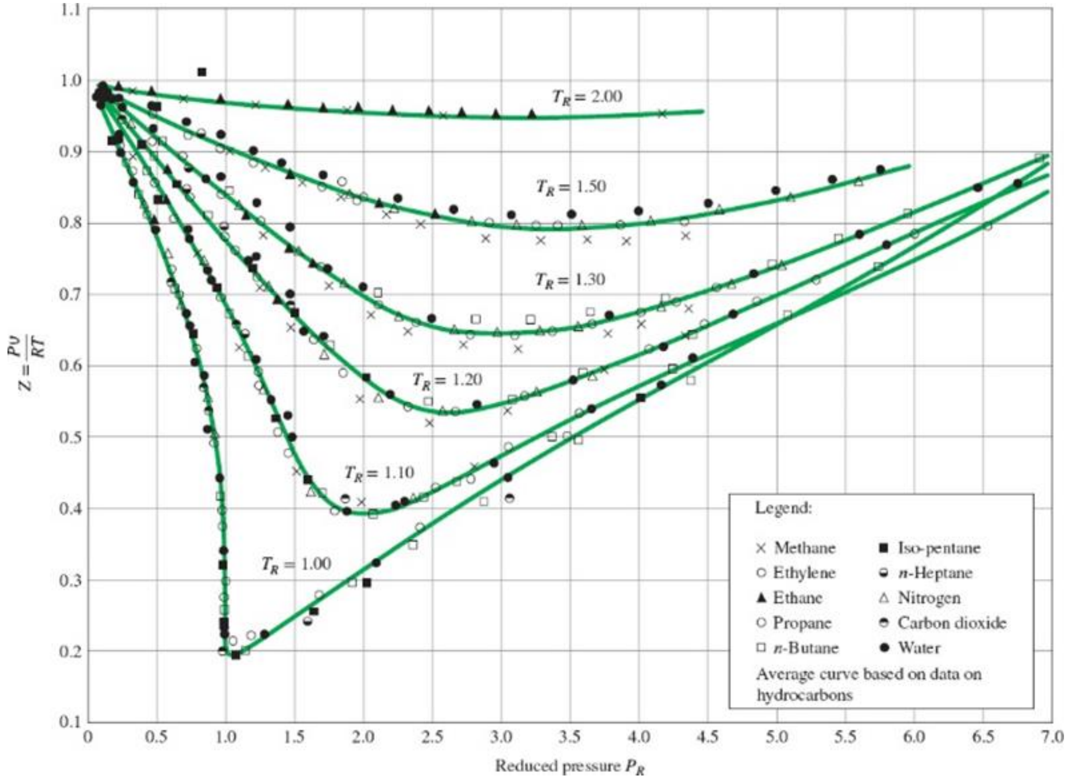
At very low pressures, all gases approach ideal-gas behavior (regardless of their temperature).

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

$$P_R = \frac{P}{P_{\text{cr}}}$$ Reduce pressure

$$T_R = \frac{T}{T_{\text{cr}}}$$ Reduced temperature

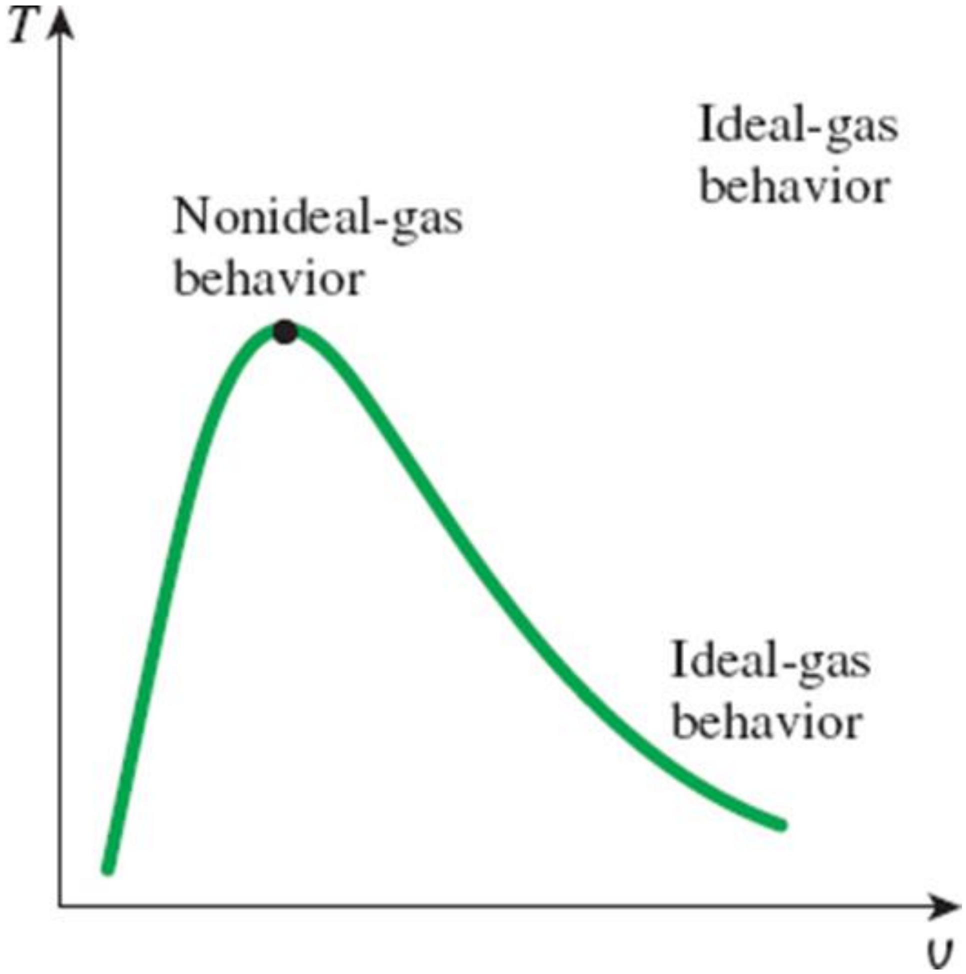
$$v_R = \frac{v_{\text{actual}}}{RT_{\text{cr}} / P_{\text{cr}}}$$ Pseudo-reduced specific volume



Comparison of Z factors for various gases.

Source: Gour-Jen Su, “Modified Law of Corresponding States,” Ind. Eng. Chem. (international ed.) 38 (19 46), p. 803.

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



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

3–8 Other Equations of State

The ideal-gas equation of state is very simple, **but its range of applicability is limited.**

It is desirable to have equations of state that represent the *P*-*v*-*T* behavior of substances accurately over a larger region with no limitations.

Such equations are naturally more complicated.

Several equations have been proposed.

Several equations of state have been proposed throughout history.

3–8 Other Equations of State

van der Waals Equation of State

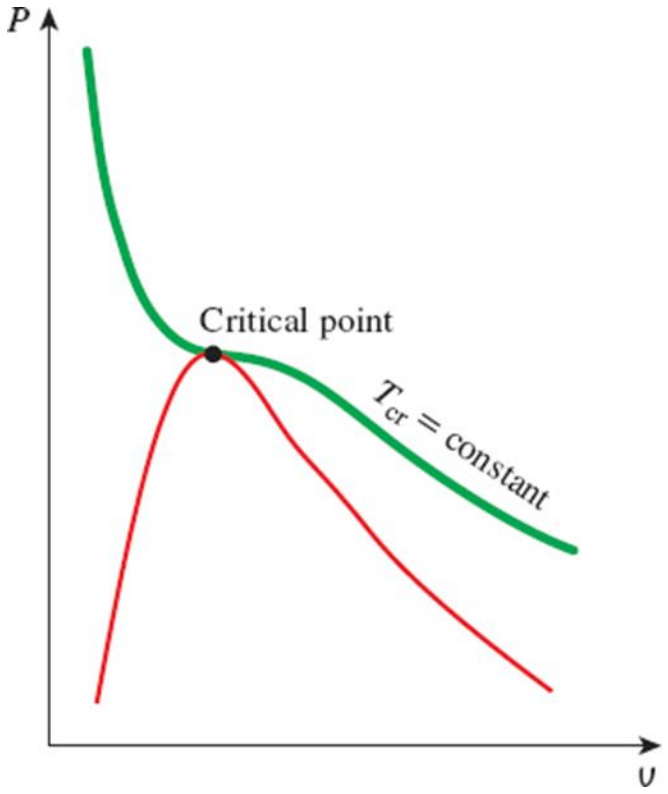
$$\left(P+\frac{a}{\mathrm{v}^2}\right)(\mathrm{v}-b)=RT$$

$$a=\frac{27R^2T^2_{\mathrm{cr}}}{64P_{\mathrm{cr}}} \qquad b=\frac{RT_{\mathrm{cr}}}{8P_{\mathrm{cr}}}$$

This model includes two effects not considered in the ideal-gas model:

- the intermolecular attraction forces.
- 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.

3–8 Other Equations of State

Beattie-Bridgeman Equation of State

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

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

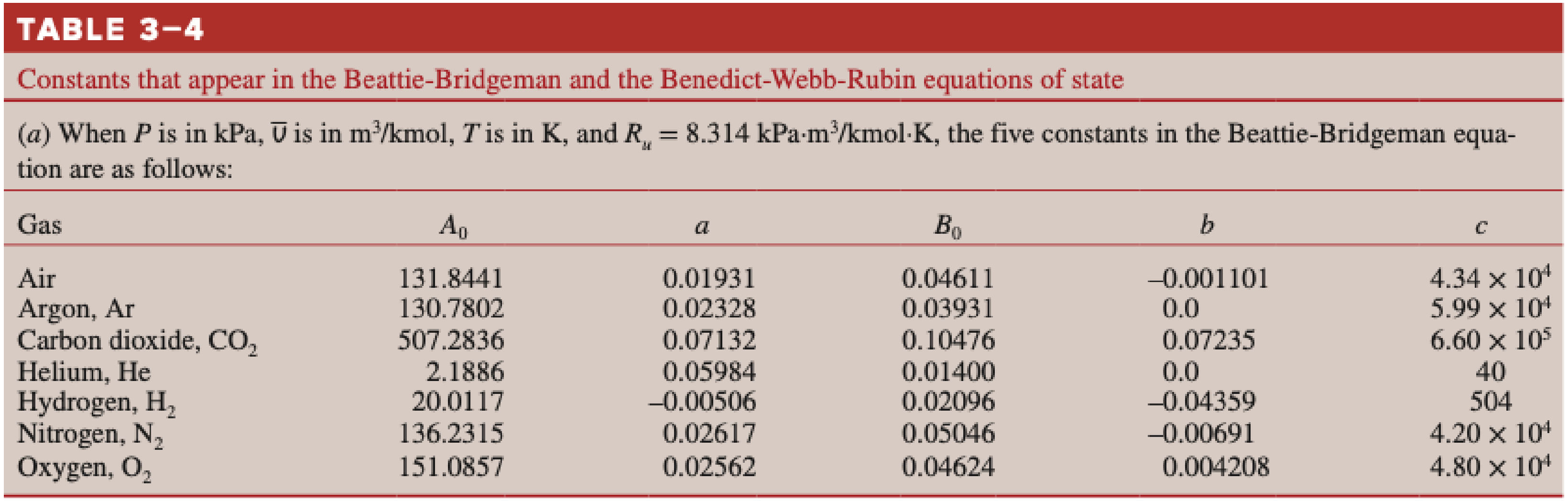


TABLE 3–4

Constants that appear in the Beattie-Bridgeman and the Benedict-Webb-Rubin equations of state

(*a*) When P is in kPa, $\overline{v}$ is in m^3/kmol, T is in K, and $R_u = 8.314$ kPa·m^3/kmol·K, the five constants in the Beattie-Bridgeman equation are as follows:

Gas	A_0	a	B_0	b	c
Air	131.8441	0.01931	0.04611	–0.001101	4.34×10^4
Argon, Ar	130.7802	0.02328	0.03931	0.0	5.99×10^4
Carbon dioxide, CO_2	507.2836	0.07132	0.10476	0.07235	6.60×10^5
Helium, He	2.1886	0.05984	0.01400	0.0	40
Hydrogen, H_2	20.0117	–0.00506	0.02096	–0.04359	504
Nitrogen, N_2	136.2315	0.02617	0.05046	–0.00691	4.20×10^4
Oxygen, O_2	151.0857	0.02562	0.04624	0.004208	4.80×10^4

3–8 Other Equations of State

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.

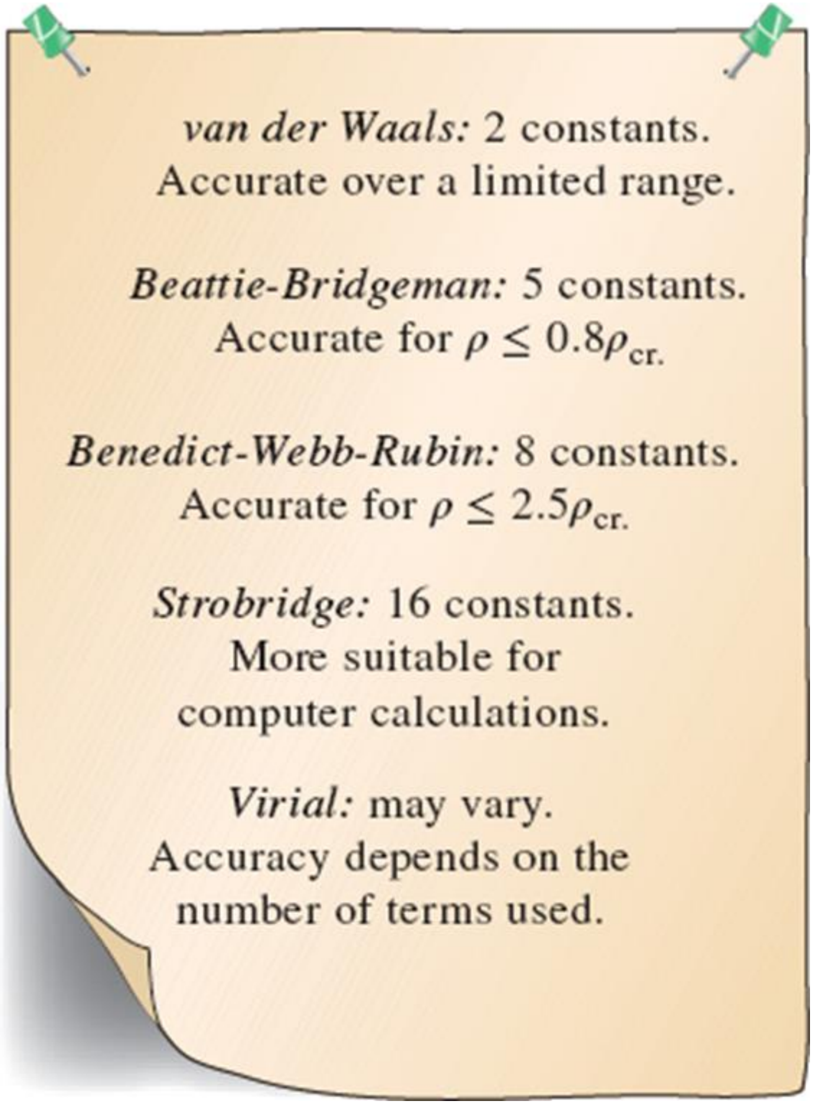
This equation can handle substances at densities up to about $2.5\rho_{cr}$.

Virial Equation of State

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

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

3–8 Other Equations of State



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.

4–1 Moving Boundary Work

Moving boundary work (*P dV* work): The expansion and compression work in a piston-cylinder device.

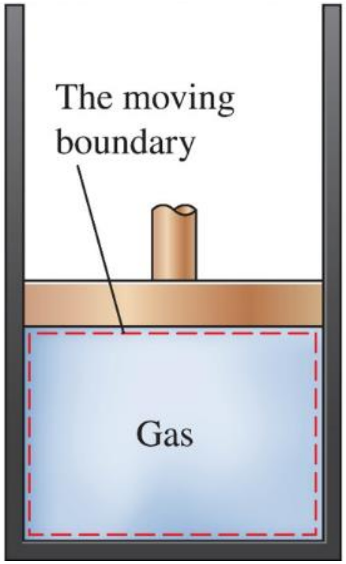
$$\delta W_b = F ds = PA ds = P d\text{V}$$

$$W_b = \int_1^2 p d\text{V} \quad (\text{kJ})$$

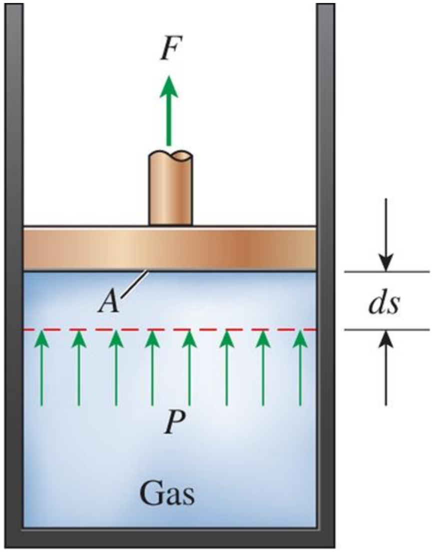
Quasi-equilibrium process: A process during which the system remains nearly in equilibrium at all times.

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.

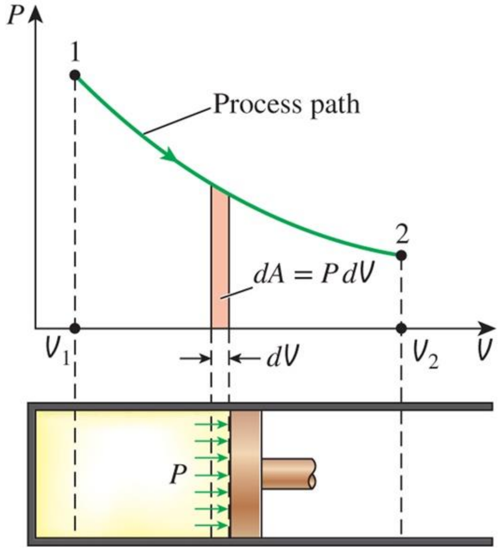


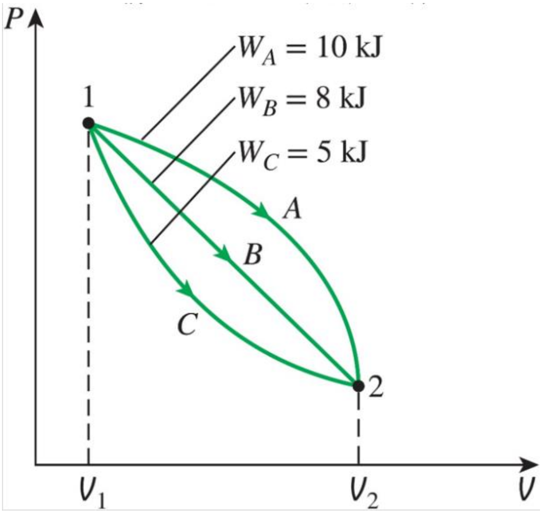
A gas does a differential amount of work

δW_b as it forces

the piston to move by a differential amount *ds*.

4–1 Moving Boundary Work





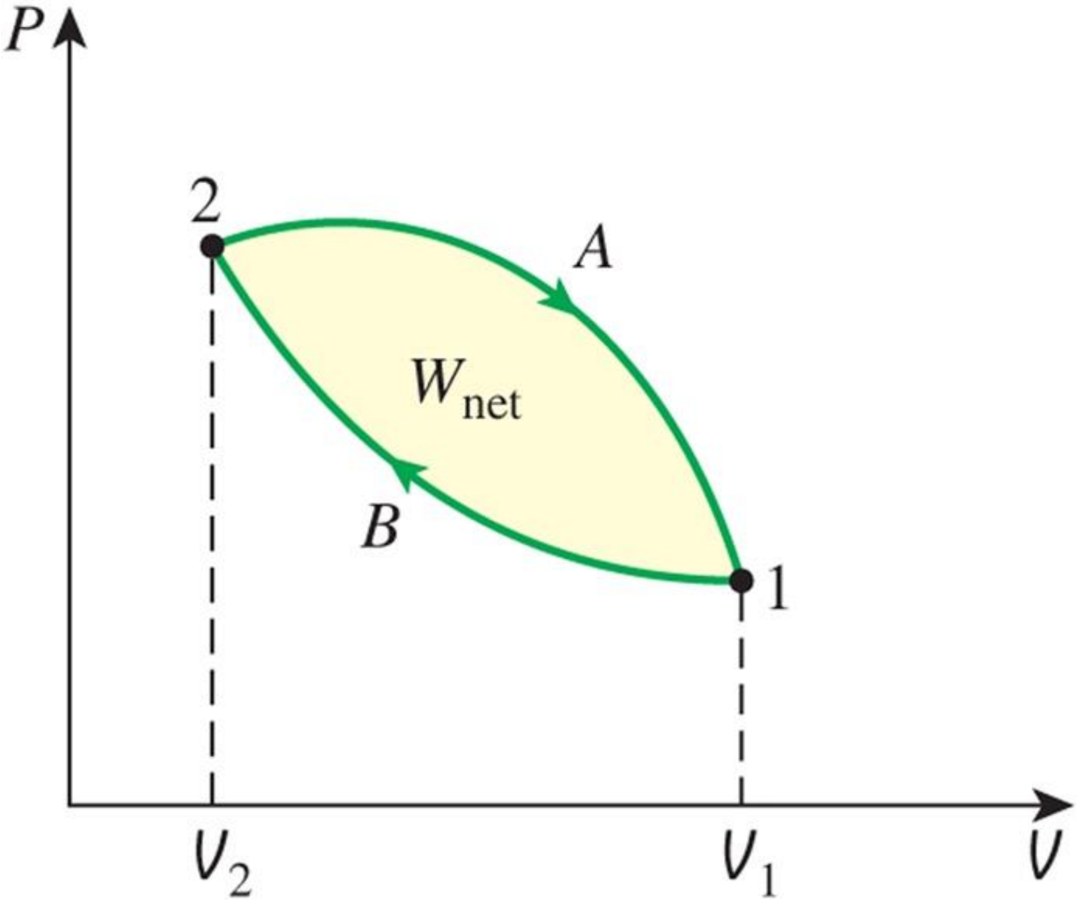
The area under the process curve on a *P*-*V* diagram represents the boundary work.

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

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

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.

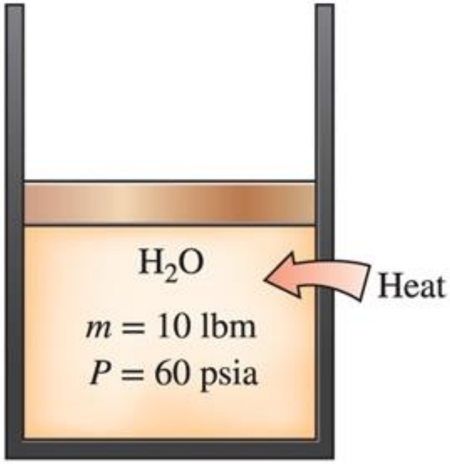
4–1 Moving Boundary Work

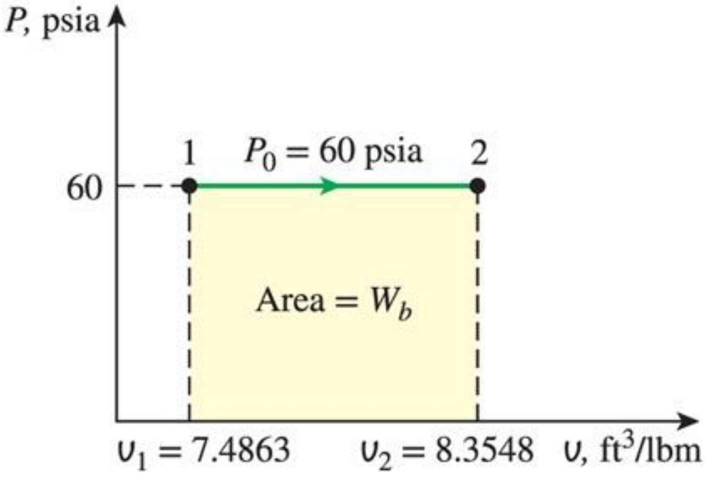


The net work done during a cycle is the difference between the work done by the system and the work done on the system.

4–1 Moving Boundary Work

Boundary Work for a Constant-Pressure Process (Piston)





$$W_b = \int_1^2 P_i \, d\mathrm{V}$$

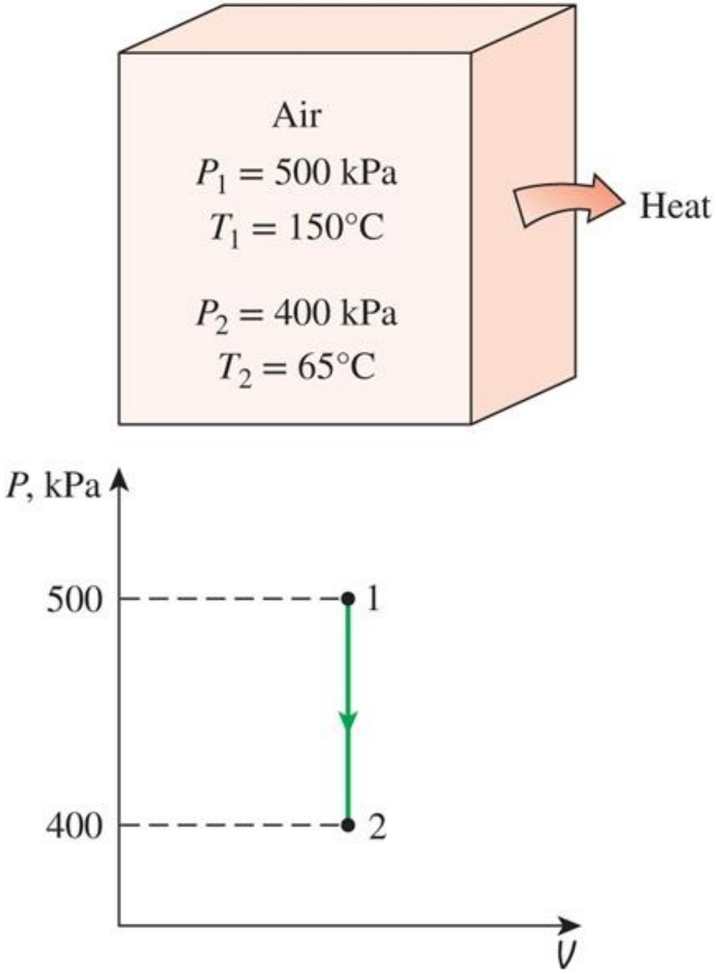
$$= P_0 \int_1^2 d\mathrm{V}$$

$$= P_0 \left(\mathrm{V}_2 - \mathrm{V}_1\right)$$

$$= mP_0 \left(\mathrm{V}_2 - \mathrm{V}_1\right)$$

4–1 Moving Boundary Work

Boundary Work for a Constant-Volume Process (Rigid container)



$$W_b = \int_1^2 P\, \cancelto{0}{dV} = \mathbf{0}$$

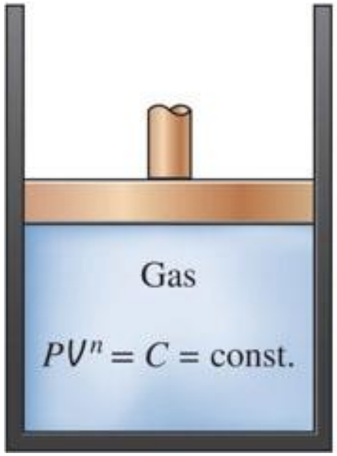
4–1 Moving Boundary Work

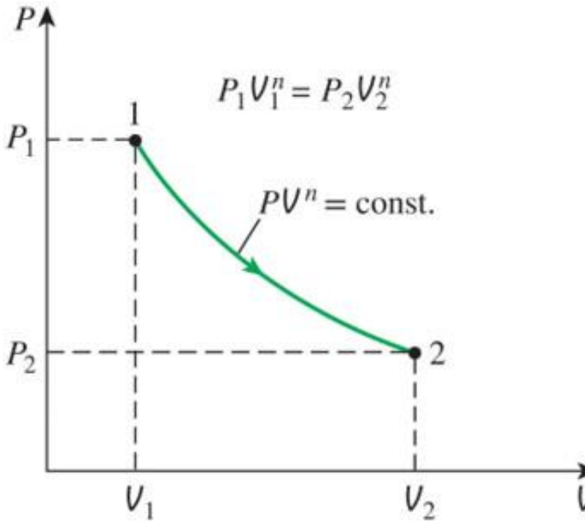
Boundary Work for a Polytropic Process

$$PV^{n} = C \qquad P = CV^{-n} = C$$

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$

$$W_b = \frac{mR\left(T_2 - T_1\right)}{1-n} \quad n \neq 1 \text{ (kJ)}$$ For ideal gas





4–2 Energy Balance for Closed Systems

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

Energy balance for any system undergoing any process

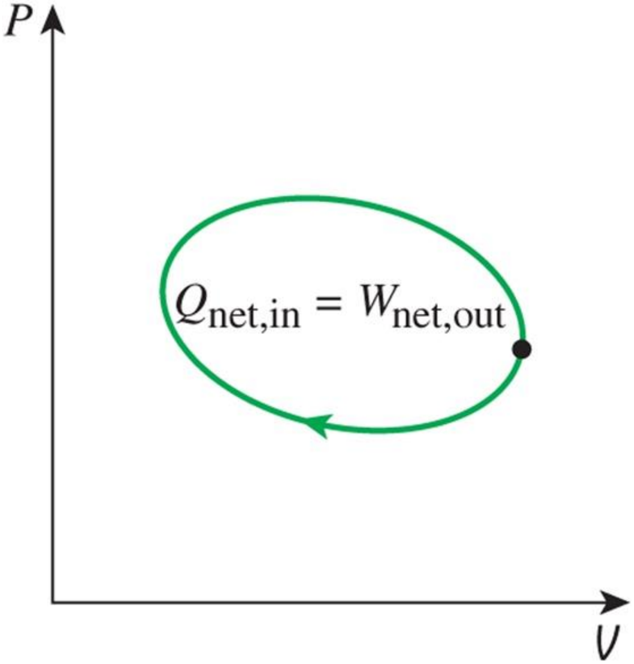
$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt}_{\substack{\text{Rate of change in internal,} \\ \text{kinetic, potential, etc., energies}}} \qquad \text{(kW)}$$

Energy balance in the **rate form**

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

4–2 Energy Balance for Closed Systems

$W_{\text{net,out}} = Q_{\text{net,in}}$ or $\dot{W}_{\text{net,out}} = \dot{Q}_{\text{net,in}}$ (for a cycle)



For a cycle $\Delta E = 0$, thus net heat input is equal to net work output.

4–2 Energy Balance for Closed Systems

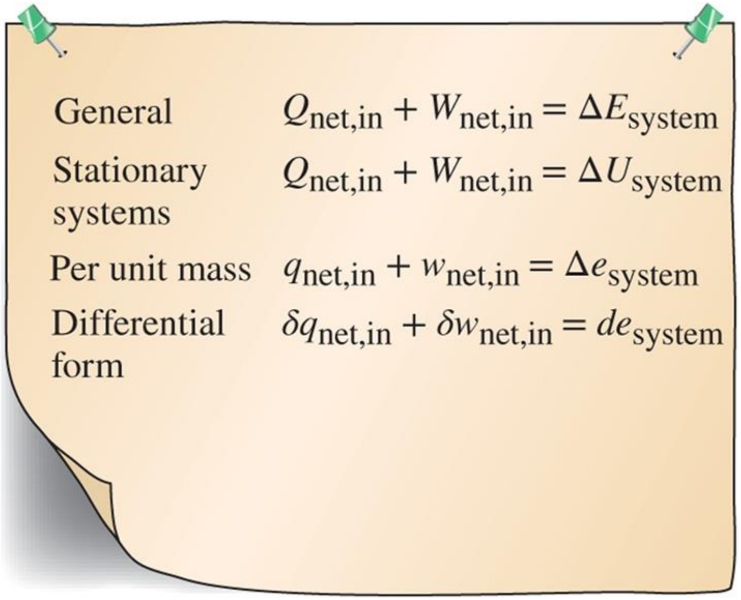
$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}}$$

$$(Q_{\text{in}} + W_{\text{in}}) - (Q_{out} + W_{\text{out}}) = \Delta U + \Delta KE + \Delta PE$$

$$Q_{\text{net,in}} + W_{\text{net,in}} = \Delta U + \Delta KE + \Delta PE$$

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

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



General	$Q_{\text{net,in}} + W_{\text{net,in}} = \Delta E_{\text{system}}$
Stationary systems	$Q_{\text{net,in}} + W_{\text{net,in}} = \Delta U_{\text{system}}$
Per unit mass	$q_{\text{net,in}} + w_{\text{net,in}} = \Delta e_{\text{system}}$
Differential form	$\delta q_{\text{net,in}} + \delta w_{\text{net,in}} = de_{\text{system}}$

Various forms of the first-law relation for closed systems.

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.

4–2 Energy Balance for Closed Systems

Constant-Pressure Processes of Closed Systems

For a constant-pressure expansion or compression process:

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

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

$$\left(Q_{\text{in}} + Q_{\text{in}}\right) - \left(Q_{\text{out}} + W_{\text{out}}\right) = \Delta U + \Delta KE + \Delta PE$$

$$Q_{\text{net,in}} + W_{\text{net , in}} = \Delta U + \Delta KE + \Delta PE$$

$$Q_{\text{net,in}} + W_{\text{net other, in}} - W_{\text{b,out}} = \Delta U + \Delta KE + \Delta PE$$

$$W_{\text{b}} = W_{\text{b,out}} = P\left(\mathrm{V}_2 - \mathrm{V}_1\right) = P_2\mathrm{V}_2 - P_1\mathrm{V}_1$$

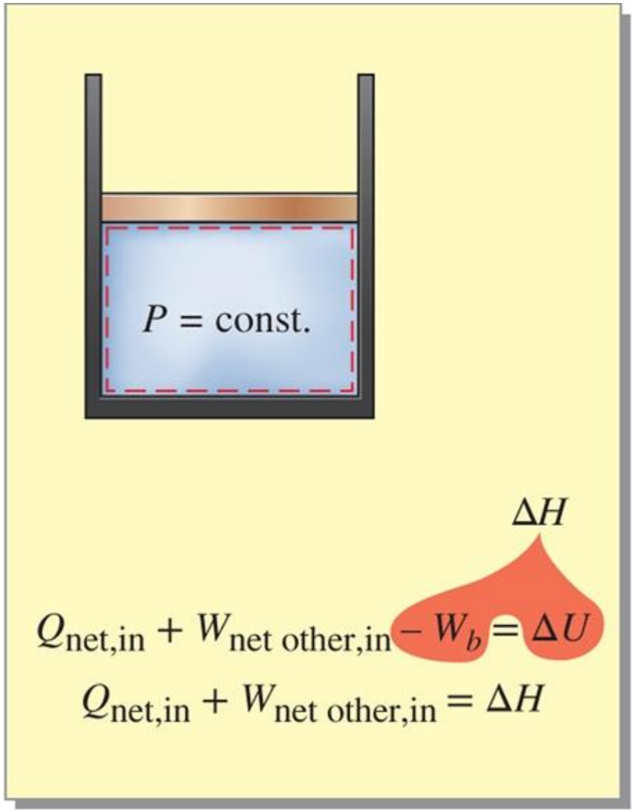
$$P_0 = P_2 = P_1 \rightarrow Q_{\text{net,in}} + W_{\text{net other,in}} = \left(U_2 + P_2\mathrm{V}_2\right) - \left(U_1 + P_1\mathrm{V}_1\right) + \Delta KE + \Delta PE$$

$$H = U + P\mathrm{V}$$

$$\left(U_2 + P_2\mathrm{V}_2\right) - \left(U_1 + P_1\mathrm{V}_1\right) = H_2 - H_1$$

$$Q_{\text{net,in}} + W_{\text{net other,in}} = \Delta H + \Delta KE + \Delta PE$$

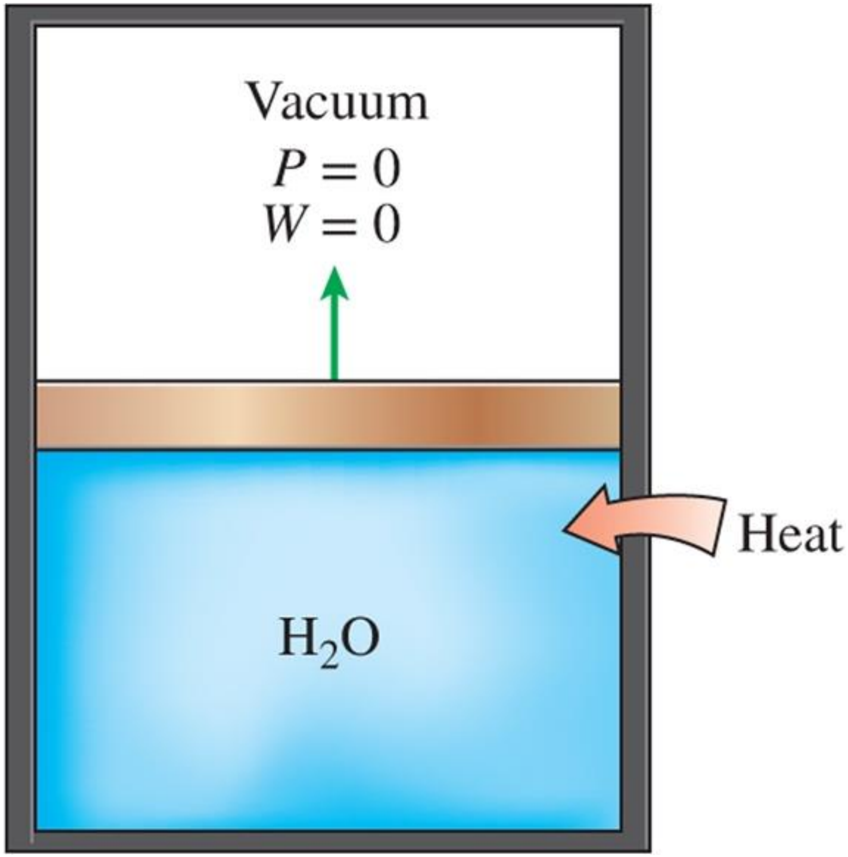
4–2 Energy Balance for Closed Systems



For a closed system undergoing a quasi-equilibrium, *P* = constant process, $\Delta U + W_b = \Delta H$.

Note that this relation is NOT valid for closed systems processes during which pressure DOES NOT remain constant.

4–2 Energy Balance for Closed Systems



Expansion against a vacuum involves no work

가톨릭대학교
THE CATHOLIC UNIVERSITY OF KOREA

Energy balance and thermodynamics

Kangmin Lee
Dept. of Energy and Environmental Engineering

4–1 Moving Boundary Work

Moving boundary work (*P dV* work): The expansion and compression work in a piston-cylinder device.

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

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

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W_b is positive $\rightarrow$ for expansion

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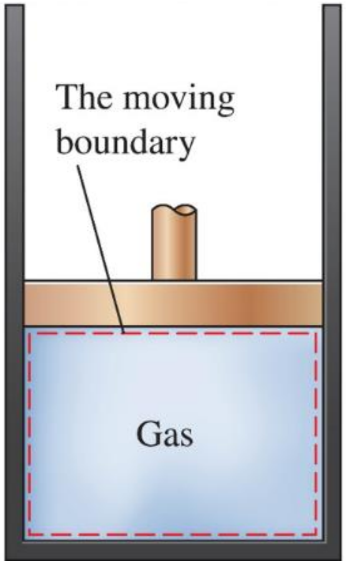
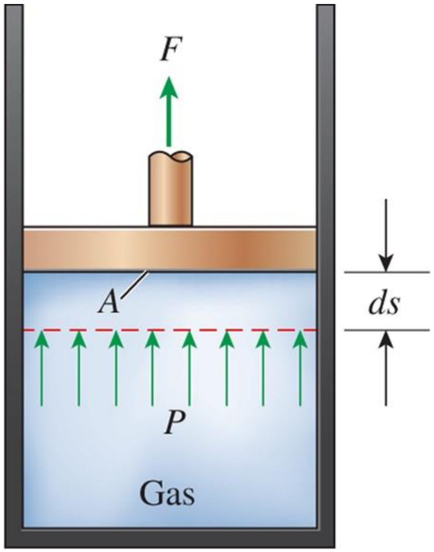
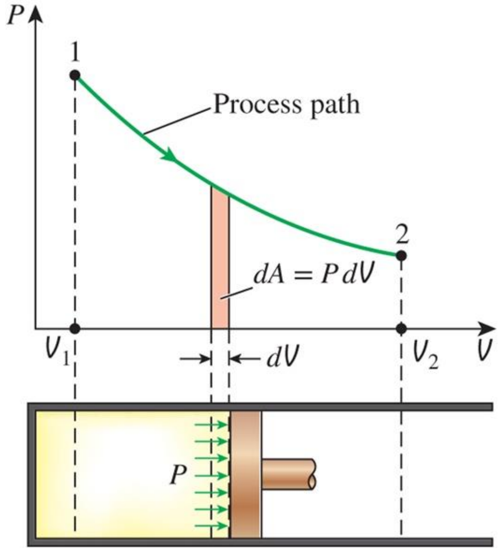


The work associated with a moving boundary is called boundary work.



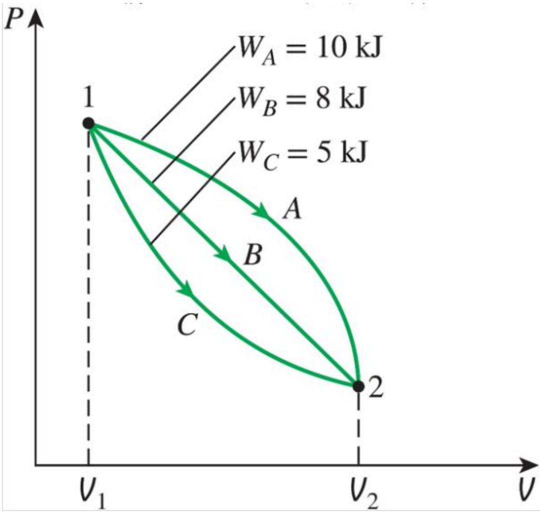
A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*.

4–1 Moving Boundary Work



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

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



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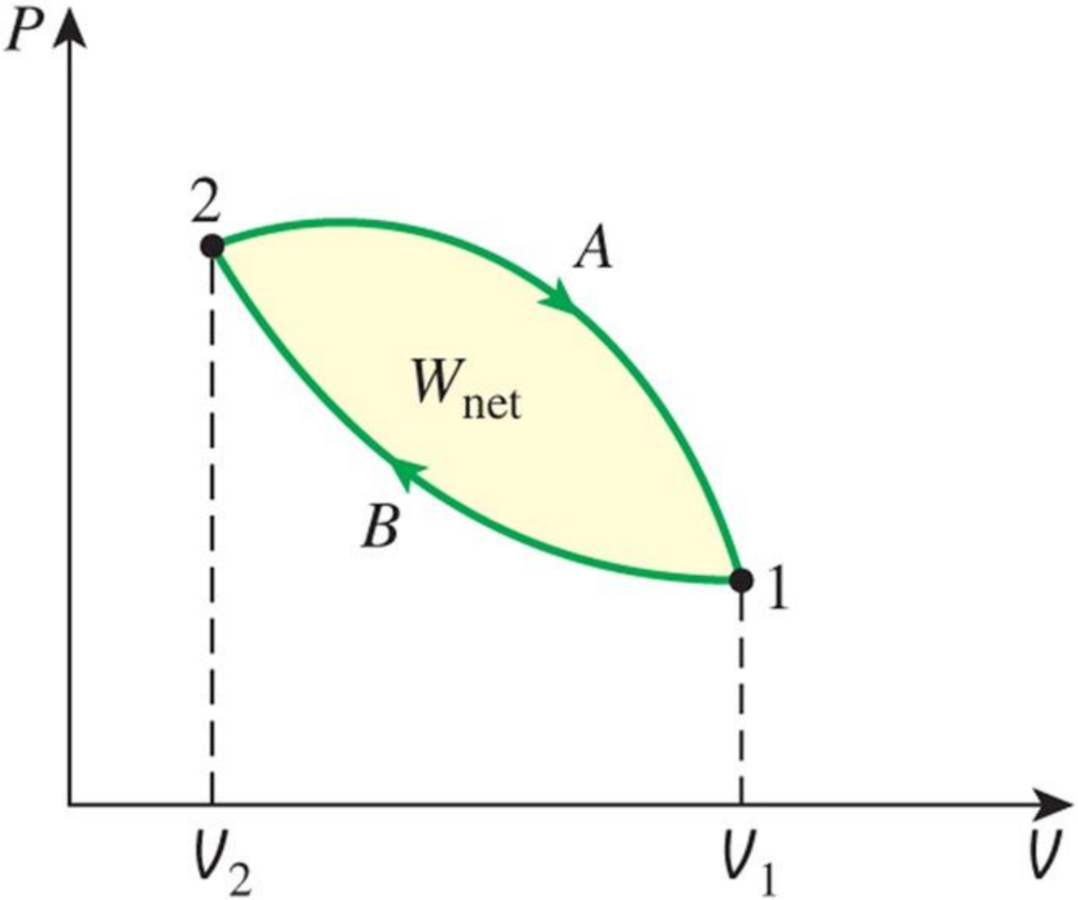
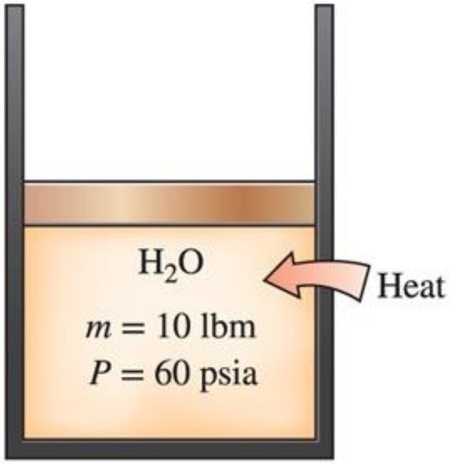
4–1 Moving Boundary Work

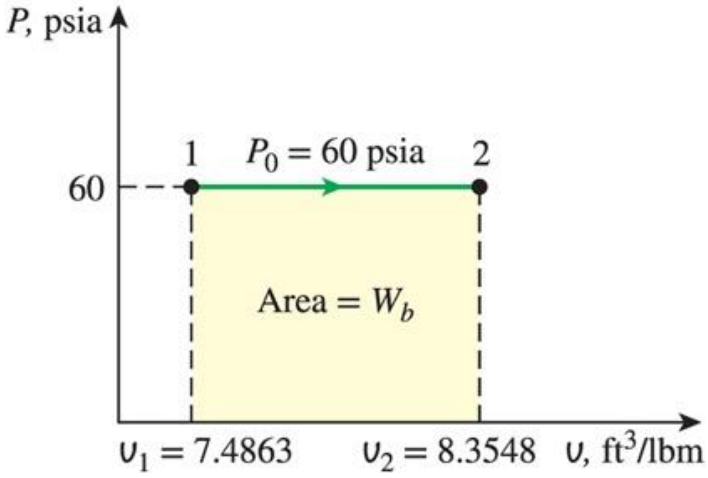


The net work done during a cycle is the difference between the work done by the system and the work done on the system.

4–1 Moving Boundary Work

Boundary Work for a Constant-Pressure Process (Piston)





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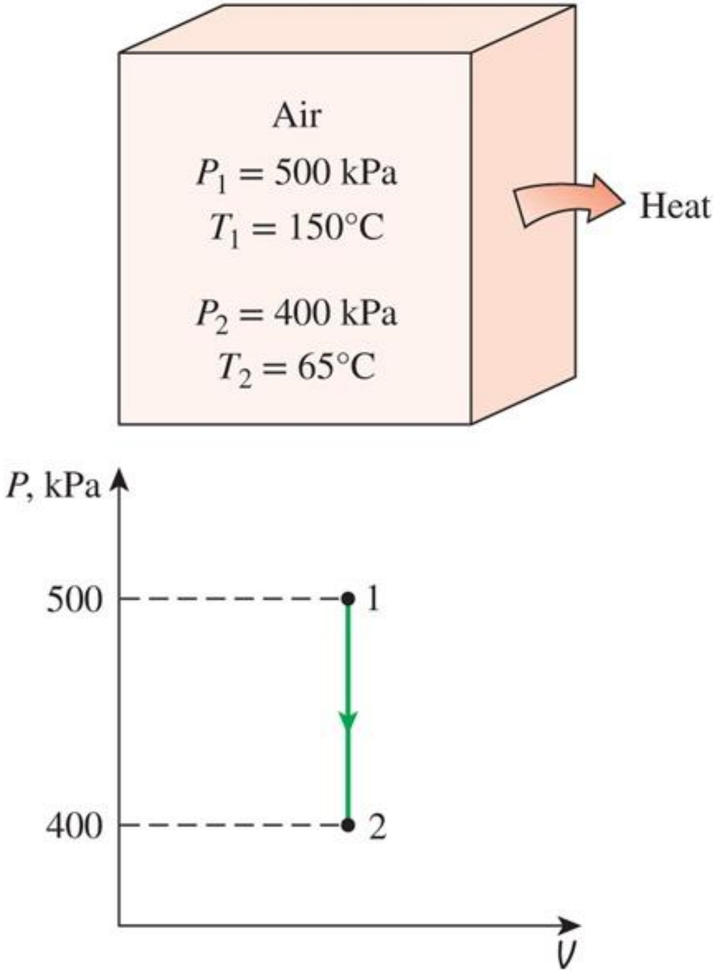
4–1 Moving Boundary Work

Boundary Work for a Constant-Volume Process (Rigid container)



$$W_b = \int_1^2 P \, \overset{0}{\cancel{d\mathcal{V}}} = \mathbf{0}$$

4–1 Moving Boundary Work

Boundary Work for a Polytropic Process

$PV^{n} = C$ $\quad$ $P = CV^{-n} = C$

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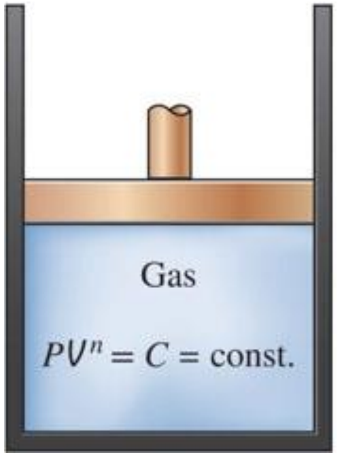

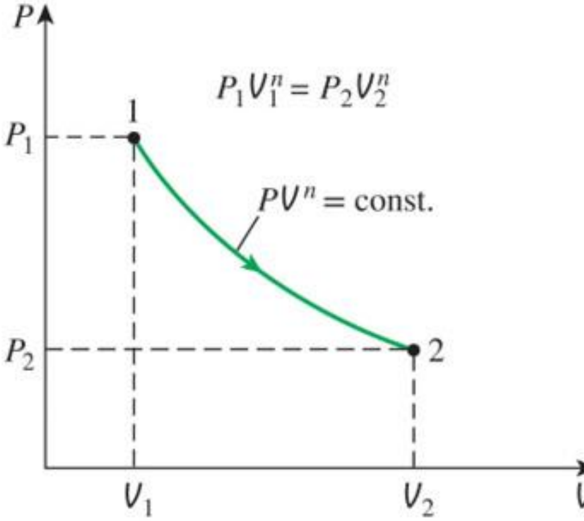

4–2 Energy Balance for Closed Systems

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

Energy balance for any system undergoing any process

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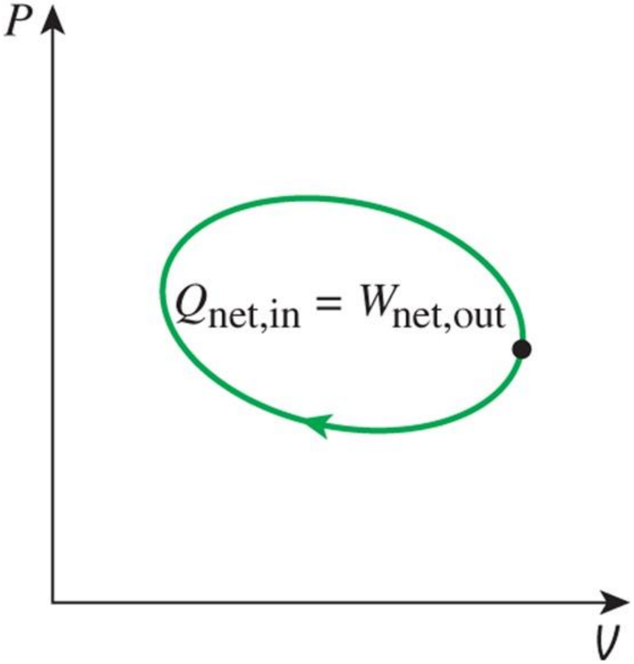
Energy balance in the **rate form**

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

4–2 Energy Balance for Closed Systems

$W_{\text{net,out}} = Q_{\text{net,in}}$ or $\overset{g}{W}_{\text{net,out}} = \overset{g}{Q}_{\text{net,in}}$ (for a cycle)



For a cycle $\Delta E = 0,$ thus net heat input is equal to net work output.

4–2 Energy Balance for Closed Systems

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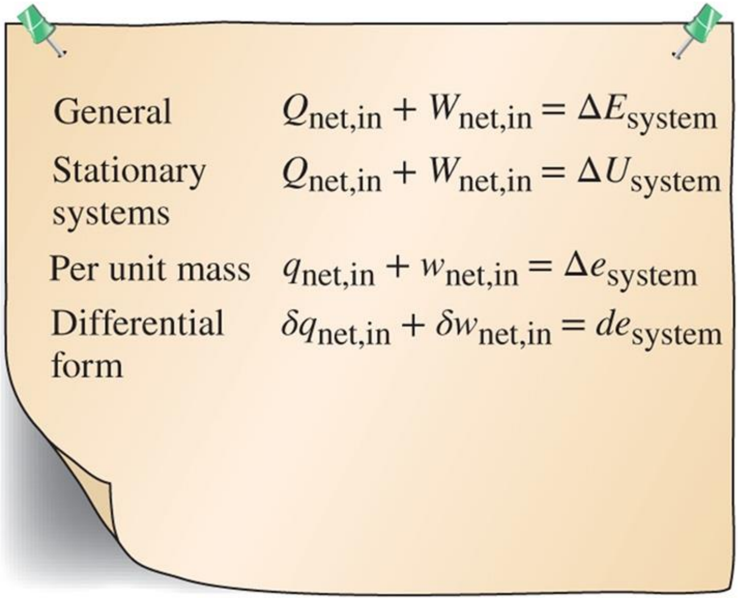
$$Q_{\text{net,in}} + W_{\text{net,in}} = \Delta U + \Delta KE + \Delta PE$$

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

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



General	$Q_{\text{net,in}} + W_{\text{net,in}} = \Delta E_{\text{system}}$
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Constant-Pressure Processes of Closed Systems

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$$Q_{\text{net,in}} + W_{\text{net , in}} = \Delta U + \Delta KE + \Delta PE$$

$$Q_{\text{net,in}} + W_{\text{net other, in}} - W_{\text{b,out}} = \Delta U + \Delta KE + \Delta PE$$

$$W_{\text{b}} = W_{\text{b,out}} = P\left(\mathrm{V}_2 - \mathrm{V}_1\right) = P_2\mathrm{V}_2 - P_1\mathrm{V}_1$$

$$P_0 = P_2 = P_1 \rightarrow Q_{\text{net,in}} + W_{\text{net other,in}} = \left(U_2 + P_2\mathrm{V}_2\right) - \left(U_1 + P_1\mathrm{V}_1\right) + \Delta KE + \Delta PE$$

$$H = U + P\mathrm{V}$$

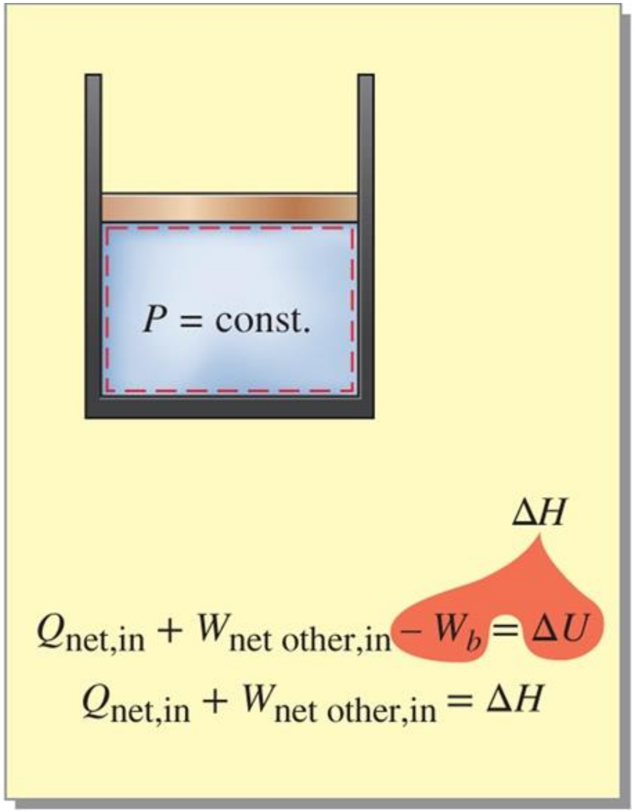
$$\left(U_2 + P_2\mathrm{V}_2\right) - \left(U_1 + P_1\mathrm{V}_1\right) = H_2 - H_1$$

$$Q_{\text{net,in}} + W_{\text{net other,in}} = \Delta H + \Delta KE + \Delta PE$$

For a constant-pressure expansion or compression process:

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

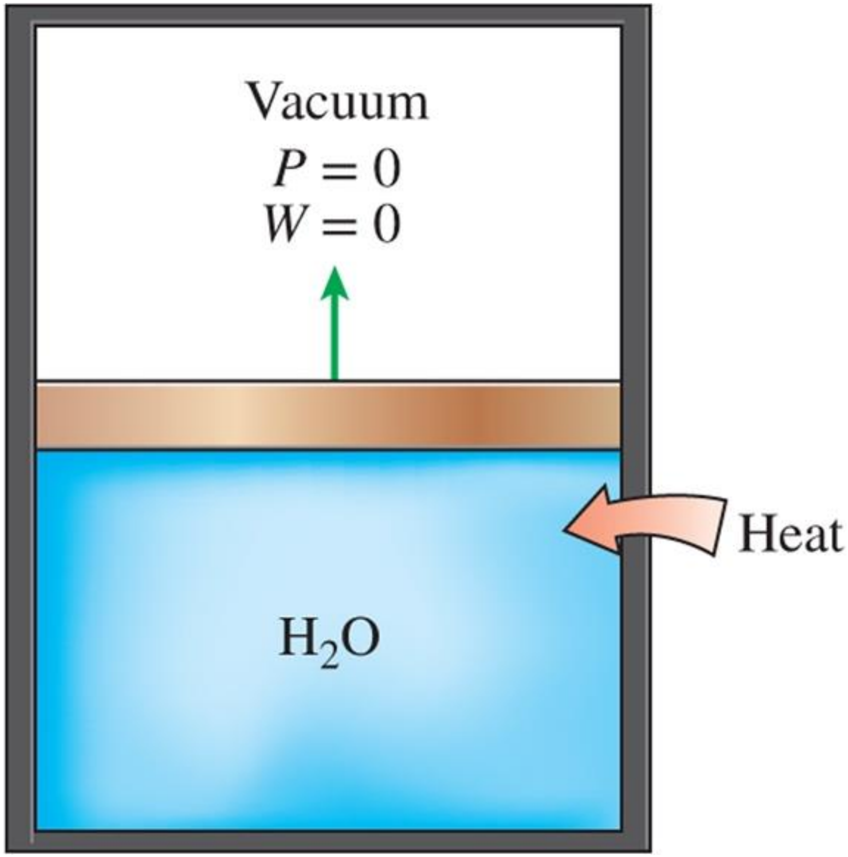
4–2 Energy Balance for Closed Systems



For a closed system undergoing a quasi-equilibrium, *P* = constant process, $\Delta U + W_b = \Delta H$.

Note that this relation is NOT valid for closed systems processes during which pressure DOES NOT remain constant.

4–2 Energy Balance for Closed Systems

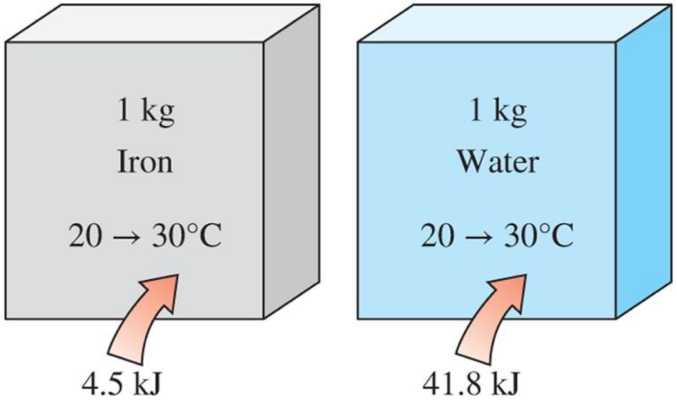


Expansion against a vacuum involves no work

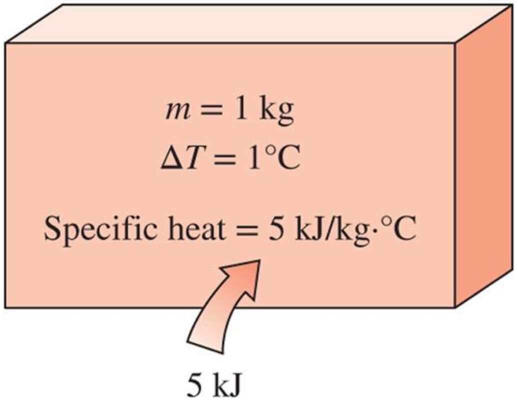
4–3 Specific Heats

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.**

$$\text{kJ/kg·°C} \quad \text{or} \quad \text{kJ/kg·K}$$



It takes different amounts of energy to raise the temperature of different substances by the same amount.

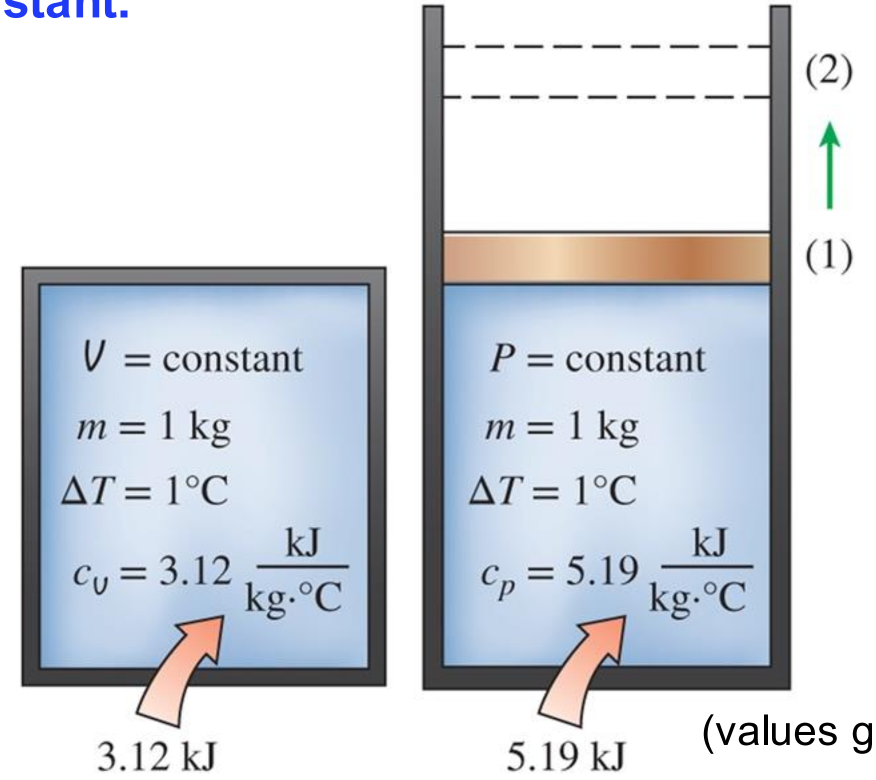


Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

4–3 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.**



$c_p > c_v$

(values given are for helium gas).

4–3 Specific Heats

Consider a fixed mass in a **stationary closed system** undergoing a constant-volume process

1.

$$C_v = \frac{\text{kJ}}{\text{kg} \cdot {}^\circ C}$$

2.

$$\Delta E = m \cdot C_v \cdot \Delta T$$

$$\left[\text{kJ} = \text{kg} \times \frac{\text{kJ}}{\text{kg} \cdot {}^\circ C} \times {}^\circ C\right]$$

-

4–3 Specific Heats

3.

On a per–unit–mass basis:

$$\Delta e = C_v \cdot \Delta T$$

$$\left[\frac{\mathrm{kJ}}{\mathrm{kg}} = \frac{\mathrm{kJ}}{\mathrm{kg} \cdot {}^{\circ}C} \times {}^{\circ}C\right]$$

4.

In differential form (for an infinitesimal process):

$$\Delta e = \Delta u + \cancel{\Delta ke} + \cancel{\Delta pe}$$

$$du = C_v \, dT$$

This applies to a **constant-volume process**.

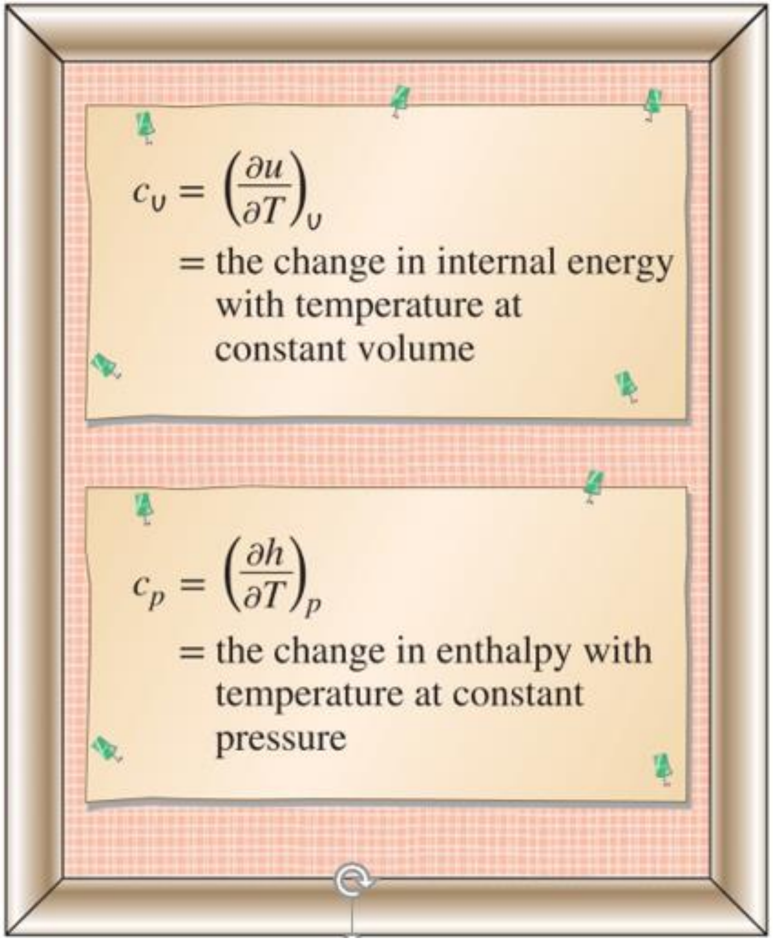
5.

Hence, the formal definition of specific heat at constant volume is:

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

4–3 Specific Heats

Consider a fixed mass in a **stationary closed system** undergoing a constant-volume process



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

= 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

c_v is related to the changes in *internal energy* and

c_p to the changes in *enthalpy*.

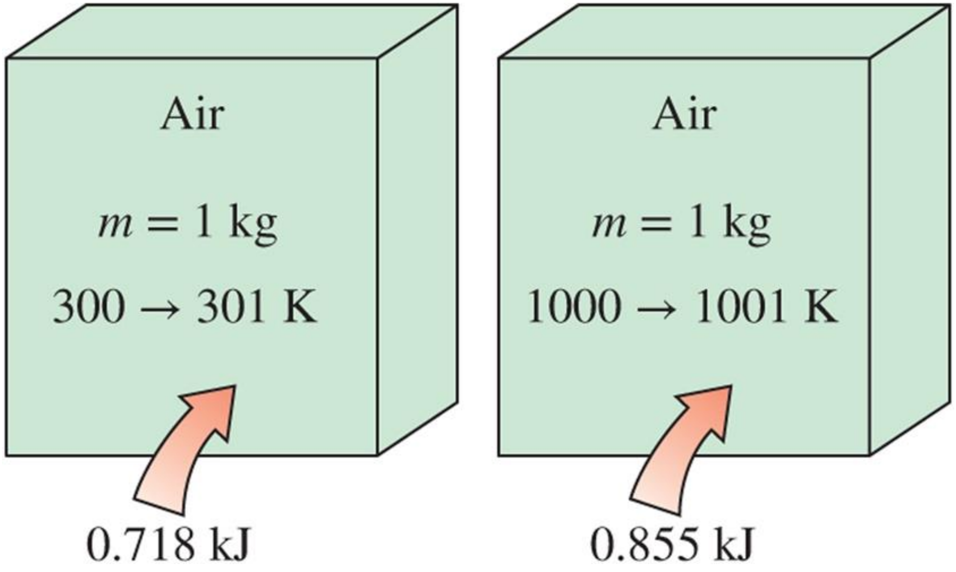
4–3 Specific Heats

c_v and c_p are properties.

The specific heats of a substance depend on the state.

The energy required to raise the temperature of a substance by one degree is different at different temperatures and pressures.

A common unit for specific heats is kJ/kg·°C or kJ/kg·K.



The specific heat of a substance changes with temperature.

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

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

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

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

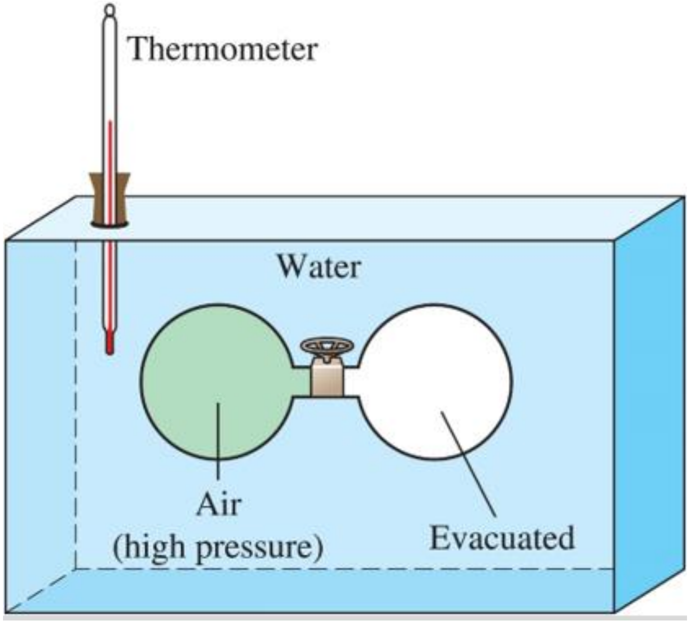
$$du = c_v(T)dT$$

$$dh = c_p(T)dT$$

Internal energy and enthalpy change of an ideal gas

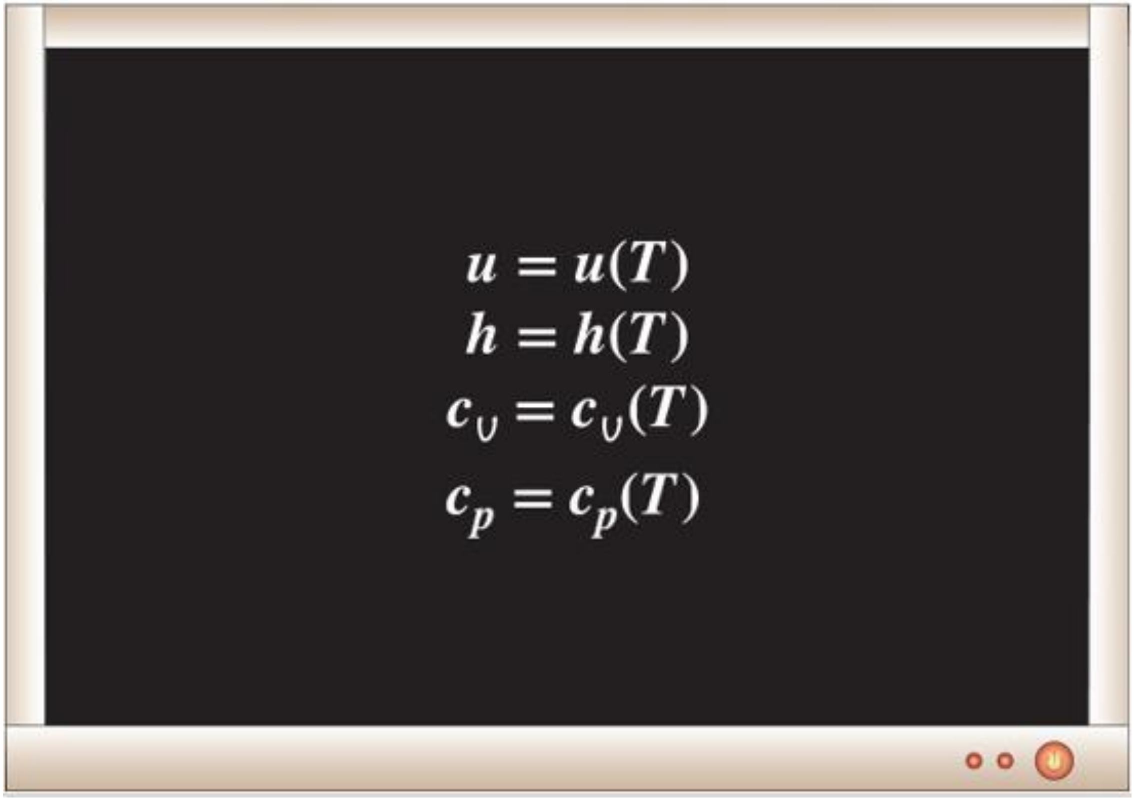
$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)dT \quad \text{(kJ/kg)}$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)dT \quad \text{(kJ / kg)}$$



Schematic of the experimental apparatus used by Joule.

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



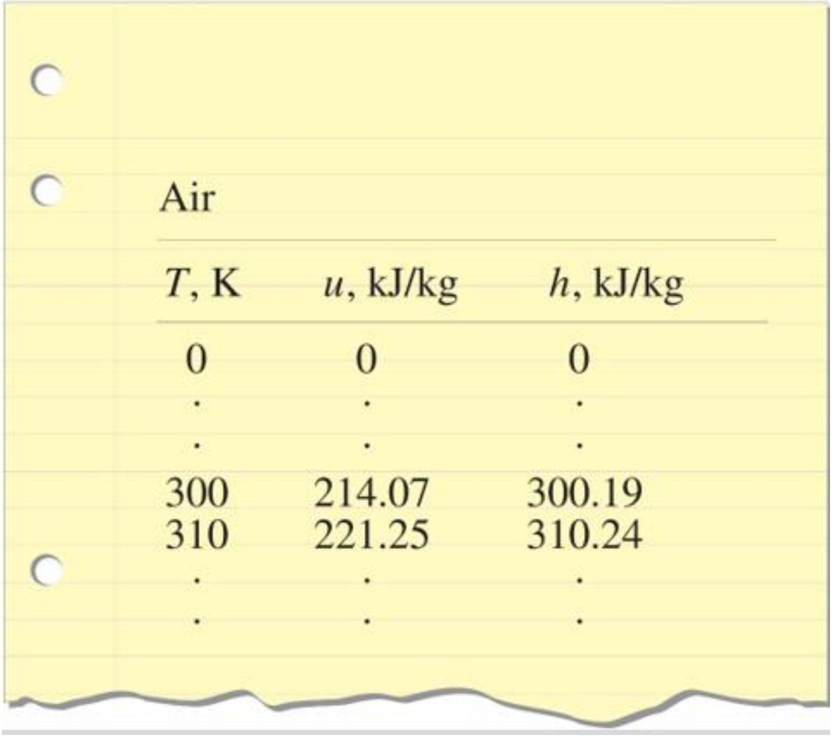
$$u = u(T)$$
$$h = h(T)$$
$$c_v = c_v(T)$$
$$c_p = c_p(T)$$

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

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

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}.



Air

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

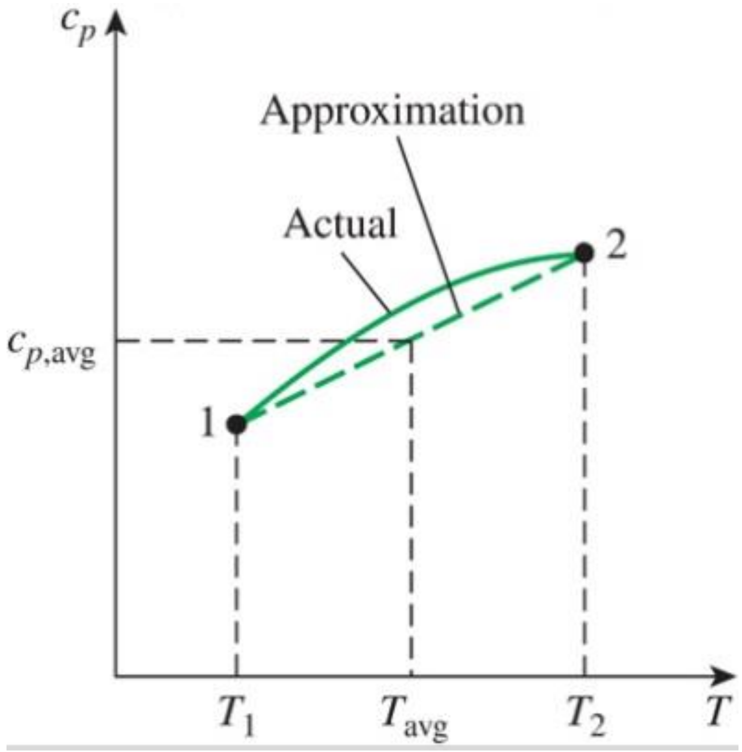
In the preparation of ideal-gas tables, 0 K is chosen as the reference temperature.

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

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

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

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



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

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

$h = u + RT$

$dh = du + RdT$

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

→

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:

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

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

The specific ratio varies with temperature, but this variation is 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.

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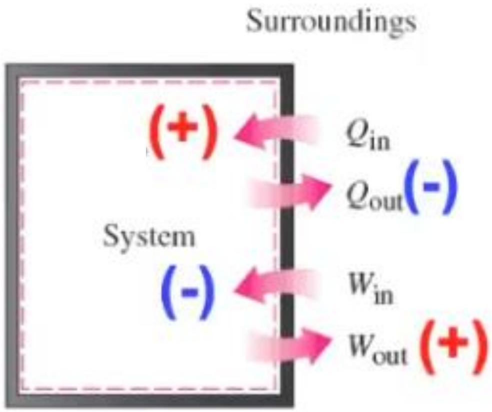
Energy balance and thermodynamics

Kangmin Lee
Dept. of Energy and Environmental Engineering

5-1 Conservation of Mass

밀폐계(닫힌계)

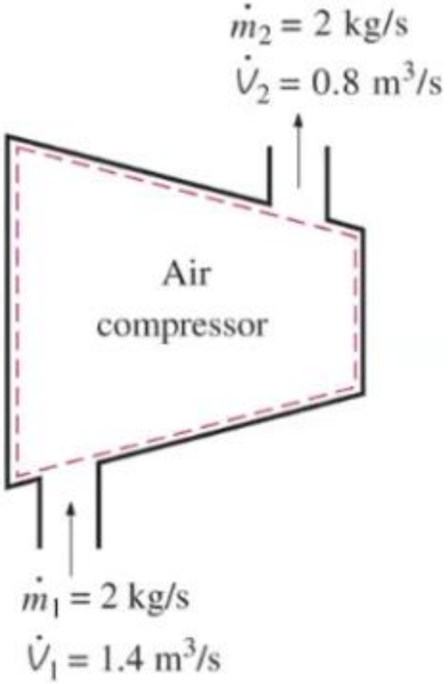
Control Mass
(검사질량)



$$\delta E_{in} - \delta E_{out} = dE_{system}$$

개방계(열린계)

Control Volume
(검사체적)



5-1 Conservation of Mass

Conservation of mass: Mass, like energy, is a conserved property, and it cannot be created or destroyed during a process.

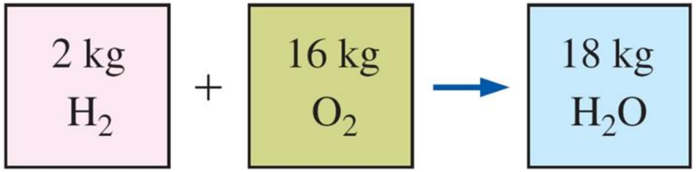
Closed systems: The mass of the system remain constant during a process.

Control volumes: Mass can cross the boundaries, and so we must keep track of the amount of mass entering and leaving the control volume.

Mass *m* and energy *E* can be converted to each other according to $E = mc^2$

c the speed of light in a vacuum $c = 2.9979 \times 10^8 \text{ m/s}.$

The mass change due to energy change is negligible.



Mass is conserved even during chemical reactions.

5-1 Conservation of Mass

Mass and Volume Flow Rates

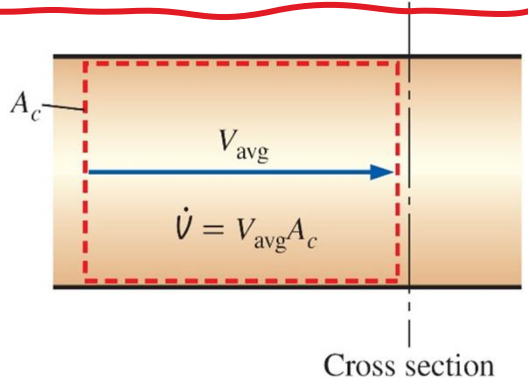
Mass flow rate

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

$$\dot{m} = \rho \dot{V} = \frac{\dot{V}}{v}$$

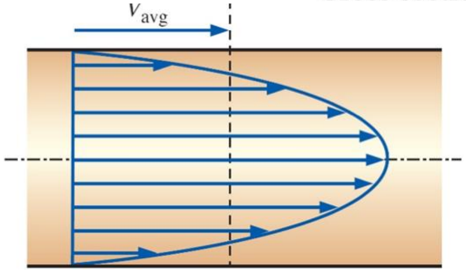
Volume flow rate

$$\dot{V} = \int_{A_c} V_n \, dA_c = V_{\text{avg}} A_c = V A_c \qquad (\text{m}^3/\text{s})$$



$$\delta \dot{m} = \rho V_n \, dA_c$$

$$\dot{m} = \int_{A_c} \delta \dot{m} = \int_{A_c} \rho V_n \, dA_c$$



The average velocity V_{avg}

is defined as the average speed through a cross section.

$$V_{\text{avg}} = \frac{1}{A_c} \int_{A_c} V_n \, dA_c$$

5-1 Conservation of Mass

The mass of a differential volume *dV* within the control volume is $dm = \rho\, dV$

The total mass within the control volume at any instant in time *t* is determined by integration to be

Total mass within the CV: $m_{\mathrm{cv}} = \int_{\mathrm{CV}} \rho\, dV$

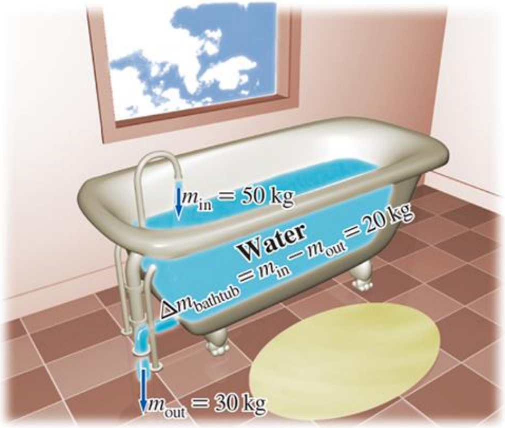
Then the time rate of change of the amount of mass within the control volume is expressed as

Rate of change of mass within the CV: $\frac{dm_{\mathrm{CV}}}{dt} = \frac{d}{dt}\int_{\mathrm{CV}} \rho\, dV$

5-1 Conservation of Mass

Conservation of Mass Principle

$$\begin{pmatrix}\text{Total mass entering}\\ \text{the CV during } \Delta t\end{pmatrix} - \begin{pmatrix}\text{Total mass leaving}\\ \text{the CV during } \Delta t\end{pmatrix} = \begin{pmatrix}\text{Net change of mass}\\ \text{within the CV during } \Delta t\end{pmatrix}$$



Conservation of mass principle for an ordinary bathtub.

The conservation of mass principle for a control volume: The net mass transfer to or from a control volume during a time interval Δt is equal to the net change (increase or decrease) in the total mass within the control volume during Δt.

$$m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{CV}} \qquad \text{(kg)}$$

$$\dot{m}_{\text{in}} - \dot{m}_{\text{out}} = dm_{\text{CV}}/dt \qquad \text{(kg/s)}$$

These equations are often referred to as the **mass balance** and are applicable to any control volume undergoing any kind of process.

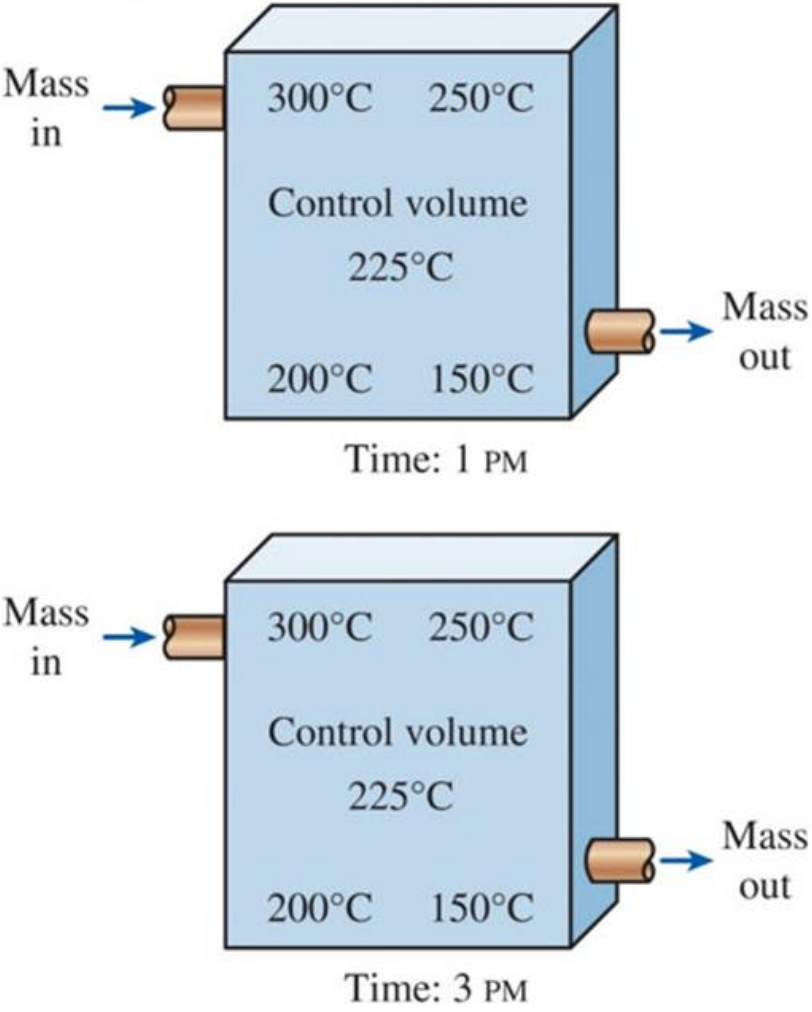
The Steady-Flow Process

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.**

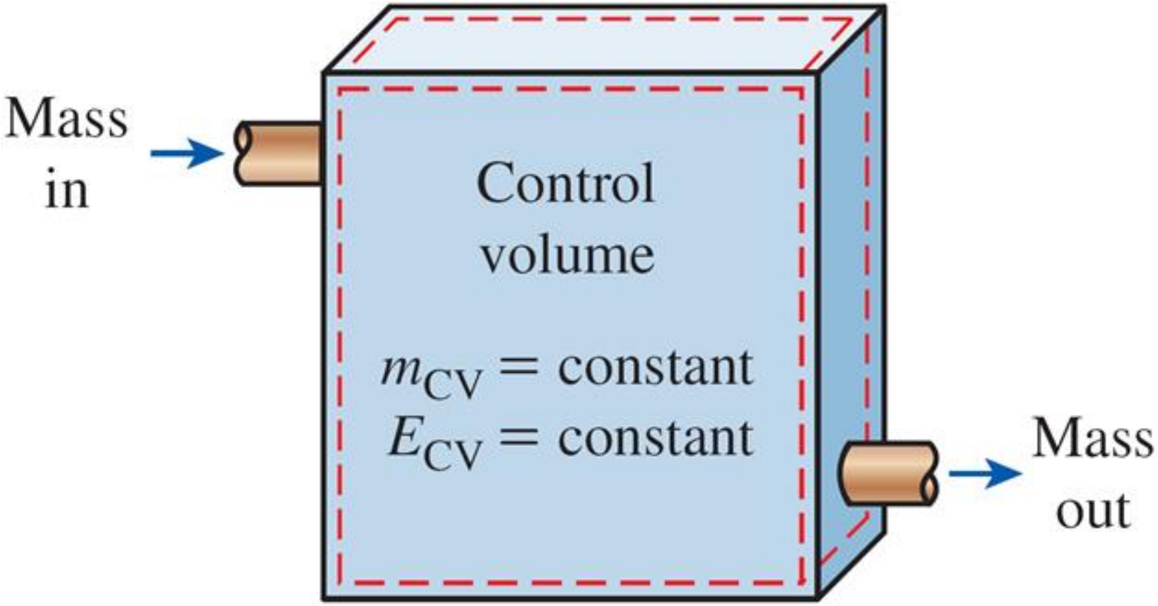


Time: 1 PM

Time: 3 PM

5-1 Energy Analysis of Steady-Flow Systems

Steady-flow process: A process during which a fluid flows through a control volume steadily.



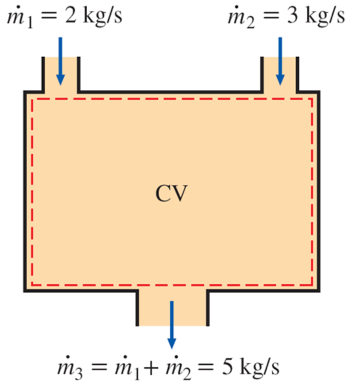
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

5-1 Conservation of Mass

Mass Balance for Steady-Flow Processes

During a steady-flow process, **the total amount of mass contained** within a control volume does not change with time $\left(m_{\mathrm{CV}} = \text{constant}\right)$.

The total amount of mass entering a control volume equal the total amount of mass leaving it.



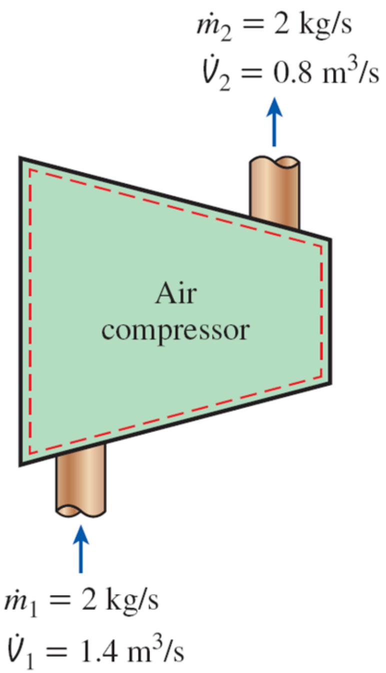
Conservation of mass principle for a two-inlet–one-outlet steady-flow system.

For steady-flow processes, we are interested in the amount of mass flowing per unit time, that is, the mass flow rate.

Steady flow: $$\sum_{\text{in}} \dot{m} = \sum_{\text{out}} \dot{m} \qquad \text{(kg/s)}$$

Steady, incompressible flow: $$\sum_{\text{in}} \dot{V} = \sum_{\text{out}} \dot{V} \qquad (\mathrm{m^3/s})$$

5-1 Conservation of Mass

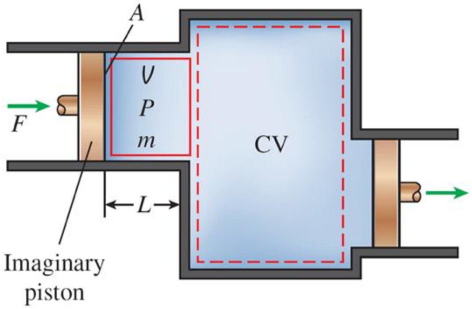


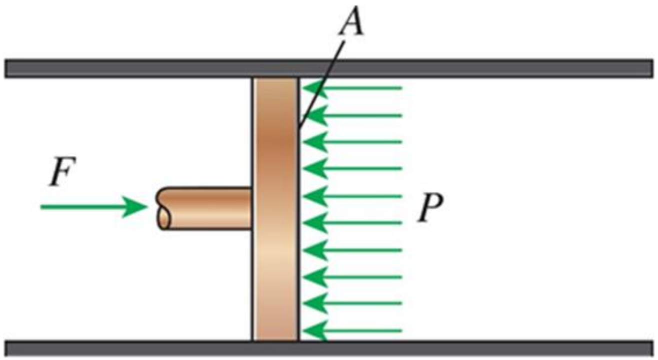
During a steady-flow process, volume flow rates are not necessarily conserved, although mass flow rates are.

5-2 Flow Work and the Energy of a Flowing Fluid

Flow work, or flow energy: The work (or energy) required to **push the mass into or out of the control volume**. This work is necessary for maintaining a continuous flow through a control volume.

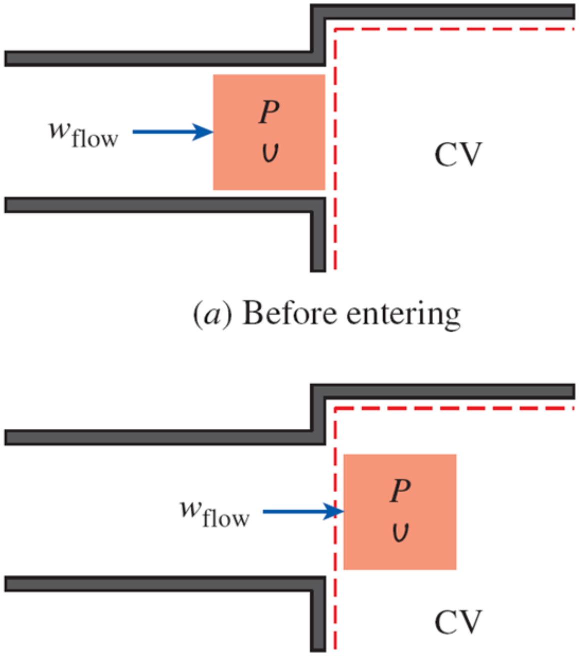
$F = PA$ $\qquad W_{\text{flow}} = FL = PAL = PV \quad \text{(kJ)}$ $\qquad w_{\text{flow}} = Pv \quad \text{(kJ/kg)}$





In the absence of acceleration, the force applied on a fluid by a piston is equal to the force applied on the piston by the fluid.

5-2 Flow Work and the Energy of a Flowing Fluid



(*a*) Before entering

Flow work is the energy needed to push a fluid into or out of a control volume, and it is equal to *P*v.

5-2 Flow Work and the Energy of a Flowing Fluid

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

$$\theta = Pv + e = Pv + (u + \text{ke} + \text{pe})$$ ⬅ **Total Energy of a Flowing Fluid**

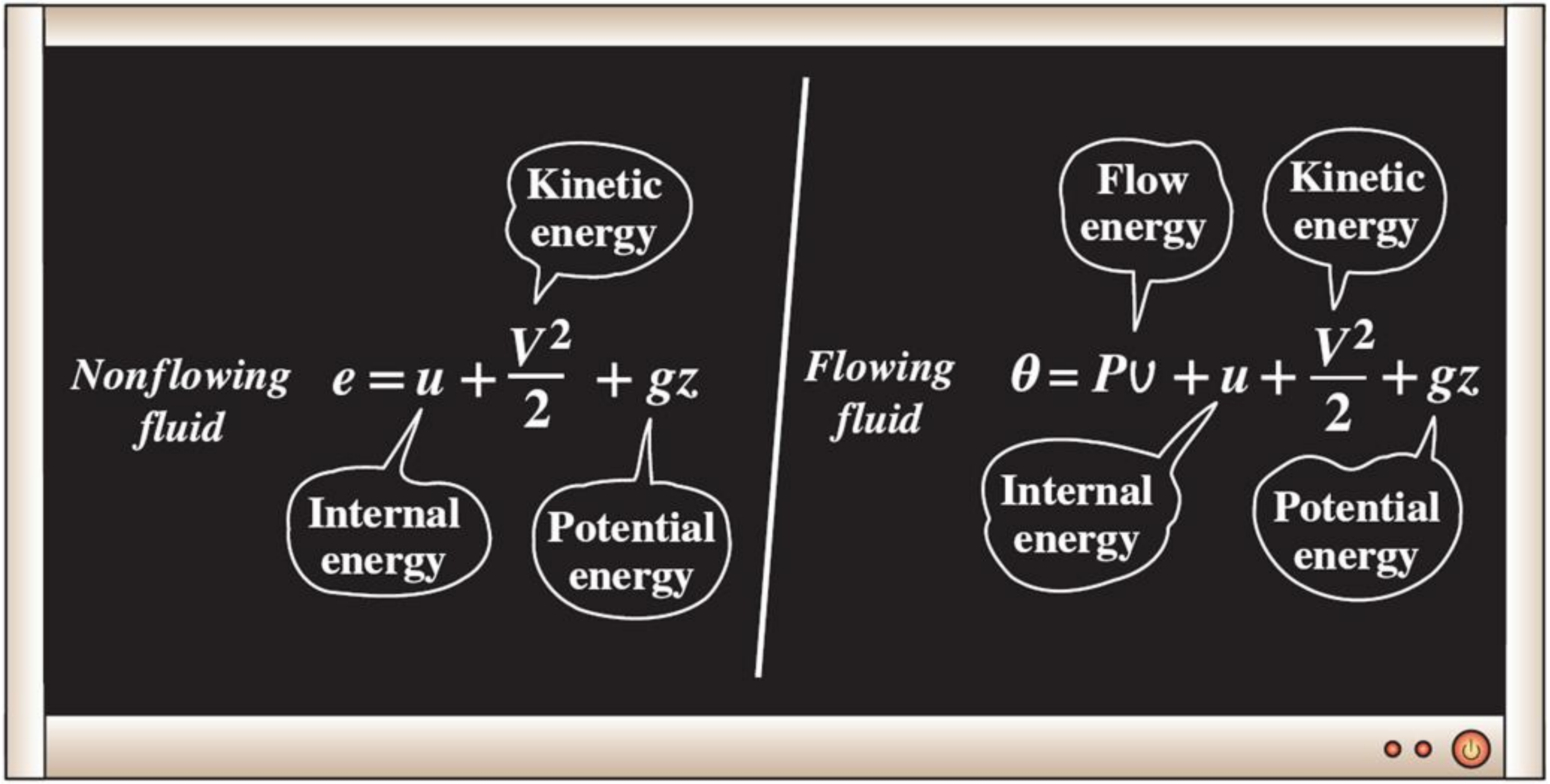
$$h = u + Pv \quad \text{(kJ/kg)}$$

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

The flow energy is automatically taken care of by enthalpy. In fact, this is the main reason for defining the property enthalpy.

5-2 Flow Work and the Energy of a Flowing Fluid

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

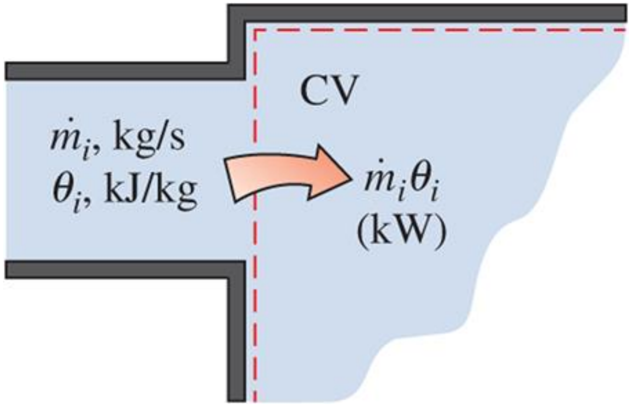


5-2 Flow Work and the Energy of a Flowing Fluid

Energy Transport by Mass

Amount of energy transport by mass: $E_{\text{mass}} = m\theta = m\left(h + \frac{V^2}{2} + gz\right)$ (kJ)

Rate of energy transport by mass: $\dot{E}_{\text{mass}} = \dot{m}\theta = \dot{m}\left(h + \frac{V^2}{2} + gz\right)$ (kW)



When the kinetic and potential energies of a fluid stream are negligible

$$E_{\text{mass}} = mh \qquad \dot{E}_{\text{mass}} = \dot{m}h$$

When the properties of the mass at each inlet or exit change with time as well as over the cross section.

$$E_{\text{in, mass}} = \int_{m_i} \theta_i \delta m_i = \int_{m_i} \left(h_i + \frac{V_i^2}{2} + gz_i\right) \delta m_i$$

5-3 Energy Analysis of Steady-Flow Systems

Mass and Energy balances for a steady-flow process

$$\sum_{\text{in}} \dot{m} = \sum_{\text{out}} \dot{m} \qquad (\text{kg/s})$$

$$\dot{m}_1 = \dot{m}_2 \longrightarrow \rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

ρ is density, V is the average flow velocity in the flow direction, and A is the cross-sectional area normal to flow direction.

$$\textit{Energy balance:} \quad \underbrace{\dot{E}_{\text{in}}}_{\substack{\text{Rate of net energy transfer in} \\ \text{by heat, work, and mass}}} = \underbrace{\dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer out} \\ \text{by heat, work, and mass}}} \qquad (\text{kW})$$

5-3 Energy Analysis of Steady-Flow Systems

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \dot{m}\theta = \dot{Q}_{\text{out}} + \dot{W}_{\text{out}} + \sum_{\text{out}} \dot{m}\theta$$

$$\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}} = \dot{Q}_{\text{out}} + \dot{W}_{\text{out}} + \sum_{\text{out}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}}$$

$$\dot{Q} - \dot{W} = \sum_{\text{out}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each exit}} - \sum_{\text{in}} \underbrace{\dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}}$$

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right]$$

5-3 Energy Analysis of Steady-Flow Systems

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right]$$

$$q - w = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

When the fluid experiences negligible changes in its kinetic and potential energies (that is, $\Delta \mathrm{ke} \cong 0$, $\Delta \mathrm{pe} \cong 0$) → The system is usually fixed

$$q - w = h_2 - h_1$$

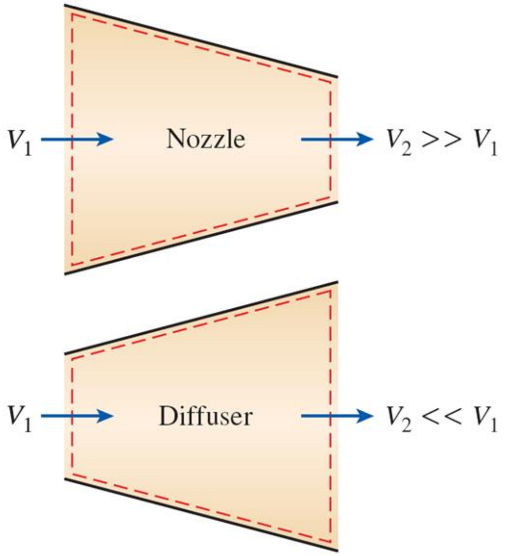
5-4 Some Steady-Flow Engineering Devices

Many engineering devices operate essentially under the same conditions for long periods of time.

The components of a steam power plant (turbines, compressors, heat exchangers, and pumps), operate nonstop for months before the system is shut down for maintenance.

Therefore, these devices can be conveniently analysed as steady-flow devices.

5-4 Some Steady-Flow Engineering Devices



Nozzles and diffusers are shaped so that they cause large changes in fluid velocities and thus kinetic energies.

Nozzles and Diffusers

Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses.

A **nozzle** is a device that increases the velocity of a fluid at the expense of pressure.

A **diffuser** is a device that increases the pressure of a fluid by slowing it down.

The cross-sectional area of a nozzle decreases in the flow direction for subsonic flows and increases for supersonic flows. The reverse is true for diffusers.

Energy balance for a nozzle or diffuser

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

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) \quad (\text{since } \dot{Q} \cong 0,\ \dot{W} = 0, \text{ and } \Delta\text{pe} \cong 0)$$

$$h_2 = h_1 - \frac{V_2^2 - V_1^2}{2}$$

5-4 Some Steady-Flow Engineering Devices

Turbine blades attached to the turbine shaft.

Turbines and Compressors

Turbine drives the electric generator In steam, gas, or hydroelectric power plants.

As the fluid passes through the turbine, work is done against the blades, which are attached to the shaft. As a result, the shaft rotates, and the turbine produces work.

Compressors, as well as **pumps** and **fans**, are devices used to increase the pressure of a fluid. Work is supplied to these devices from an external source through a rotating shaft.

A **fan** increases the pressure of a gas slightly and is mainly used to mobilize a gas.

A **compressor** is capable of compressing the gas to very high pressures.

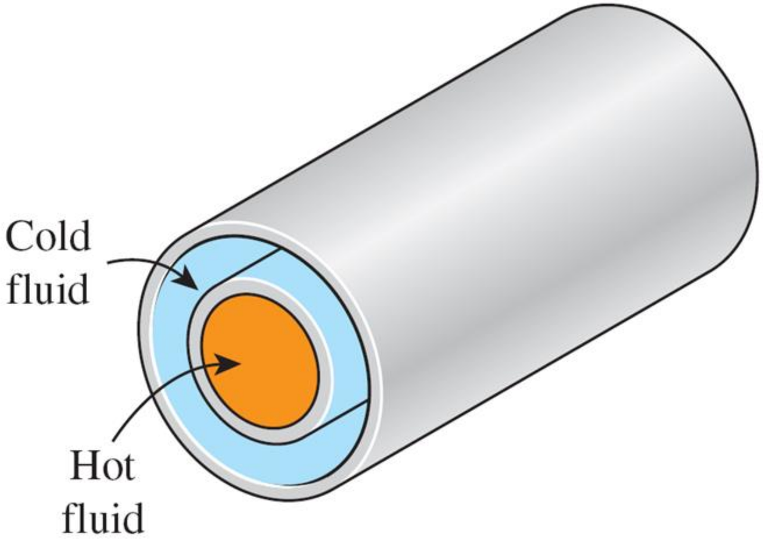
Pumps work very much like compressors except that they handle liquids instead of gases.

5-4 Some Steady-Flow Engineering Devices

Heat Exchangers

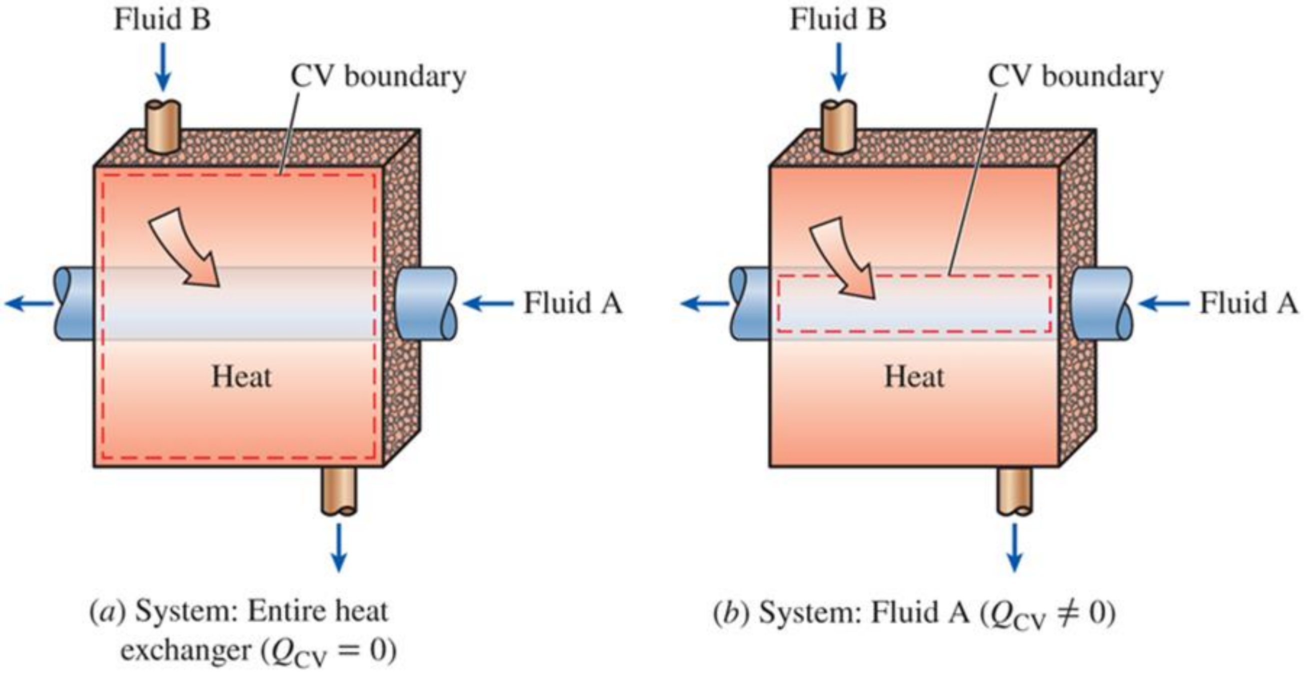
Heat exchangers are devices where two moving fluid streams exchange heat without mixing.

Heat exchangers are widely used in various industries, and they come in various designs.



A heat exchanger can be as simple as two concentric pipes.

5-4 Some Steady-Flow Engineering Devices



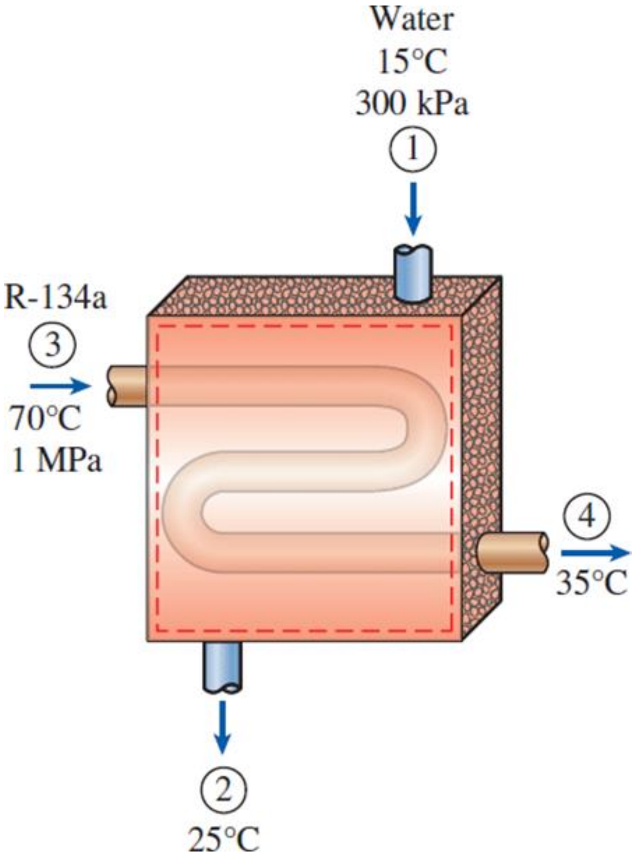
(*a*) System: Entire heat exchanger ($Q_{CV} = 0$)

(*b*) System: Fluid A ($Q_{CV} \neq 0$)

The heat transfer associated with a heat exchanger may be zero or nonzero depending on how the control volume is selected.

5-4 Some Steady-Flow Engineering Devices

Cooling of Refrigerant-134a by Water



$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

Energy balance:

$$\dot{E}_{\text{in}} - \dot{E}_{\text{out}} = dE_{\text{system}} / dt = 0 \qquad \text{(steady)}$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

$$\left(\text{since } \dot{Q} \cong 0,\ \dot{W} = 0,\ \text{KE} \cong \text{PE} \cong 0\right)$$

$$\dot{m}_w \left(h_1 - h_2\right) = \dot{m}_R \left(h_4 - h_3\right)$$