

Study Guide for
Thermodynamics: an Engineering Approach

By

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Nomenclature

A	area (m^2)
C_p	specific heat at constant pressure ($\text{kJ}/(\text{kg}\cdot\text{K})$)
C_v	specific heat at constant volume ($\text{kJ}/(\text{kg}\cdot\text{K})$)
COP	coefficient of performance
d	exact differential
E	stored energy (kJ)
e	stored energy per unit mass (kJ/kg)
F	force (N)
g	acceleration of gravity (9.807 m/s^2)
H	enthalpy ($H= U + PV$) (kJ)
h	specific enthalpy ($h= u + Pv$) (kJ/kg)
h	convective heat transfer coefficient ($\text{W}/(\text{m}^2\cdot\text{K})$)
K	Kelvin degrees
k	specific heat ratio, C_p/C_v
k	10^3
k_t	thermal conductivity ($\text{W}/(\text{m}\cdot^\circ\text{C})$)
M	molecular weight or molar mass (kg/kmol)
M	10^6
m	mass (kg)
N	moles (kmol)
n	polytropic exponent (isentropic process, ideal gas $n = k$)
η	isentropic efficiency for turbines, compressors, nozzles
η_{th}	thermal efficiency (net work done/heat added)
P	pressure (kPa, MPa, psia, psig)
Pa	Pascal (N/m^2)
Q_{net}	net heat transfer ($\sum Q_{\text{in}} - \sum Q_{\text{out}}$) (kJ)
q_{net}	Q_{net}/m , net heat transfer per unit mass (kJ/kg)
R	particular gas constant ($\text{kJ}/(\text{kg}\cdot\text{K})$)
R_u	universal gas constant ($= 8.314 \text{ kJ}/(\text{kmol}\cdot\text{K})$)
S	entropy (kJ/K)
s	specific entropy ($\text{kJ}/(\text{kg}\cdot\text{K})$)
T	temperature ($^\circ\text{C}$, K, $^\circ\text{F}$, R)
U	internal energy (kJ)
u	specific internal energy ($\text{kJ}/(\text{kg}\cdot\text{K})$)
V	volume (m^3)
\dot{V}	volume flow rate (m^3/s)
\vec{V}	velocity (m/s)
v	specific volume (m^3/kg)

\bar{v}	molar specific volume (m^3/kmol)
X	distance (m)
X	exergy (kJ)
x	quality
Z	elevation (m)
W_{net}	net work done $[(\sum W_{\text{out}} - \sum W_{\text{in}})_{\text{other}} + W_{\text{b}}]$ (kJ) where $W_{\text{b}} = \int_1^2 P dV$ for closed systems and 0 for control volumes
w_{net}	W_{net}/m , net work done per unit mass (kJ/kg)
W_t	weight (N)
δ	inexact differential
ε	regenerator effectiveness
ϕ	relative humidity
ρ	density (kg/m^3)
ω	humidity ratio

Subscripts, superscripts

a	actual
b	boundary
f	saturated liquid state
g	saturated vapor state
fg	saturated vapor value minus saturated liquid value
gen	generation
H	high temperature
HP	heat pump
L	low temperature
net	net heat added to system or net work done by system
other	work done by shaft and electrical means
P	constant pressure
REF	refrigerator
rev	reversible
s	isentropic or constant entropy or reversible, adiabatic
sat	saturation value
v	constant volume
1	initial state
2	final state
i	inlet state
e	exit state
\cdot	per unit time

REFERENCE

Cengel, Yunus A. and Michael A. Boles, Thermodynamics: An Engineering Approach, 4th ed., New York, McGraw-Hill: 2001.

Chapter 1: Basic Concepts of Thermodynamics

INTRODUCTION

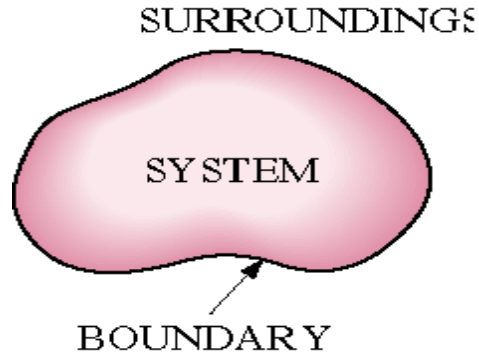
The study of thermodynamics is concerned with the ways energy is stored within a body and how energy transformations, which involve heat and work, may take place. One of the most fundamental laws of nature is the conservation of energy principle. It simply states that during an energy interaction, energy can change from one form to another but the total amount of energy remains constant. That is, energy cannot be created or destroyed.

This review of thermodynamics is based on the macroscopic approach where a large number of particles, called molecules, make up the substance in question. The macroscopic approach to thermodynamics does not require knowledge of the behavior of individual particles and is called classical thermodynamics. It provides a direct and easy way to obtain the solution of engineering problems without being overly cumbersome. A more elaborate approach, based on the average behavior of large groups of individual particles, is called statistical thermodynamics. This microscopic approach is rather involved and is not reviewed here and leads to the definition of the second law of thermodynamics. We will approach the second law of thermodynamics from the classical point of view and will learn that the *second law of thermodynamics* asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.

Closed, Open, and Isolated Systems

A thermodynamic system, or simply **system**, is defined as a quantity of matter or a region in space chosen for study. The region outside the system is called the **surroundings**. The real or imaginary surface that separates the system from its surroundings is called the **boundary**. The boundary of a system may be fixed or movable.

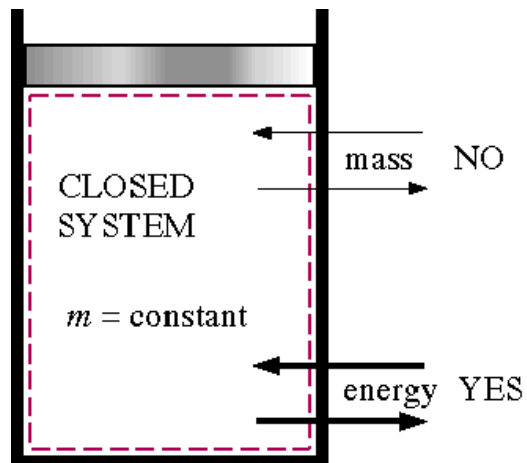
Surroundings are physical space outside the system boundary.

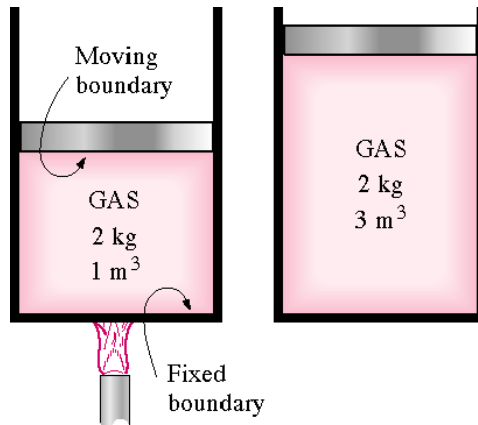


Systems may be considered to be **closed** or **open**, depending on whether a fixed mass or a fixed volume in space is chosen for study.

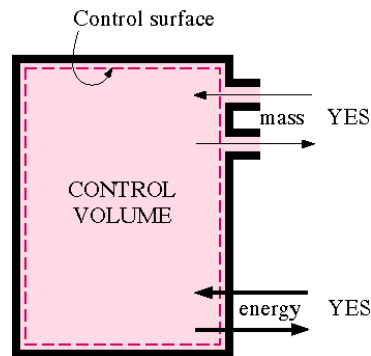
A **closed system** consists of a fixed amount of mass and no mass may cross the system boundary. The closed system boundary may move.

Examples of closed systems are sealed tanks and piston cylinder devices (note the volume does not have to be fixed). However, energy in the form of heat and work may cross the boundaries of a closed system.

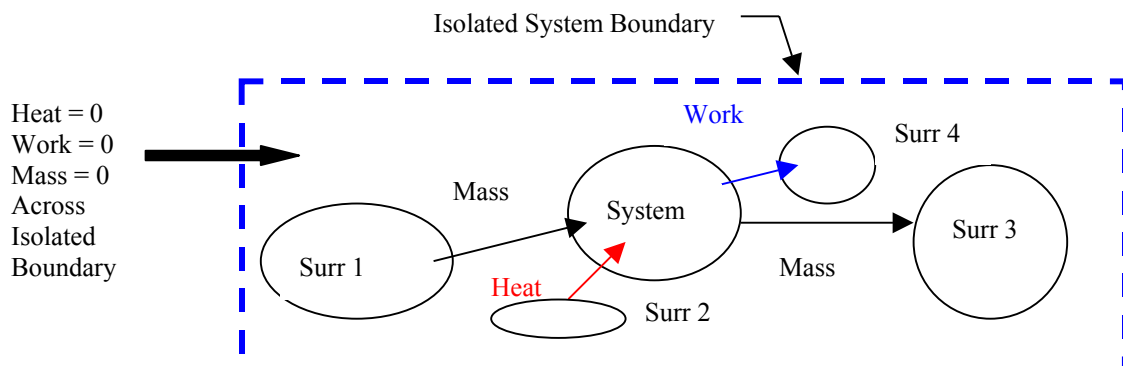




An **open system**, or **control volume**, has mass as well as energy crossing the boundary, called a control surface. Examples of open systems are pumps, compressors, turbines, valves, and heat exchangers.



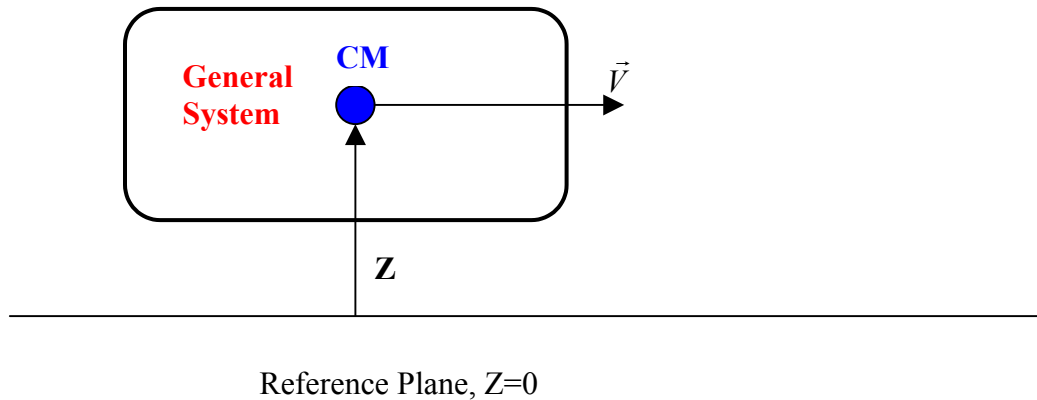
An **isolated system** is a general system of fixed mass where no heat or work may cross the boundaries. An isolated system is a closed system with no energy crossing the boundaries and is normally a collection of a main system and its surroundings that are exchanging mass and energy among themselves and no other system.



Since some of the thermodynamic relations that are applicable to closed and open systems are different, it is extremely important that we recognize the type of system we have before we start analyzing it.

Energy

Consider the system shown below moving with a velocity \vec{V} at an elevation Z relative to the reference plane.



The total energy E of a system is the sum of all forms of energy that can exist within the system such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear. The total energy of the system is normally thought of as the sum of the internal energy, kinetic energy, and potential energy. The internal energy U is that energy associated with the molecular structure of a system and the degree of the molecular activity (see Section 1-4 of text). The kinetic energy KE exists as a result of the system's motion relative to an external reference frame. When the system moves with velocity \vec{V} the kinetic energy is expressed as

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

The energy that a system possesses as a result of its elevation in a gravitational field relative to the external reference frame is called potential energy PE and is expressed as

$$PE = mgZ \quad (kJ)$$

where g is the gravitational acceleration and z is the elevation of the center of gravity of a system relative to the reference frame. The total energy of the system is expressed as

$$E = U + KE + PE \quad (kJ)$$

or, on a unit mass basis,

$$\begin{aligned} e &= \frac{E}{m} = \frac{U}{m} + \frac{KE}{m} + \frac{PE}{m} \quad \left(\frac{kJ}{kg}\right) \\ &= u + \frac{\vec{V}^2}{2} + gZ \end{aligned}$$

where $e = E/m$ is the specific stored energy, and $u = U/m$ is the specific internal energy. The change in stored energy of a system is given by

$$\Delta E = \Delta U + \Delta KE + \Delta PE \quad (kJ)$$

Most closed systems remain stationary during a process and, thus, experience no change in their kinetic and potential energies. The change in the stored energy is identical to the change in internal energy for stationary systems.

If $\Delta KE = \Delta PE = 0$,

$$\Delta E = \Delta U \quad (kJ)$$

Property

Any characteristic of a system in equilibrium is called a **property**. The property is **independent** of the path used to arrive at the system condition.

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

Properties may be **intensive** or **extensive**.

Extensive properties are those that vary directly with size--or extent--of the system.

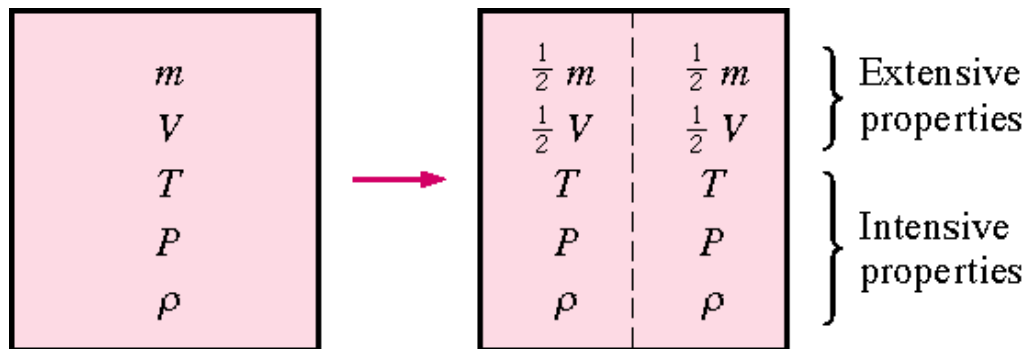
Some Extensive Properties

- a. mass
- b. volume
- c. total energy
- d. mass dependent property

Intensive properties are those that are independent of size.

Some Intensive Properties

- a. temperature
- b. pressure
- c. age
- d. color
- e. any mass independent property



Extensive properties per unit mass are intensive properties. For example, the specific volume v , defined as

$$v = \frac{\text{Volume}}{\text{mass}} = \frac{V}{m} \quad \left(\frac{m^3}{kg} \right)$$

and density ρ , defined as

$$\rho = \frac{\text{mass}}{\text{volume}} = \frac{m}{V} \quad \left(\frac{\text{kg}}{\text{m}^3} \right)$$

are intensive properties.

Units

An important component to the solution of any engineering thermodynamic problem requires the proper use of units. The unit check is the simplest of all engineering checks that can be made for a given solution. Since units present a major hindrance to the correct solution of thermodynamic problems, we must learn to use units carefully and properly. The system of units selected for this course is the SI System, also known as the International System (sometimes called the metric system). In SI, the units of mass, length, and time are the kilogram (kg), meter (m), and second (s), respectively. We consider force to be a derived unit from Newton's second law, i.e.,

$$\text{Force} = (\text{mass})(\text{acceleration})$$

$$F = ma$$

In SI, the force unit is the newton (N), and it is defined as the force required to accelerate a mass of 1 kg at a rate of 1 m/s². That is,

$$1N = (1kg)\left(1\frac{m}{s^2}\right)$$

The term weight is often misused to express mass. Unlike mass, weight W_i is a force. Weight is the gravitational force applied to a body, and its magnitude is determined from Newton's second law.

$$W_t = mg$$

where m is the mass of the body and g is the local gravitational acceleration (g is 9.807 m/s^2 at sea level and 45° latitude). The weight of a unit volume of a substance is called the specific weight w and is determined from $w = \rho g$, where ρ is density.

Oftentimes, the engineer must work in other systems of units. Comparison of the United States Customary System (USCS), or English System, and the slug system of units with the SI system is shown below.

	SI	USCS	Slug
mass	kilogram (kg)	pound-mass (lbm)	slug-mass (slug)
time	second (s)	second (s)	second (s)
length	meter (m)	foot (ft)	foot (ft)
force	newton (N)	pound-force (lbf)	pound-force (lbf)

Sometimes we use the mole number in place of the mass. In SI units the mole number is in kilogram-moles, or kmol.

Newton's second law is often written as

$$F = \frac{ma}{g_c}$$

where g_c is called the gravitational constant and is obtained from the force definition. In the SI System 1 newton is that force required to accelerate 1 kg mass 1 m/s^2 . The gravitational constant in the SI System is

$$g_c = \frac{ma}{F} = \frac{(1\text{kg})(1\frac{m}{s^2})}{1\text{N}} = 1 \frac{\text{kg m}}{\text{N s}^2}$$

In the USCS 1 pound-force is that force required to accelerate 1 pound-mass 32.176 ft/s². The gravitational constant in the USCS is

$$g_c = \frac{ma}{F} = \frac{(1\text{lbm})(32.2\frac{\text{ft}}{\text{s}^2})}{1\text{lbf}} = 32.2 \frac{\text{lbm ft}}{\text{lbf s}^2}$$

In the slug system, the gravitational constant is

$$g_c = \frac{ma}{F} = \frac{(1\text{slug})(1\frac{\text{ft}}{\text{s}^2})}{1\text{lbf}} = 1 \frac{\text{lbm ft}}{\text{lbf s}^2}$$

Example 1-1

An object at sea level has a mass of 400 kg.

- a) Find the weight of this object on earth.
- b) Find the weight of this object on the moon where the local gravitational acceleration is one-sixth that of earth.

(a)

$$W_t = mg$$

$$\begin{aligned}
 W_t &= (400 \text{ kg}) \left(9.807 \frac{\text{m}}{\text{s}^2} \right) \left(\frac{1 \text{ N}}{\text{kg} \frac{\text{m}}{\text{s}^2}} \right) \\
 &= 3922.8 \text{ N}
 \end{aligned}$$

(b)

$$\begin{aligned}
 W_t &= mg \\
 &= (400 \text{ kg}) \left(\frac{9.807 \text{ m}}{6 \text{ s}^2} \right) \left(\frac{1 \text{ N}}{\text{kg} \frac{\text{m}}{\text{s}^2}} \right) \\
 &= 653.8 \text{ N}
 \end{aligned}$$

Example 1-2E

An object has a mass of 180 lbm. Find the weight of this object at a location where the local gravitational acceleration is 30 ft/s^2 .

$$\begin{aligned}
 W_t &= mg \\
 &= (180 \text{ lbm}) \left(30 \frac{\text{ft}}{\text{s}^2} \right) \left(\frac{1 \text{ lbf}}{32.2 \text{ lbm} \frac{\text{ft}}{\text{s}^2}} \right) \\
 &= 167.7 \text{ lbf}
 \end{aligned}$$

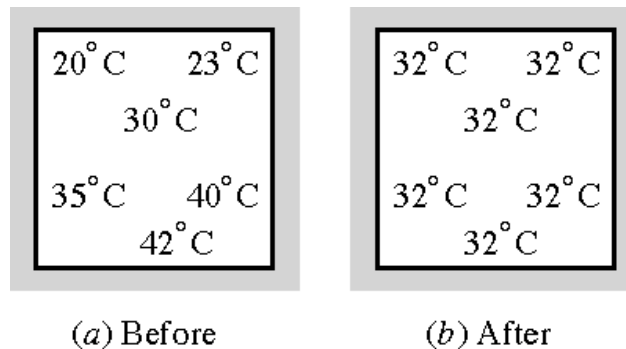
State, Equilibrium, Process, and Properties

State

Consider a system that is not undergoing any change. The properties can be measured or calculated throughout the entire system. This gives us a set of properties that completely describe the condition or state of the system. At a given state all of the properties are known; changing one property changes the state.

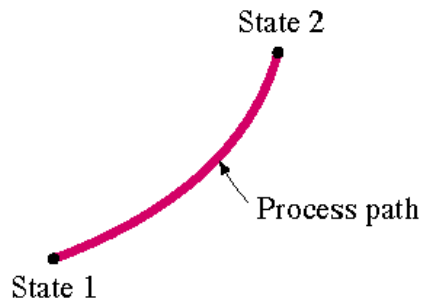
Equilibrium

A system is said to be in thermodynamic equilibrium if it maintains thermal (uniform temperature), mechanical (uniform pressure), phase (the mass of two phases, e.g., ice and liquid water, in equilibrium) and chemical equilibrium.



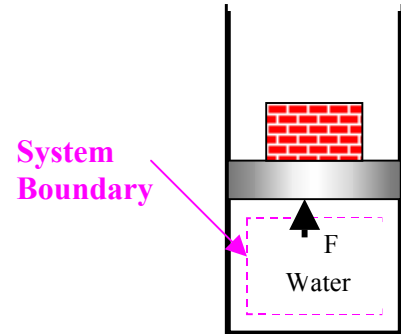
Process

Any change from one state to another is called a process. During a quasi-equilibrium or quasi-static process the system remains practically in equilibrium at all times. We study quasi-equilibrium processes because they are easy to analyze (equations of state apply) and work-producing devices deliver the most work when they operate on the quasi-equilibrium process.



In most of the processes that we will study, one thermodynamic property is held constant. Some of these processes are

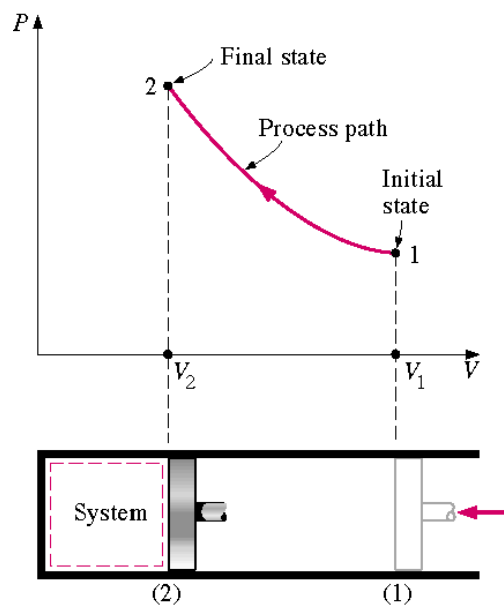
Process	Property held constant
isobaric	pressure
isothermal	temperature
isochoric	volume
isentropic	entropy (see Chapter 6)



Constant Pressure Process

We can understand the concept of a constant pressure process by considering the above figure. The force exerted by the water on the face of the piston has to equal the force due to the combined weight of the piston and the bricks. If the combined weight of the piston and bricks is constant, then F is constant and the pressure is constant even when the water is heated.

We often show the process on a P - V diagram as shown below.



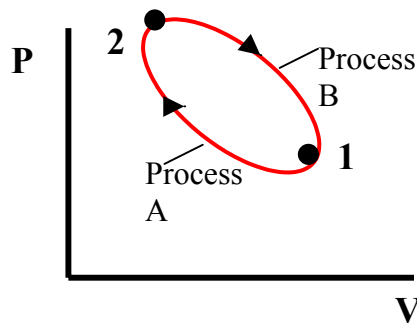
State Postulate

As noted earlier, the state of a system is described by its properties. But by experience not all properties must be known before the state is specified. Once a sufficient number of properties are known, the state is specified and all other properties are known. The number of properties required to fix the state of a simple, homogeneous system is given by the state postulate:

The thermodynamic state of a simple compressible system is completely specified by two independent, intensive properties.

Cycle

A process (or a series of connected processes) with identical end states is called a cycle. Below is a cycle composed of two processes, A and B. Along process A, the pressure and volume change from state 1 to state 2. Then to complete the cycle, the pressure and volume change from state 2 back to the initial state 1 along process B. Keep in mind that all other thermodynamic properties must also change so that the pressure is a function of volume as described by these two processes.



Pressure

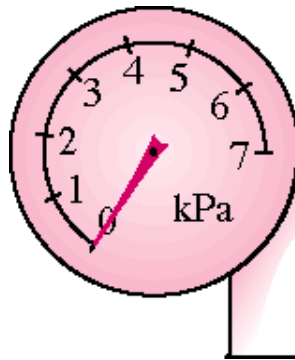
Force per unit area is called pressure, and its unit is the pascal, N/m^2 , in the SI system and psia, lbf/in^2 absolute, in the English system.

$$P = \frac{\text{Force}}{\text{Area}} = \frac{F}{A}$$

$$1 \text{ kPa} = 10^3 \frac{\text{N}}{\text{m}^2}$$

$$1 \text{ MPa} = 10^6 \frac{\text{N}}{\text{m}^2} = 10^3 \text{ kPa}$$

The pressure used in **all** calculations of state is the **absolute pressure** measured relative to absolute zero pressure. However, pressures are often measured relative to **atmospheric pressure**, called **gage** or **vacuum** pressures. In the English system the absolute pressure and gage pressures are distinguished by their units, psia (pounds force per square inch absolute) and psig (pounds force per square inch gage), respectively; however, the SI system makes no distinction between absolute and gage pressures.



These pressures are related by

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

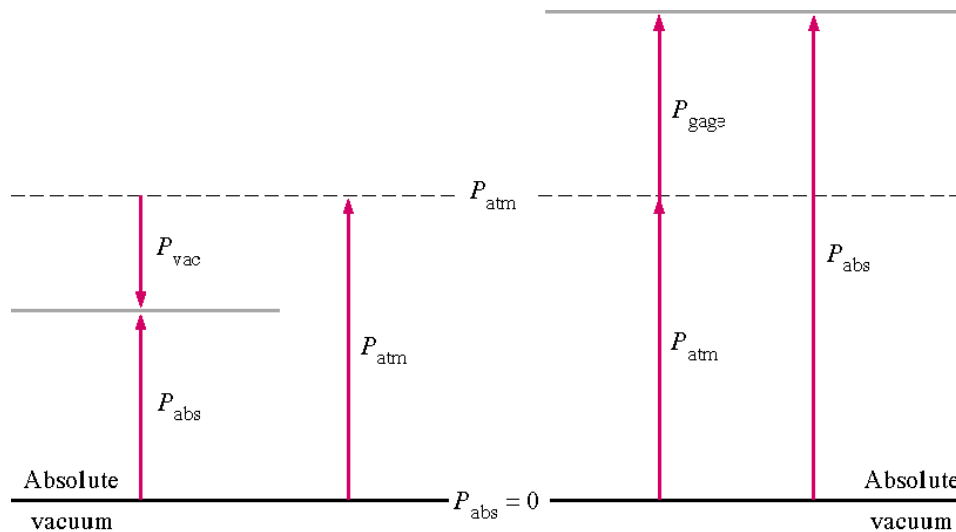
$$P_{vac} = P_{atm} - P_{abs}$$

Or these last two results may be written as

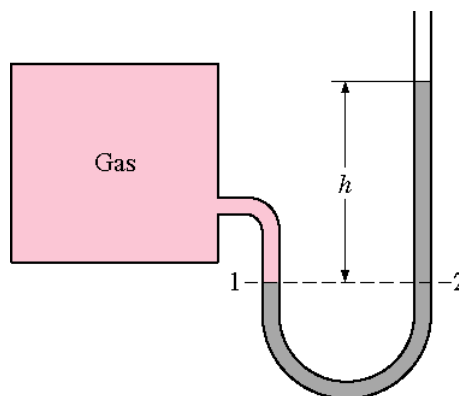
$$P_{abs} = P_{atm} \pm P_{gage}$$

Where the $+P_{\text{gage}}$ is used when $P_{\text{abs}} > P_{\text{atm}}$ and $-P_{\text{gage}}$ is used for a vacuum gage.

The relation among atmospheric, gage, and vacuum pressures is shown below.



Small to moderate pressure differences are measured by a manometer and a differential fluid column of height h corresponds to a pressure difference between the system and the surroundings of the manometer.

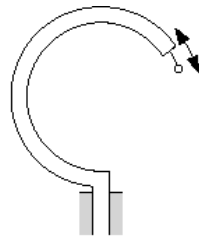


This pressure difference is determined from the manometer fluid displaced height as

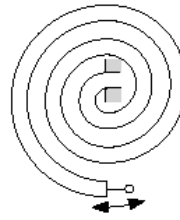
$$\Delta P = \rho g h \quad (kPa)$$

The text gives an extensive review of the manometer pressure relations. For further study of the manometer pressure relations, see the text.

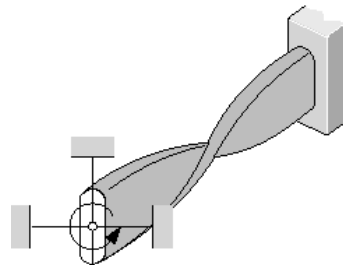
Other devices for measuring pressure differences are shown below.



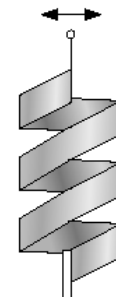
C-type



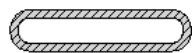
Spiral



Twisted tube



Helical



Tube cross section

Example 1-3

A vacuum gage connected to a tank reads 30 kPa at a location where the atmospheric pressure is 98 kPa. What is the absolute pressure in the tank?

$$\begin{aligned}P_{abs} &= P_{atm} - P_{gage} \\ &= 98 \text{ kPa} - 30 \text{ kPa} \\ &= 68 \text{ kPa}\end{aligned}$$

Example 1-4

A pressure gage connected to a valve stem of a truck tire reads 240 kPa at a location where the atmospheric pressure is 100 kPa. What is the absolute pressure in the tire, in kPa and in psia?

$$\begin{aligned}P_{abs} &= P_{atm} + P_{gage} \\ &= 100 \text{ kPa} + 240 \text{ kPa} \\ &= 340 \text{ kPa}\end{aligned}$$

The pressure in psia is

$$P_{abs} = 340 \text{ kPa} \frac{14.7 \text{ psia}}{101.3 \text{ kPa}} = 49.3 \text{ psia}$$

What is the gage pressure of the air in the tire, in psig?

$$\begin{aligned}
 P_{gage} &= P_{abs} - P_{atm} \\
 &= 49.3 \text{ psia} - 14.7 \text{ psia} \\
 &= 34.6 \text{ psig}
 \end{aligned}$$

Check the side walls of the tires on your car or truck. What is the maximum allowed pressure? Is this pressure in gage or absolute values?

Example 1-5

Both a gage and a manometer are attached to a gas tank to measure its pressure. If the pressure gage reads 80 kPa, determine the distance between the two fluid levels of the manometer if the fluid is mercury, whose density is 13,600 kg/m³.

$$h = \frac{\Delta P}{\rho g}$$

$$\begin{aligned}
 h &= \frac{80 \text{ kPa}}{13600 \frac{\text{kg}}{\text{m}^3} 9.807 \frac{\text{m}}{\text{s}^2}} \frac{10^3 \text{ N} / \text{m}^2}{\frac{\text{kPa}}{1 \text{ N}} \frac{\text{kg m}}{\text{s}^2}} \\
 &= 0.6 \text{ m}
 \end{aligned}$$

Temperature

Although we are familiar with temperature as a measure of “hotness” or “coldness,” it is not easy to give an exact definition of it. However, temperature is considered as a thermodynamic property that is the

measure of the energy content of a mass. When heat energy is transferred to a body, the body's energy content increases and so does its temperature. In fact it is the difference in temperature that causes energy, called heat transfer, to flow from a hot body to a cold body. Two bodies are in thermal equilibrium when they have reached the same temperature. If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other. This simple fact is known as the **zeroth law of thermodynamics**.

The temperature scales used in the SI and the English systems today are the Celsius scale and Fahrenheit scale, respectively. These two scales are based on a specified number of degrees between the freezing point of water (0°C or 32°F) and the boiling point of water (100°C or 212°F) and are related by

$$T^{\circ} F = \frac{9}{5} T^{\circ} C + 32$$

Example 1-6

Water boils at 212 °F at one atmosphere pressure. At what temperature does water boil in °C.

$$T = (T^{\circ} F - 32) \frac{5}{9} = (212 - 32) ^{\circ} F \frac{5^{\circ} C}{9^{\circ} F} = 100^{\circ} C$$

Like pressure, the temperature used in thermodynamic calculations must be in absolute units. The absolute scale in the SI system is the Kelvin scale, which is related to the Celsius scale by

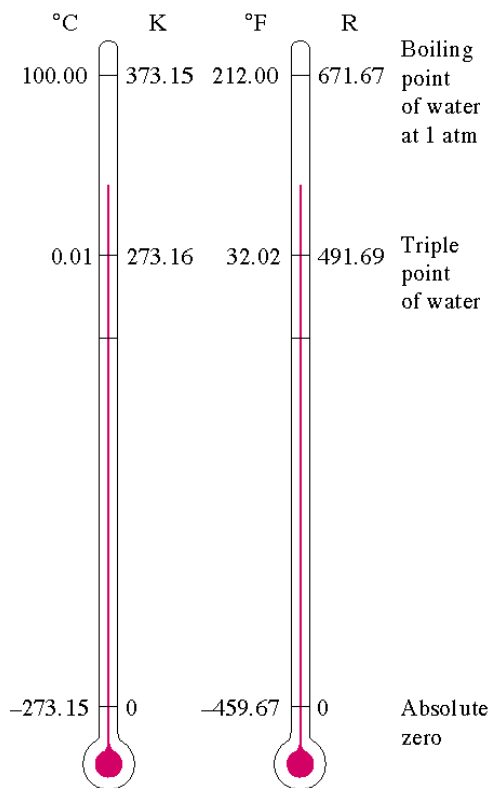
$$T K = T^{\circ} C + 273.15$$

In the English system, the absolute temperature scale is the Rankine scale, which is related to the Fahrenheit scale by

$$T_R = T^{\circ}\text{F} + 459.69$$

Also, note that

$$T_R = 1.8 T_K$$



The magnitudes of each division of 1 K and 1°C are identical, and so are the magnitudes of each division of 1 R and 1°F. That is,

$$\begin{aligned}\Delta T K &= (T_2^{\circ}\text{C} + 273.15) - (T_1^{\circ}\text{C} + 273.15) \\ &= T_2^{\circ}\text{C} - T_1^{\circ}\text{C} = \Delta T^{\circ}\text{C}\end{aligned}$$

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

