Introduction to Thermodynamics

Thermodynamics

The science that deals with the conversion of energy from one form to another, the direction of the flow of heat, and the availability of energy to do work.

To further understand the concept of thermodynamics let's look at the transformation of energy that is happening in a wind turbine. The kinetic energy from the wind is converted by the wind turbine to mechanical energy and then to electrical energy. According to the First Law of Thermodynamics, all the energy that is put into the blade of the wind turbine plus all the remaining energy in the air must all be converted into the same exact amount of energy after it passes the wind turbine.

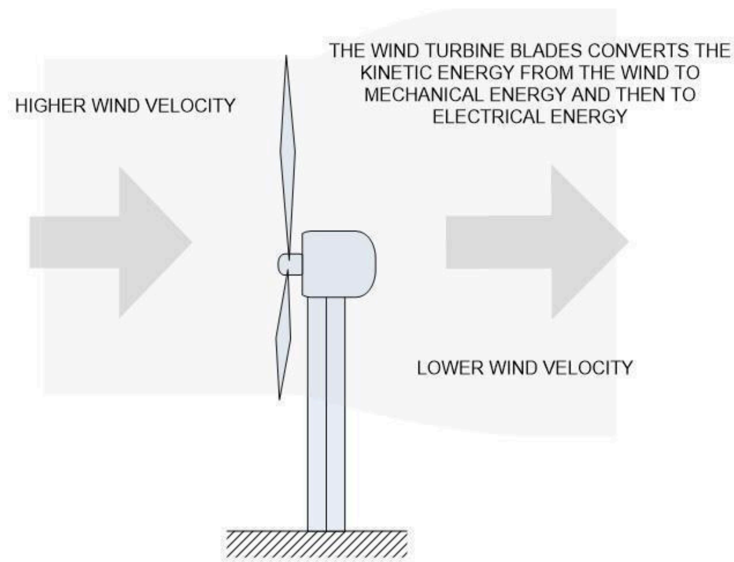
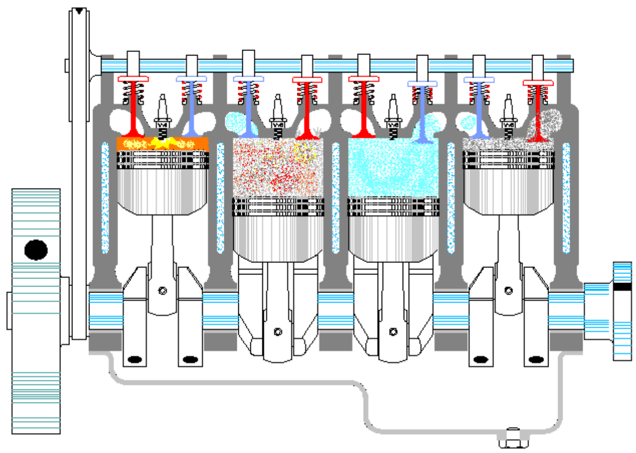


FIGURE 1: A wind turbine converting kinetic energy from the wind to produce electrical power

But of course, in real situations, not all energies will be converted into the same exact amount of energy after the air passes the wind turbine blades, therefore scientists and engineers have to discover another law of thermodynamics – the Second Law of Thermodynamics.

Another example is the energy transformation of fuel energy from an engine. The energy comes from the fuel mixed with air (chemical energy) that is injected inside the combustion chamber. The piston inside the combustion chamber compresses the mixture, until the pressure and temperature reach its combustion state. The heat produced during combustion causes the piston to move in a reciprocating manner. The power produced by the piston is generally known as the indicated power.



The reciprocating motion of the piston is then converted into rotational motion through the crankshaft. This rotational motion creates the brake power output to the shaft of the engine. The brake power is utilized for various applications, such as running the wheels of an automobile or to produce electricity when connected to a generator.

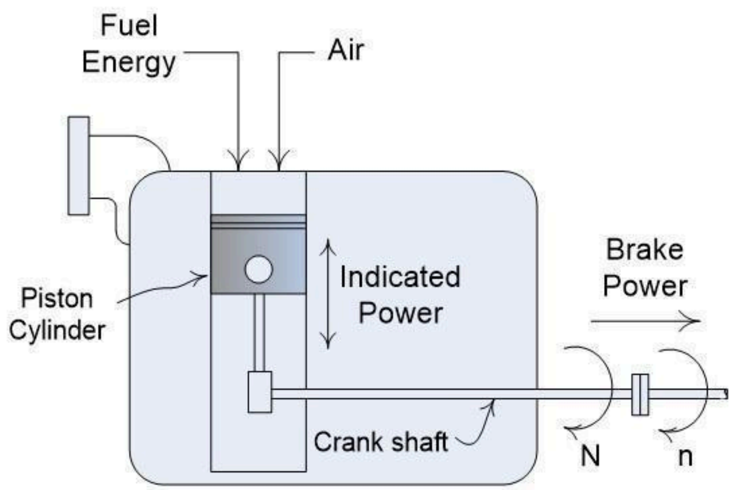


FIGURE 2: An internal combustion engine converting chemical energy from fuel to produce brake power

Again, not all energy from the fuel is converted into indicated power and brake power. The rotating shaft that rests in a bearing and the metal to metal contact between parts of the engine produces friction, and some are converted into heat that just flows out to the surroundings. The Second Law of thermodynamics takes this into consideration.

SYSTEM OF UNITS

In the study of thermodynamics, it is important to familiarize ourselves with the fundamental units that are commonly used to measure physical quantities of thermodynamic substances. Some of these units are given in Table 1.

Quantity	SI Units	English Units
Length	m	in, ft
Mass	kg	lb_m
Time	s	sec
Temperature	^oC, K	^oF, ^oR
Area	m^2	ft^2
Volume	m^3	ft^3
Velocity	m/s	ft/sec
Acceleration	m/s^2	ft/sec^2
Force	N	lb_f
Energy	N-m, J	Btu
Pressure	N/m^2, Pa	lb_f/in^2, psi
Power	J/s, W	Hp, Btu/sec

TABLE 1: Fundamental units used to quantify thermodynamic substances

Other Nomenclatures

H = Total enthalpy, kJ
h = Specific enthalpy, kJ/kg

U = Total internal energy, kJ
u = Specific internal energy, kJ/kg

S = Total entropy, kJ/K
s = Specific entropy, kJ/kg-K

V = Total volume, m^3
v = specific volume, m^3/kg

Temperature

Term used to measure the degree of hotness or coldness of a thermodynamic substance with reference to standard value. Thermometer is the instrument used to measure temperature.

Arbitrary scale, t:

Centigrade or Celsius (^oC)

On the Centigrade or Celsius scale the boiling point of water at standard atmospheric pressure is 100^oC and the freezing point is 0^oC.

Fahrenheit (^oF)

On the Fahrenheit scale the boiling point of water at standard atmospheric pressure is 212^oF and the freezing point is 32^oF.

Conversion: $^oC = \frac{5}{9}(\ ^oF - 32)$

Absolute Temperature, T: Kelvin (K) = ^oC + 273

Rankine (^oR) = ^oF + 460

ZEROTH LAW OF THERMODYNAMICS

Zeroth Law of thermodynamics states that if two closed systems with different temperatures are brought together in thermal contact with a third system, the heat will flow from the system with a high temperature to the system with low temperature until the bodies reach thermal equilibrium with each other.

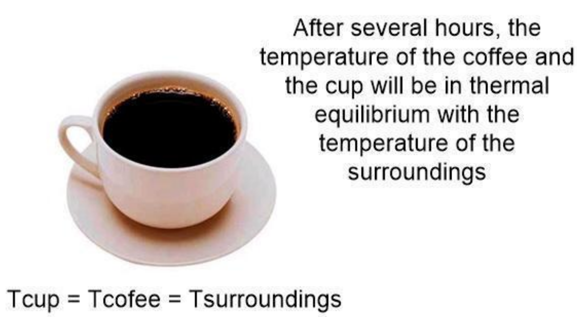


FIGURE 3: A cup of coffee obeying the Zeroth law of thermodynamics

Thermal equilibrium occurs when two objects in thermal contact no longer affect each other's temperature. One example of this is a cup of coffee on a table. If you leave it for several hours, the coffee will cool off until the coffee and the cup will reach thermal equilibrium with the surroundings.

NEWTON’S FIRST LAW OF MOTION (LAW OF INERTIA)

An object will remain at rest or move in a straight line at a constant velocity unless acted upon by an external force.

NEWTON’S SECOND LAW OF MOTION (LAW OF ACCELERATION)

Newton’s second law of motion states that the object will accelerate in the direction directly proportional to the unbalanced force acting on it.

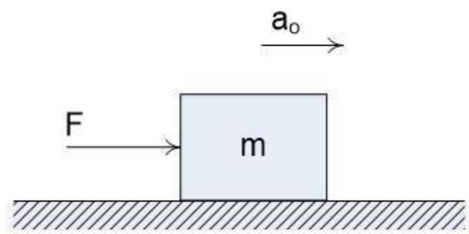


FIGURE 4: An unbalanced force applied in an object

$$F \,\alpha\, a_o$$

$$F = m\left(\frac{a_o}{g_C}\right)$$

Where: F = unbalance force

m = mass of the object

$a_o = g_o$ = observed acceleration or local gravitational acceleration

$$g_o = 9.81\,\frac{m}{s^2} = 32.2\,\frac{ft}{sec^2}$$

g_C = proportionality constant

$$g_C = 1\,\frac{kg - m}{N - s^2} = 32.2\,\frac{lb_m - ft}{lb_f - sec^2}$$

NEWTON’S THIRD LAW OF MOTION (LAW OF ACTION-REACTION)

For every action, there is an equal and opposite reaction. When one object applies a force on another, the second object applies an equal force in the opposite direction on the first object. These forces act on different objects and do not cancel each other out.

Sample Problem:

The weight of the object measured in Mars is 10 N where the observed gravitational acceleration is 3.40 m/s^2. Determine the weight of the object on earth where the gravitational acceleration is 9.81 m/s^2.

Given: Weight of the object on Mars, W_m = 10N
Gravitational acceleration on Mars, g_M = 3.40 m/s^2
Gravitational acceleration on Earth, g_e = 9.81 m/s^2

Solution:

To find the mass of the object, we can use and rearrange the formula:

$$W_m = m_{object}\left(\frac{g_M}{g_c}\right)$$

$$10N = m_{object}\left(\frac{3.40\,\frac{m}{s^2}}{1\,\frac{kg-m}{N-s}}\right)$$

$$m_{object} = 2.9412\,kg$$

The mass of the object in Mars will be the same if it is brought down on earth, therefore the weight of the object on earth is:

$$W_{object} = m_{object}\left(\frac{g_e}{g_c}\right)$$

$$W_{object} = 2.9412\,kg\left(\frac{9.81\,\frac{m}{s^2}}{1\,\frac{kg-m}{N-s}}\right)$$

$$W_{object} = 28.8532\,N$$

Fluid Properties

DENSITY and SPECIFIC VOLUME

The density is defined as mass per unit volume, and specific volume is defined as volume per unit mass. Specific volume is the inverse of density.

$$Density = \rho = \frac{m}{V}$$

$$Specific\,Volume = \bar{v} = \frac{V}{m} = \frac{1}{\rho}$$

Note:

$$\rho_{water} = 1000\,\frac{kg}{m^3} = 1\,\frac{kg}{L} = 62.4\,\frac{lb_m}{ft^3}$$

SPECIFIC WEIGHT

Specific weight is defined as weight (Force) of the thermodynamic substance per unit volume.

$$Specific\,Weight = \gamma = \frac{F}{V}$$

$$\gamma = \frac{m}{V}\left(\frac{g_o}{g_c}\right)$$

$$\gamma = \rho\left(\frac{g_o}{g_c}\right)$$

Note:

$$\gamma_{water} = 9.81\,\frac{kN}{m^3} = 62.4\,\frac{lb_f}{ft^3}$$

SPECIFIC GRAVITY or RELATIVE DENSITY

Specific gravity or Relative Density is defined as the ratio of the density of a substance by the density of standard substance, such as water at 4°C (39.2°F).

$$SG = \frac{\rho_{substance}}{\rho_{water}} = \frac{\gamma_{substance}}{\gamma_{water}}$$

Sample Problem:

The specific weight of an object is 3.5 kN/m^3. Determine the

(a) Mass density
(b) Mass if the dimension of the object is 6cm x 15cm x 8cm
(c) Specific Volume
(d) Specific Gravity

Given: $\gamma_{object} = 3.5\,\frac{kN}{m^3}$

Solution:

1. Solving for Mass density, ρ

$$\gamma_{object} = \rho_{object}\left(\frac{g_o}{g_c}\right)$$

$$3.5\,\frac{kN}{m^3} = \rho_{object}\left(\frac{9.81\,\frac{m}{s^2}}{1\,\frac{kg-m}{kN-s^2}}\right)$$

$$\rho_{object} = 356.7788\,\frac{kg}{m^3}$$

2. Solving for the mass if volume is 6cm x 15cm x 8cm

$$\rho_{object} = \frac{m_{object}}{V_{object}}$$

$$356.7788\,\frac{kg}{m^3} = \frac{m_{object}}{(0.06\,x\,0.15\,x\,0.08)m^3}$$

$$m_{object} = 0.2568\,kg$$

3. Solving for the specific volume, $\bar{v}_{object}$

$$\bar{v}_{object} = \frac{V_{object}}{m_{object}} = \frac{(0.06\,x\,0.15\,x\,0.08)m^3}{0.2568\,kg}$$

$$\bar{v}_{object} = 2.8029\,x\,10^{-3}\,\frac{m^3}{kg}$$

4. Solving for the specific gravity, SG_{object}

$$SG_{object} = \frac{\rho_{object}}{\rho_{water}} = \frac{356.7788 \frac{kg}{m^3}}{1000 \frac{kg}{m^3}}$$

$$SG_{object} = 0.3568$$

PRESSURE
The pressure of a fluid is defined as force per unit area, measured in Pascal defined as 1 Newton per square meter.

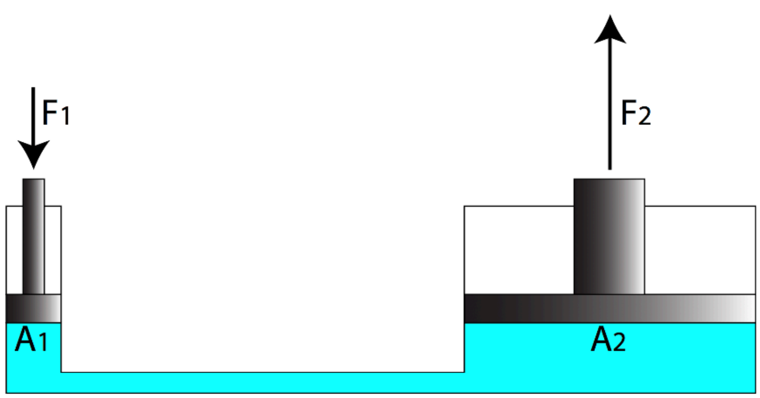
$$Pressure = \frac{Force}{Area}$$

$$P = \frac{F}{A}$$

Pascal's Principle, also known as Pascal's Law, states that when a change in pressure is applied to an enclosed fluid, the change is transmitted undiminished to all portions of the fluid and to the walls of its container. In simpler terms, any pressure applied to a fluid in a closed container is transmitted equally in all directions, allowing for the transmission of force through the fluid.

This principle was formulated by Blaise Pascal, a French mathematician, physicist, and philosopher, in the 17th century. And expressed by:

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$



This principle is the foundation for the operation of [hydraulic systems](), where a small force applied to a small area can generate a larger force on a larger area by utilizing the incompressibility of fluids. It's the reason why, for instance, pressing the brake pedal in a car can result in the activation of the braking mechanism in all the wheels.

Absolute Pressure

Absolute pressure is measured from the datum of absolute zero pressure or perfect vacuum.

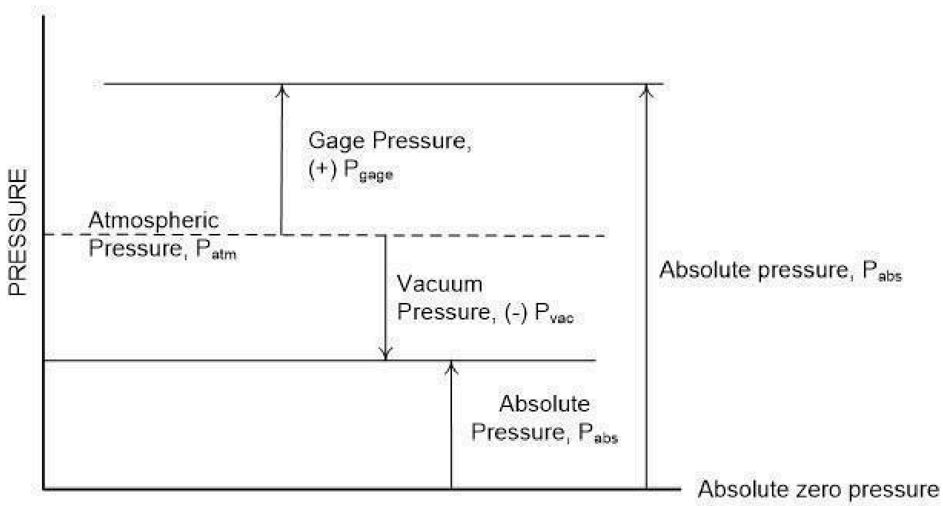


FIGURE 1: A graphical representation of pressure

Atmospheric Pressure

Atmospheric pressure is the pressure caused by the weight of the atmosphere.

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

At standard sea-level, the atmospheric pressure is:
1 atm = 101.325 kPa = 14.7 psi = 760 mmHg

Gage Pressure

Gage pressure is a pressure difference between the system and the atmospheric pressure. An ordinary pressure gage will have a reading of zero this simply means that there is no excess pressure other than the atmospheric pressure.

Vacuum Pressure

Vacuum pressure is a pressure which is significantly lower than atmospheric pressure.

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

Bourdon gage is commonly used instrument to measure gage pressure

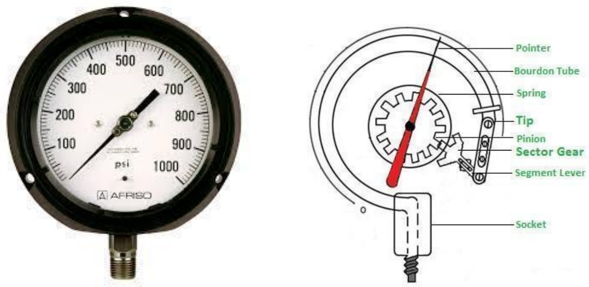


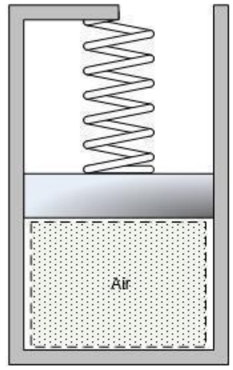
FIGURE 2: Bourdon gage

A manometer is another instrument used to measure gage pressure or vacuum (negative pressure)

FIGURE 3: U-tube manometer

Sample Problem:

Consider a vertical spring-loaded piston cylinder. The gas inside the cylinder has a pressure of 130 kPa. And the spring exerts a downward force of 200 N on the top of the piston. The diameter of the piston is 10 cm and the atmospheric pressure is 1 bar. Determine the mass of the piston that will maintain equilibrium. Neglect the friction effects between the surface of the piston and the cylinder.



Solution:

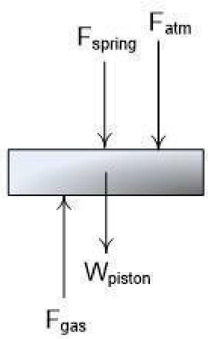
Given: $P_{gas} = 130\ kPa = 130,000\ Pa = 130,000\ \frac{N}{m^2}$

$F_{spring} = 200\ N$

$d_{piston} = 0.10\ m$

$P_{atm} = 1\ bar = 100\ kPa = 100,000\ Pa = 100,000\ \frac{N}{m^2}$

Free-body diagram of the piston:



Summation of Forces:

$$+\uparrow\left[\sum F_y = 0\right]$$

$$F_{gas} - F_{spring} - W_{piston} - F_{atm} = 0$$

$$W_{piston} = F_{gas} - F_{spring} - F_{atm}$$

$$m_{piston}\left[\frac{g_o}{g_c}\right] = P_{gas}A_{piston} - F_{spring} - P_{atm}A_{piston}$$

For the Area of the Piston: $A_{piston} = \pi\frac{d_{piston}^{\ 2}}{4} = \pi\frac{(0.10m)^2}{4} = 0.007854\ m^2$

Substitute:

$$m_{piston}\left[\frac{9.81\ \frac{m}{s^2}}{1\ \frac{kg-m}{N-s^2}}\right] = \left(130,000\ \frac{N}{m^2}\right)\left(0.007854\ m^2\right) - 200\ N - \left(100,000\ \frac{N}{m^2}\right)\left(0.007854\ m^2\right)$$

$$m_{piston} = 3.6309\ kg$$

Pressure and Depth of the Fluid

If an object P is placed in a container, the object experiences a pressure acting normal all over its surface. This pressure is due to the weight of the fluid above it and increases proportionally as the object goes deeper inside the container.

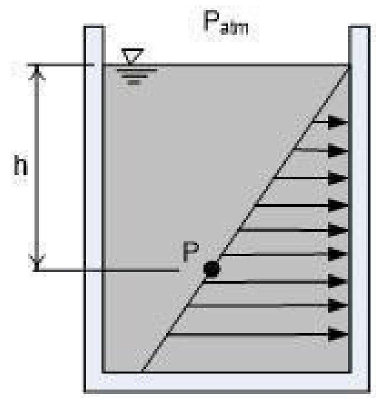
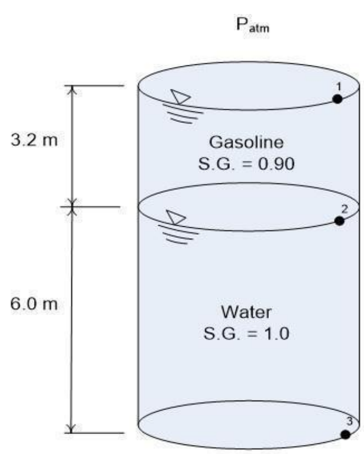


FIGURE 4: A graphical representation of pressure exerted by fluid in a container

Sample Problem:

An open tank is filled with 6.0 meters of water and 3.2 meters of gasoline with specific gravity of 0.90. Determine:

(a) The interface pressure between the water and gasoline
(b) The pressure at the bottom of the tank.
(c) The force exerted by the fluids at the bottom when the diameter of the tank is 1.3 meters.



Solution:

Given: $h_{water} = 6\, m$
$h_{gasoline} = 3.2\, m$
$SG_{gasoline} = 0.90$
$d_{tank} = 1.3\, m$

a. The interface pressure between the water and gasoline, P_2

$$P_2 - P_1 = \gamma_{gasoline} h_{gasoline}$$

Since the tank is open to the atmosphere, $P_1 = 0_{gage}$

$$P_2 = SG_{gasoline}\gamma_{water}h_{gasoline} = (0.90)\left(9.81\frac{kN}{m^2}\right)(3.2\, m)$$

$$P_2 = 28.2528\, KPa$$

b. The pressure at the bottom of the tank, P_3

$$P_3 - P_2 = \gamma_{water} h_{water}$$

$$P_3 - 28.2528\, kPa = \left(9.81\frac{kN}{m^2}\right)(6\, m)$$

$$P_3 - 28.2528\, kPa = \left(9.81\frac{kN}{m^2}\right)(6\, m)$$

$$P_3 = 87.1128\, KPa$$

c. The force exerted by the fluids at the bottom when the diameter of the tank is 1.3m, F_3

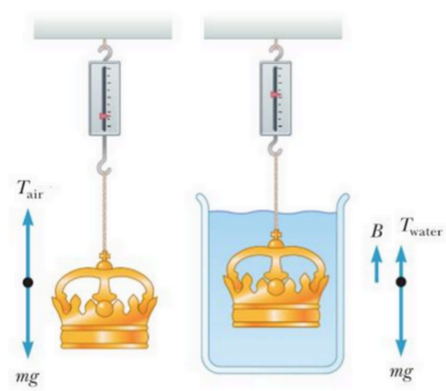
$$F_3 = P_3 A = P_3\left[\frac{\pi}{4}d_{tank}^{\ 2}\right] = \left(87.1128\,\frac{kN}{m^2}\right)\frac{\pi}{4}(1.3m)^2$$

$$F_3 = 115.6268\, kN$$

BUOYANCY
When a body is immersed in a fluid either fully or partially, it is subjected to an upward force which tends to lift or buoy it up. This tendency of an immersed body to be lifted up due to an upward force opposite to the gravitational force is known as *buoyancy* and the force is known as *buoyant force or upthrust*.

Archimedes' Principle
The buoyant force acting on the body is equal to the weight of the fluid displaced by the body. A floating body displaces volume of fluid, just sufficient to balance its weight.

Sample Problem:
A bargain hunter purchases a "gold" crown at a flea market. After she gets home, she hangs it from the scale and finds its weight to be 7.84 N. She then weighs the crown while it is immersed in water, and now the scale reads 6.86 N. Is the crown made of pure gold?



Solution:
Solving for Buoyant force, F_B:

$$F_B = W - T_{water}$$

$$F_B = (7.84 - 6.86)N = 0.98N$$

According to Archimedes Principle:

$$F_B = \gamma_{water} V_{water}$$

$$0.98N = 9810 \frac{N}{m^3}$$

$$V_{water} = 9.9898 \, x \, 10^{-5} \, m^3$$

The crown is totally submerged, therefore $V_{water} = V_{crown}$

$$\rho_{crown} = \frac{m_{crown}}{V_{crown}} = \frac{7.84N\left(\frac{1\frac{kg-m}{N-s^2}}{9.81\ \frac{m}{s^2}}\right)}{9.9898\ x\ 10^{-5}\ m^3}$$

$$\rho_{crown} = 8,000\ \frac{kg}{m^3}$$

Because the density of gold is $\rho_{gold} = 19,300\ \frac{kg}{m^3}$, the crown is hollow or made of an alloy.