Part I

Introduction to Basic Principles of Pumps and Hydraulics

Chapter 1

Basic Fluid Principles

Pumps are devices that expend energy to raise, transport, or compress fluids. The earliest pumps were made for raising water. These are known today as *Persian* and *Roman waterwheels* and the more sophisticated *Archimedes screw*.

Mining operations of the Middle Ages led to development of the *suction* or *piston pump*. There are many types of suction pumps. They were described by Georgius Agricola in his *De re Metallica* written in 1556 A.D. A suction pump works by atmospheric pressure. That means when the piston is raised, it creates a partial vacuum. The outside atmospheric pressure then forces water into the cylinder. From there, it is permitted to escape by way of an outlet valve. Atmospheric pressure alone can force water to a maximum height of about 34 feet (10 meters). So, the force pump was developed to drain deeper mines. The downward stroke of the force pump forces water out through a side valve. The height raised depends on the force applied to the piston.

Fluid is employed in a closed system as a medium to cause motion, either linear or rotary. Because of improvements in seals, materials, and machining techniques, the use of fluids to control motions has greatly increased in the recent past.

Fluid can be either in a liquid or gaseous state. Air, oil, water, oxygen, and nitrogen are examples of fluids. They can all be pumped by today's highly improved devices.

Physics

A branch of science that deals with matter and energy and their interactions in the field of mechanics, electricity, nuclear phenomena, and others is called *physics*. Some of the basic principles of fluids must be studied before subsequent chapters in this book can be understood properly.

Matter

Matter can be defined as anything that occupies space, and all matter has inertia. Inertia is that property of matter by which it will remain at rest or in uniform motion in the same straight line or direction unless acted upon by some external force. *Matter* is any substance that can be weighed or measured. Matter may exist in one of three states:

- Solid (coal, iron, ice)
- Liquid (oil, alcohol, water)
- Gas (air, hydrogen, helium)

Water is the familiar example of a substance that exists in each of the three states of matter (see Figure 1-1) as ice (solid), water (liquid), and steam (gas).

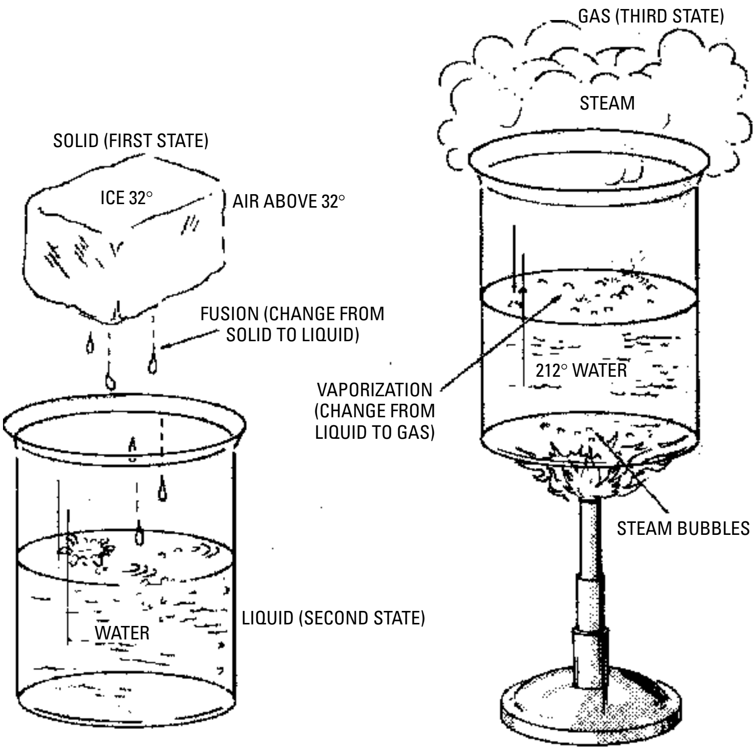


Figure 1-1 The three states of matter: solid, liquid, and gas. Note that the change of state from a solid to a liquid is called fusion, and the change of state from liquid to a gas is called vaporization.

Body

A body is a mass of matter that has a definite quantity. For example, a mass of iron 3 inches × 3 inches × 3 inches has a definite quantity of 27 cubic inches. It also has a definite weight. This weight can be determined by placing the body on a scale (either a lever or platform scale or a spring scale). If an accurate weight is required, a lever or platform scale should be employed. Since weight depends on gravity, and since gravity decreases with elevation, the reading on a spring scale varies, as shown in Figure 1-2.

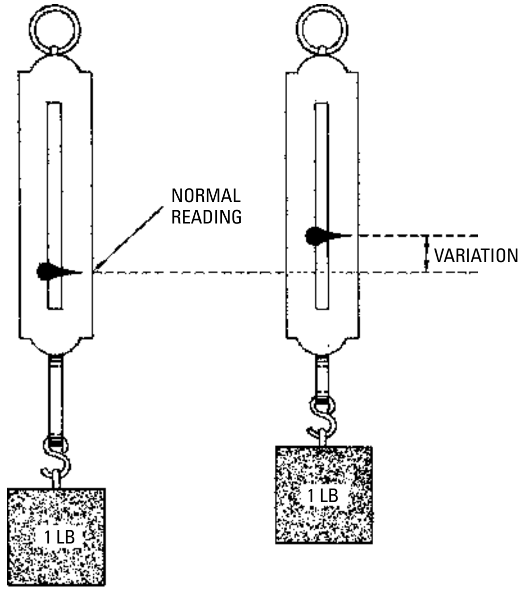


Figure 1-2 Variation in readings of a spring scale for different elevations.

Energy

Energy is the capacity for doing work and overcoming resistance. Two types of energy are *potential* and *kinetic* (see Figure 1-3).

Potential energy is the energy that a body has because of its relative position. For example, if a ball of steel is suspended by a chain, the position of the ball is such that if the chain is cut, work can be done by the ball.

Kinetic energy is energy that a body has when it is moving with some velocity. An example would be a steel ball rolling down an incline. Energy is expressed in the same units as work (foot-pounds).

As shown in Figure 1-3, water stored in an elevated reservoir or tank represents potential energy, because it may be used to do work as it is liberated to a lower elevation.

Conservation of Energy

It is a principle of physics that energy can be transmitted from one body to another (or transformed) in its manifestations, but energy may be neither created nor destroyed. Energy may be dissipated.

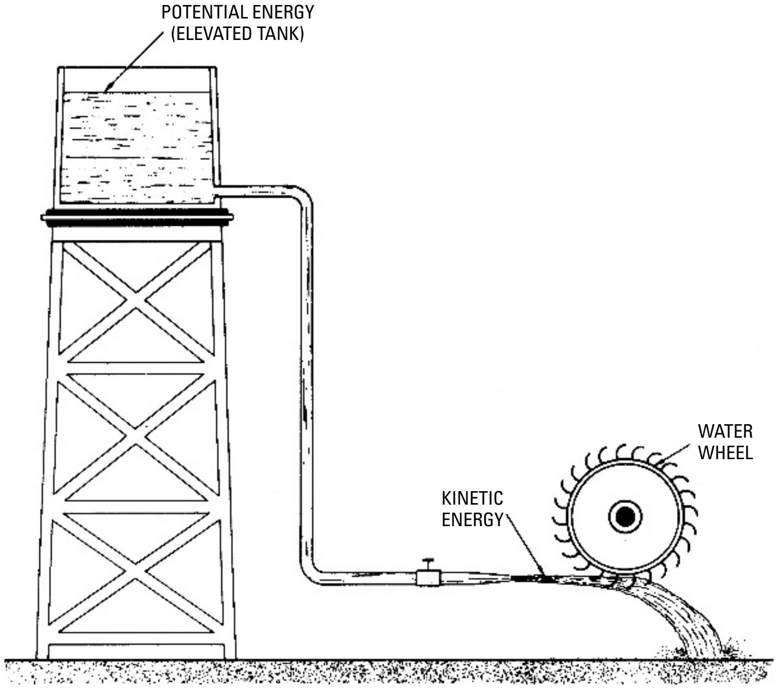


Figure 1-3 Potential energy and kinetic energy.

That is, it may be converted into a form from which it cannot be recovered (the heat that escapes with the exhaust from a locomotive, for example, or the condensed water from a steamship). However, the total amount of energy in the universe remains constant, but variable in form.

Joule's Experiment

This experiment is a classic illustration (see Figure 1-4) of the conservation of energy principle. In 1843, Dr. Joule of Manchester, England, performed his classic experiment that demonstrated to the world the mechanical equivalent of heat. It was discovered that the work performed by the descending weight (*W* in Figure 1-4) was not lost, but appeared as heat in the water—the agitation of the paddles having increased the water temperature by an amount that can be measured by a thermometer. According to Joule's experiment, when 772 foot-pounds of work energy had been expended on the 1 pound of water, the temperature of the water had increased 1°F.

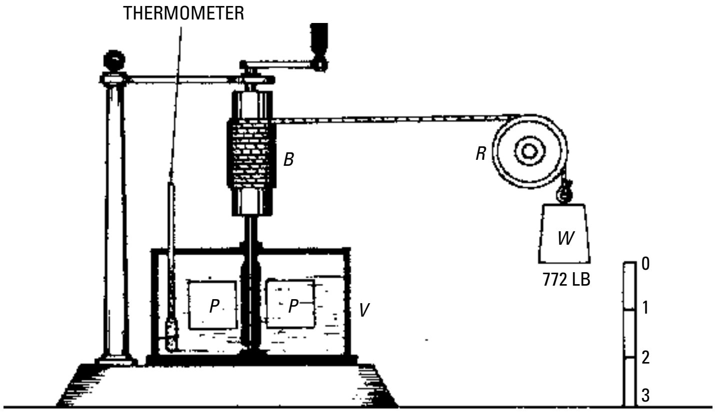


Figure 1-4 Joule's experiment revealed the mechanical equivalent of heat.

This is known as *Joule's equivalent*: That is, 1 unit of heat equals 772 foot-pounds (ft-lb) of work. (It is generally accepted today that ft-lb. be changed to lb.ft. in the meantime or transistion period you will find it as ft-lb. or lb.ft.)

Experiments by Prof. Rowland (1880) and others provide higher values. A value of 778 ft-lb is generally accepted, but 777.5 ft-lb is probably more nearly correct, the value 777.52 ft-lb being used by Marks and Davis in their steam tables. The value 778 ft-lb is sufficiently accurate for most calculations.

Heat

Heat is a form of energy that is known by its effects. The effect of heat is produced by the accelerated vibration of molecules. Theoretically, all molecular vibration stops at –273°C (known as absolute zero), and there is no heat formed. The two types of heat are *sensible* heat and *latent* heat.

Sensible Heat

The effect of this form of heat is indicated by the sense of touch or feeling (see Figure 1-5).

Sensible heat is measured by a thermometer. A thermometer is an instrument used to measure the temperature of gases, solids, and liquids. The three most common types of thermometers are *liquid-in-glass*, *electrical*, and *deformation*.

The liquid-in-glass generally employs mercury as the liquid unless the temperature should drop below the freezing point of mercury,

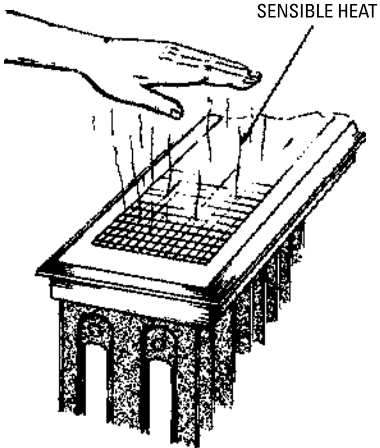


Figure 1-5 The radiator is an example of sensible heat.

in which case alcohol is used. The liquid-in-glass is relatively inexpensive, easy to read, reliable, and requires no maintenance. The thermometer consists of a glass tube with a small uniform bore that has a bulb at the bottom and a sealed end at the top. The bulb and part of the tube are filled with liquid. As the temperature rises, the liquid in the bulb and tube expand and the liquid rises in the tube. When the liquid in the thermometer reaches the same temperature as the temperature outside of the thermometer, the liquid ceases to rise.

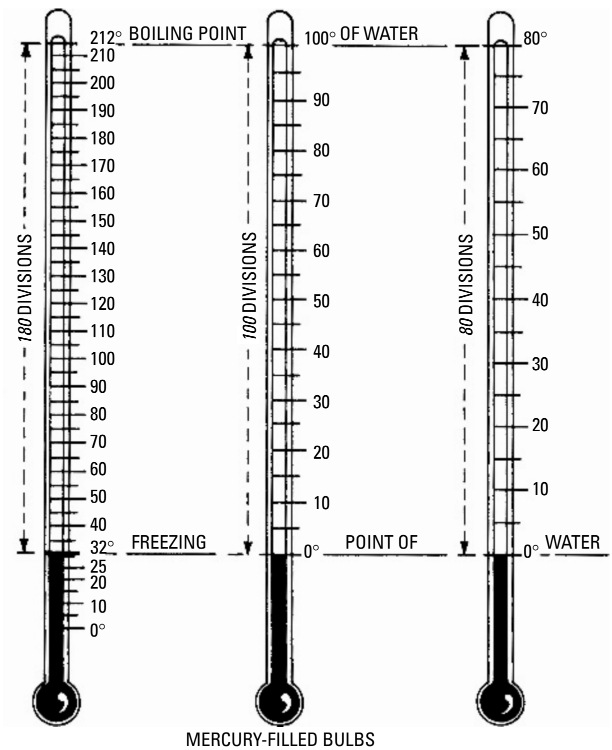
In 1714, Gabriel Daniel Fahrenheit built a mercury thermometer of the type now commonly in use.

Electrical thermometers are of the more sophisticated type. A *thermocouple* is a good example. This thermometer measures temperatures by measuring the small voltage that exists at the junction of two dissimilar metals. Electrical thermometers are made that can measure temperatures up to 1500°C.

Deformation thermometers use the principle that liquids increase in volume and solids increase in length as temperatures rise. The *Bourdon tube thermometer* is a deformation thermometer.

Extremely high temperatures are measured by a *pyrometer*. One type of pyrometer matches the color (such as that of the inside of a furnace) against known temperatures of red-hot wires.

Figure 1-6 shows the Fahrenheit, Celsius, and Reaumur thermometer scales. Figure 1-7 illustrates the basic principle of a thermocouple pyrometer.



(A) Fahrenheit. (B) Celsius. (C) Reaumur.

Figure 1-6 Three types of thermometer scales.

Latent Heat

This form of heat is the quantity of heat that becomes concealed or hidden inside a body while producing some change in the body other than an increase in temperature.

When water at atmospheric pressure is heated to 212°F, a further increase in temperature does not occur, even though the supply of heat is continued. Instead of an increase in temperature, vaporization occurs, and a considerable quantity of heat must be added to the liquid to transform it into steam. The total heat consists of *internal* and *external* latent heats. Thus, in water at 212°F and at

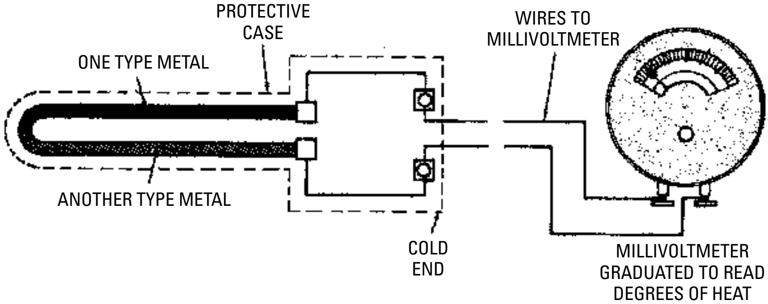


Figure 1-7 Basic principle of a thermocouple pyrometer. A thermocouple is used to measure high temperatures. In principle, when heat is applied to the junction of two dissimilar metals, a current of electricity begins to flow in proportion to the amount of heat applied. This current is brought to a meter and translated in terms of heat.

atmospheric pressure, considerable heat is required to cause the water to begin boiling (internal latent heat). The additional heat that is required to boil the water is called *external latent heat*. Figure 1-8 shows a familiar example of both internal and external latent heat.

(A) Internal latent heat—waiting for the pot to boil.

(B) External latent heat—when the pot boils.

Figure 1-8 Domestic setting for illustrating internal (left) and external (right) latent heat.

Unit of Heat

The *heat unit* is the amount of heat required to raise the temperature of 1 pound of water 1°F at the maximum density of the water. The *British thermal unit* (abbreviated Btu) is the standard for heat measure. A unit of heat (Btu) is equal to 252 calories, which is the quantity of heat required to raise the temperature of 1 pound of water from 62°F to 63°F.

Assuming no loss of heat, 180 Btu are required to raise the temperature of 1 pound of water from 32°F to 212°F. If the transfer of heat occurs at a uniform rate and if six minutes are required to increase the temperature of the water from 32°F to 212°F, 1 Btu is transferred to the water in $(6 \times 60) \div 180$, or 2 seconds.

Specific Heat

This is the ratio of the number of Btu required to raise the temperature of a substance 1°F to the number of Btu required to raise the temperature of an equal amount of water 1°F. Some substances can be heated more quickly than other substances. Metal, for example, can be heated more quickly than glass, wood, or air. If a given substance requires one-tenth the amount of heat to bring it to a given temperature than is required for an equal weight of water, the number of Btu required is $^1/_{10}$ (0.1), and its specific heat is $^1/_{10}$ (0.1).

Example

The quantity of heat required to raise the temperature of 1 pound of water 1°F is equal to the quantity of heat required to raise the temperature of 8.4 pounds of cast iron 1°F. Since the specific heat of water is 1.0, the specific heat of cast iron is 0.1189 ($1.0 \div 8.4$).

Thus, the specific heat is the ratio between the two quantities of heat. Table 1-1 shows the specific heat of some common substances.

Transfer of Heat

Heat may be transferred from one body to another that is at a lower temperature (see Figure 1-9) by the following:

- Radiation
- Conduction
- Convection

When heat is transmitted by radiation, the hot material (such as burning fuel) sets up waves in the air. In a boiler-type furnace, the heat is given off by *radiation* (the heat rays radiating in straight lines in all directions). The heat is transferred to the crown sheet and the sides of the furnace by means of radiation.

Contrary to popular belief that heat is transferred through solids by radiation; heat is transferred through solids (such as a boilerplate) by conduction (see Figure 1-10). The temperature of the furnace boilerplate is only slightly higher than the temperature of the water that is in contact with the boilerplate. This is because of the extremely high conductivity of the plate.

Conduction of heat is the process of transferring heat from molecule to molecule. If one end of a metal rod is held in a flame and

Table 1-1 Specific Heat of Common Substances

Solids		***Liquids***	
Copper	0.0951	Water	1.0000
Wrought Iron	0.1138	Sulfuric acid	0.3350
Glass	0.1937	Mercury	0.0333
Cast Iron	0.1298	Alcohol	0.7000
Lead	0.0314	Benzene	0.9500
Tin	0.0562	Ether	0.5034
Steel, Hard	0.1175		
Steel, Soft	0.1165		
Brass	0.0939		
Ice	0.5040		
Gases			
Type	***At Constant Pressure***	***At Constant Volume***	
Air	0.23751	0.16847	
Oxygen	0.21751	0.15507	
Hydrogen	3.40900	2.41226	
Nitrogen	0.24380	0.17273	
Ammonia	0.50800	0.29900	
Alcohol	0.45340	0.39900	

the other end in the hand, the end in the hand will become warm or hot. The reason for this is that the molecules in the rod near the flame become hot and move rapidly, striking the molecules next to them. This action is repeated all along the rod until the opposite end is reached. Heat is transferred from one end of the rod to the other by conduction. Conduction depends upon unequal temperatures in the various portions of a given body.

Convection of heat is the process of transmitting heat by means of the movement of heated matter from one location to another. Convection is accomplished in gases and liquids.

In a place heated by a radiator, the air next to the radiator becomes warm and expands. The heated air becomes less dense than the surrounding cold air. It is forced up from the radiator by the denser, colder air. Most home heating systems operate on the principle of transmission of heat by convection.

Nearly all substances expand with an increase in temperature, and they contract or shrink with a decrease in temperature. There

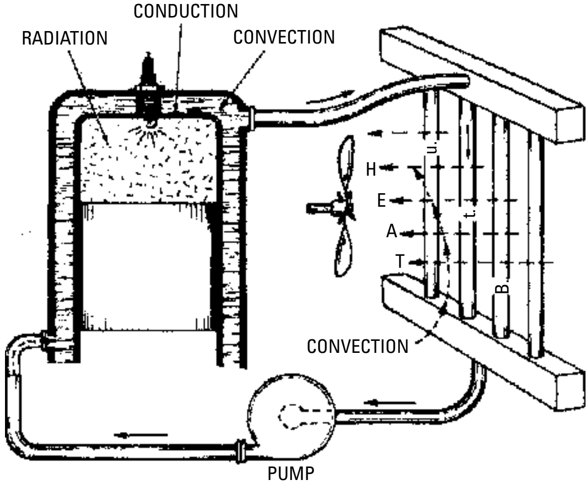


Figure 1-9 Transfer of heat by radiation, conduction, and convection. It should be noted that the air, not the water, is the cooling agent. The water is only the medium for transferring the heat to the point where it is extracted and dissipated by the air.

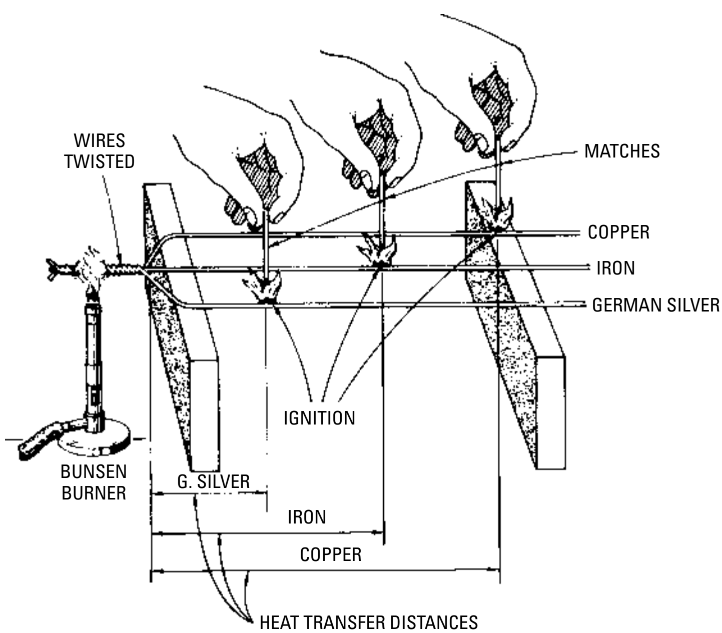


Figure 1-10 Differences in heat conductivity of various metals.

is one exception to this statement for all temperature changes, the exception being water. It is a remarkable characteristic of water that at its maximum density (39.1°F) water expands as heat is added and that it also expands slightly as the temperature decreases from that point.

Increase in heat causes a substance to expand, because of an increase in the velocity of molecular action. Since the molecules become more separated in distance by their more frequent violent collisions, the body expands.

Linear expansion is the expansion in a longitudinal direction of solid bodies, while *volumetric expansion* is the expansion in volume of a substance.

The *coefficient of linear expansion* of a solid substance is the ratio of increase in length of body to its original length, produced by an increase in temperature of 1°F.

Expansion and contraction caused by a change in temperature have some advantages, but also pose some disadvantages. For example, on the plus side, rivets are heated red-hot for applying to bridge girders, structural steel, and large boilerplates. As the rivets cool, they contract, and provide a solid method of fastening. Iron rims are first heated and then placed on the wheel. As the iron cools, the rim contracts and binds the wheel so that it will not come off. Common practice is to leave a small space between the ends of the steel sections that are laid end on end. This is to allow for longitudinal expansion and contraction. Table 1-2 shows values that can be used in calculation of linear expansion.

Some of the disadvantages of expansion and contraction caused by change in temperatures are setting up of high stresses, distortion, misalignment, and bearing problems.

Pressure

Pressure (symbol *P*) is a force exerted against an opposing body, or a thrust distributed over a surface. Pressure is a force that tends to compress a body when it is applied.

If a force is applied in the direction of its axis, a spring is compressed (see Figure 1-11). The resistance of the spring constitutes an opposing force, equal and opposite in direction to the applied force. Pressure is distributed over an entire surface. This pressure is usually stated in pounds per square inch (psi).

If a given force is applied to a spring, the spring will compress to a point where its resistance is equal to the given force.

In Figure 1-11b, the condition of the pressure system is in a state of equilibrium.

Table 1-2 Linear Expansion of Common Metals (between 32°F and 212°F)

Metal	*Linear Expansion per Unit Length per Degree F*
Aluminum	0.00001234
Antimony	0.00000627
Bismuth	0.00000975
Brass	0.00000957
Bronze	0.00000986
Copper	0.00000887
Gold	0.00000786
Iron, cast	0.00000556
Iron, wrought	0.00000648
Lead	0.00001571
Nickel	0.00000695
Steel	0.00000636
Tin	0.00001163
Zinc, cast	0.00001407
Zinc, rolled	0.00001407

Volumetric expansion = 3 times linear expansion.

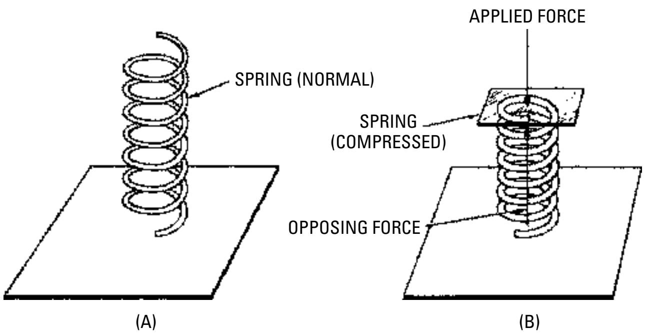


Figure 1-11 The nature of pressure: (a) spring in its normal state; and (b) pressure system in state of equilibrium.

Problem

The total working area of the plunger of a pump is 10 square inches. What is the amount of pressure on the plunger when pumping against 125 psi (see Figure 1-12)?

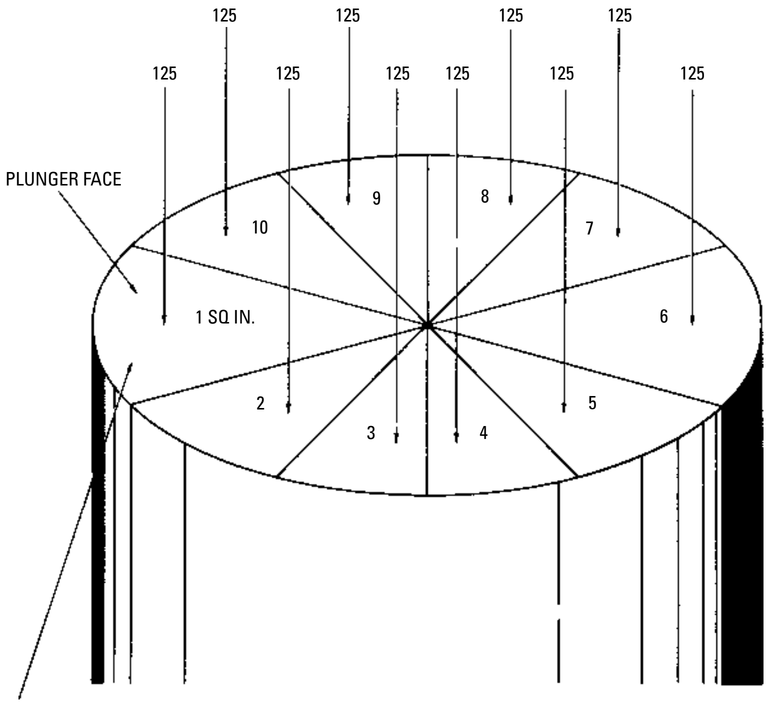


Figure 1-12 The distribution of pressure over a surface. A pressure of 125 psi is exerted on each sector (1 square inch).

Solution

Since 125 pounds of pressure are exerted on each square inch of the working face of the plunger, and since the area of the working face of the plunger is 10 square inches, the total pressure exerted on the plunger face is 1250 pounds, as shown here:

$$10 \text{ sq in} \times 125\text{psi} = 1250 \text{ lb}$$

The ball-peen hammer is used for peening and riveting operations. The peening operation indents or compresses the surface of the metal, expanding or stretching that portion of the metal adjacent to the indentation. As shown in Figure 1-13, the contact area is nearly zero if the flat and special surfaces are perfectly smooth. However, perfectly smooth surfaces do not exist. The most polished surfaces (as seen under a microscope) are similar to emery paper. Therefore, the contact area is very small. As shown in Figure 1-14,

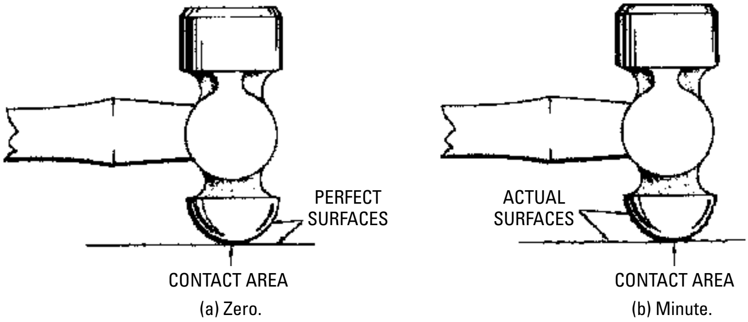


Figure 1-13 Theoretical contact area (a) and actual contact area (b) of flat and spherical surfaces.

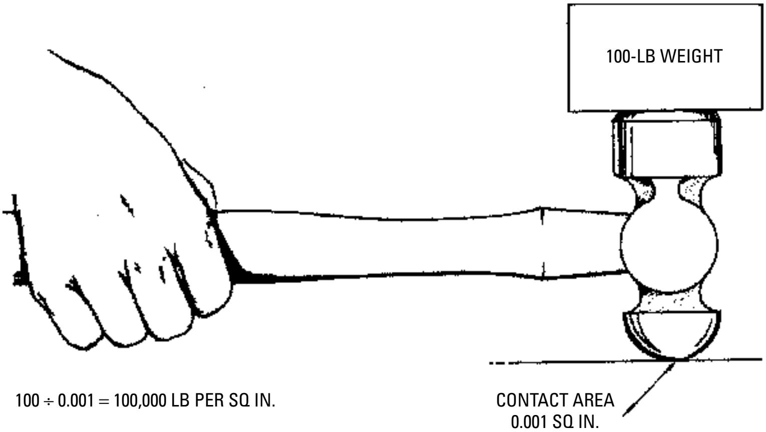


Figure 1-14 The pressure (psi) is multiplied when it is applied to the flat surface through a spherical contact area.

the pressure, in psi, is multiplied when applied through a spherical contact surface.

Problem

If the ball-peen of a machinist's hammer is placed in contact with a flat surface (see Figure 1-14) and a weight of 100 lb is placed on the hammer (not including the weight of the hammer), how many pounds of pressure are exerted at the point of contact if the contact area is 0.01 square inch?

Solution

If the contact area were 1 square inch in area, the pressure would equal 100 pounds on the 1 square inch of flat surface. Now, if the entire 100-pound weight or pressure is borne on only 0.01 square inch (see Figure 1-14), the pressure in psi is equal to 10,000 psi $(100 \div 0.01)$.

Perhaps another example (see Figure 1-15) may illustrate this point more clearly.

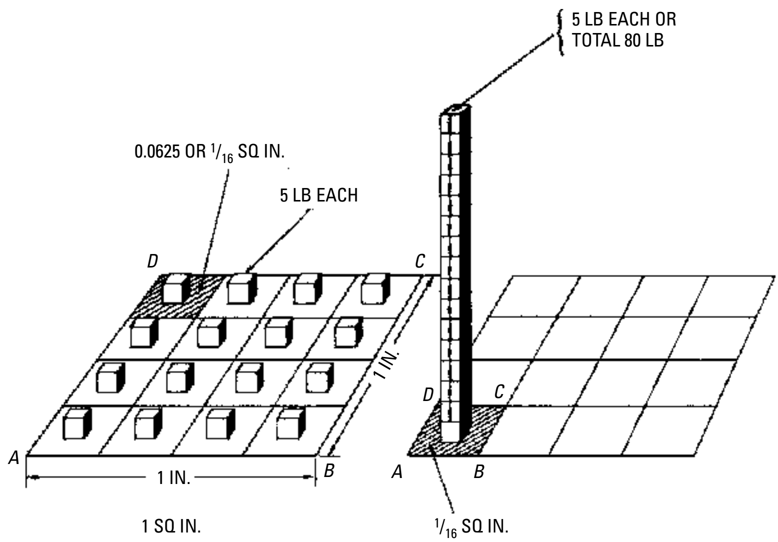


Figure 1-15 Pressure per square inch of flat surface.

Problem

Lay out entire surface ABDC equal to 1 square inch, and divide the surface into 16 small squares ($^1/_{16}$ square inch), placing a 5-pound weight on each small square. The area of each small square is $(^1/_{16})^2$, or 0.0625 square inches. If all the 5-pound weights are placed on one small square (as in the diagram), the total weight or pressure on that small square is 80 pounds (5×16), or, on 0.0625 square inches of surface.

In the left-hand diagram (see Figure 1-15), the 5-pound weights are distributed over the entire 1 square inch of area, the pressure totaling 80 psi of surface (5×16). In the right-hand diagram, the sixteen 5-pound weights (80 lb) are borne on only 0.0625 square inches of surface. This means the total weight or pressure (if each of the sixteen small squares were to bear 80 pounds) would be 1280 psi of surface (16 × 80).

Atmospheric Pressure

Unless stated otherwise, the term *pressure* indicates pressure psi. The various qualifications of pressure are *initial pressure*, *mean effective pressure*, *terminal pressure*, *backpressure*, and *total pressure*.

The atmospheric pressure is due to the weight of the Earth's atmosphere. At sea level it is equal to approximately 14.69 psi. The pressure of the atmosphere does not remain constant at a given location, because weather conditions are changing continually.

Figure 1-16 illustrates atmospheric pressure. If a piston having a surface area of 1 square inch is connected to a weight by a string passing over a pulley, then, a weight of 14.69 pounds is required to raise the weight from the bottom of the cylinder (assuming air tightness and no friction) against the atmosphere that distributes a pressure of 14.69 pounds over the entire face area of the piston

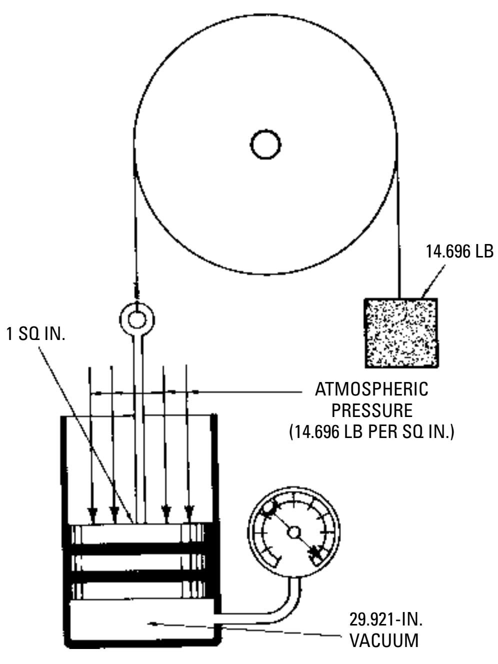


Figure 1-16 Atmospheric pressure.

(area = 1 square inch). Then the system is in a *state of equilibrium*, the weight balancing the resistance or weight of the atmosphere. A slight excess pressure is then required to move the piston.

Atmospheric pressure decreases approximately 0.5 pounds for each 1000-foot increase in elevation. When an automobile climbs a high mountain, the engine gradually loses power because air expands at higher altitudes. The volume of air taken in by the engine does not weigh as much at the higher altitudes as it weighs at sea level. The mixture becomes too rich at higher altitudes, causing a poor combustion of fuel.

A *perfect vacuum* is a space that has no matter in it. This is unattainable even with the present pumps and chemical processes. Space in which the air pressure is about one-thousandth of that of the atmosphere is generally called a vacuum. *Partial vacuum* has been obtained in which there are only a few billion molecules in each cubic inch. In normal air, there are about four hundred billion times a billion molecules of gas to each cubic inch.

Gage Pressure

Pressure measured above that of atmospheric pressure is called *gage pressure*. Pressure measured above that of a perfect vacuum is called *absolute pressure*. Figure 1-17 illustrates the difference between gage pressure and absolute pressure.

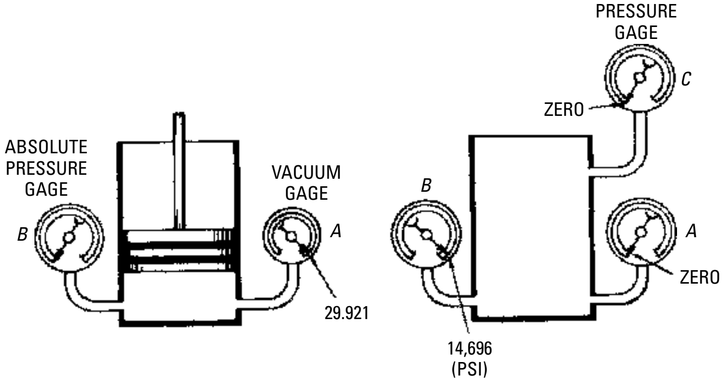


Figure 1-17 Absolute pressure (left) and gage pressure (right).

In the cylinder containing the piston (the left of Figure 1-17), a perfect vacuum exists below the piston, as registered by the value 29.921 inches of mercury (explained later) on the vacuum gage *A*. The equivalent reading on the absolute pressure gage *B* is zero psi.

If the piston is removed from the cylinder (the right of Figure 1-17), air rushes into the cylinder. That is, the vacuum is replaced by air at atmospheric pressure, the vacuum gage *A* drops to zero, the absolute pressure gage *B* reads 14.696, and the pressure gage *C* indicates a gage pressure of zero.

Barometer

A *barometer* is an instrument that is used to measure atmospheric pressure. The instrument can be used to determine height or altitude above sea level, and it can be used in forecasting weather.

The barometer reading is expressed in terms of *inches of mercury* (in. Hg). This can be shown (see Figure 1-18) by filling a 34-inch length of glass tubing with mercury and then inverting the tubing in an open cup of mercury. The mercury inside the glass tubing falls until its height above the level of the mercury in the cup is approximately 30 inches (standard atmosphere). The weight of the 30-inch column of mercury is equivalent to the weight of a similar column of air approximately 50 miles in height.

The barometer reading in inches of mercury can be converted to psi by multiplying the barometer reading by 0.49116. This value corresponds to the weight of a 1-inch column of mercury that has a cross-sectional area of 1 square inch.

The barometer readings (in. Hg) are converted to atmospheric pressure (psi) in Table 1-3. The table calculations are based on the standard atmosphere (29.92 inches of mercury) and pressure (14.696 psi). Thus, 1 inch of mercury is equivalent to 0.49116 psi ($14.696 \div 29.921$).

Problem

What absolute pressure reading corresponds to a barometer reading of 20 inches of mercury?

Solution

The absolute pressure reading can be calculated by means of the formula:

$$\text{barometer reading (in. Hg)} \times 0.49116 = \text{psi}$$

Therefore, the absolute pressure reading is (20×0.49116), or 9.82 psi.

In an engine room, for example, the expression "28-inch vacuum" signifies an absolute pressure in the condenser of 0.946 psi ($14.696 - 13.75$). This indicates that the mercury in a column connected to a condenser having a 28-inch vacuum rises to a height of 28 inches, which represents the difference between the atmospheric

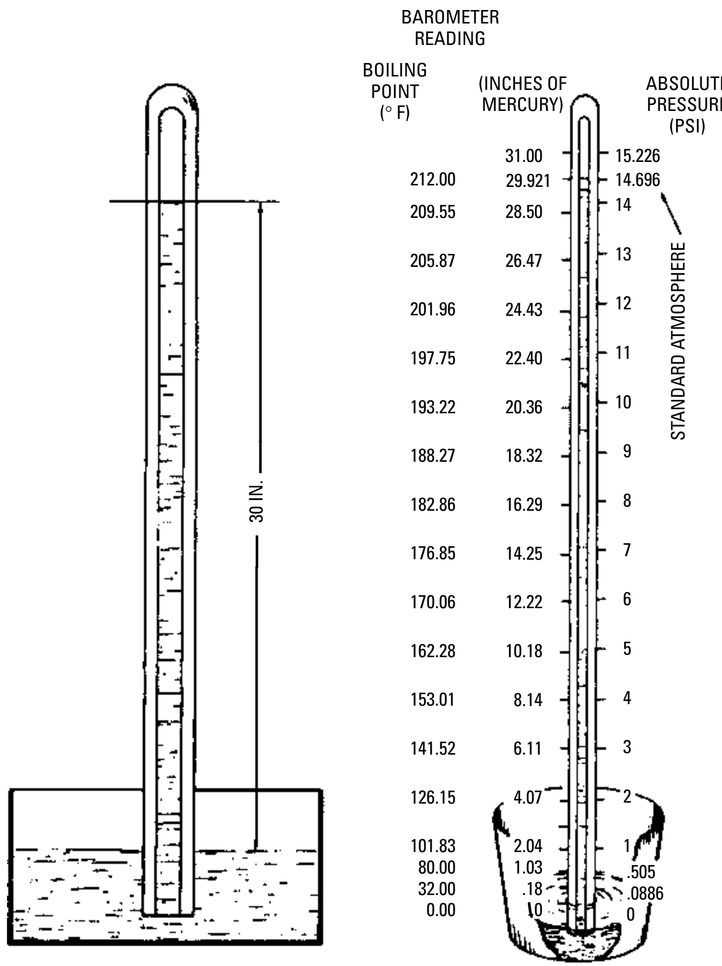


Figure 1-18 The basic principle of the barometer and the relation of the Fahrenheit scale, barometric pressure reading, and absolute pressure.

pressure and the pressure inside the condenser 13.804 pounds (14.73 – 0.946).

Gravity

The force that tends to attract all bodies in the Earth's sphere toward the center point of the earth is known as *gravity*. The symbol for

Table 1-3 Conversion of Barometer Reading to Absolute Pressure

Barometer (in. Hg)	*Pressure (psi)*
28.00	13.75
28.25	13.88
28.50	14.00
28.75	14.12
29.00	14.24
29.25	14.37
29.50	14.49
29.75	14.61
29.921	14.696
30.00	14.74
30.25	14.86
30.50	14.98
30.75	15.10
31.00	15.23

gravity is g. The rate of acceleration of gravity is 32.16 feet per second. Starting from a state of rest, a free-falling body falls 32.16 feet during the first second; at the end of the next second, the body is falling at a velocity of 64.32 feet per second (32.16 + 32.16).

Center of Gravity

That point in a body about which all its weight or parts are evenly distributed or balanced is known as its *center of gravity* (abbreviated *c.g.*). If the body is supported at its center of gravity, the entire body remains at rest, even though it is attracted by gravity. A higher center of gravity and a lower center of gravity are compared in Figure 1-19, as related to the center of gravity in automobiles.

Centrifugal Force

The force that tends to move rotating bodies away from the center of rotation is called *centrifugal force*. It is caused by inertia. A body moving in a circular path tends to be forced farther from the axis (or center point) of the circle described by its path.

If the centrifugal force balances the attraction of the mass around which it revolves, the body continues to move in a uniform path. The operating principle of the centrifugal pump (see Figure 1-20) is based on centrifugal force.

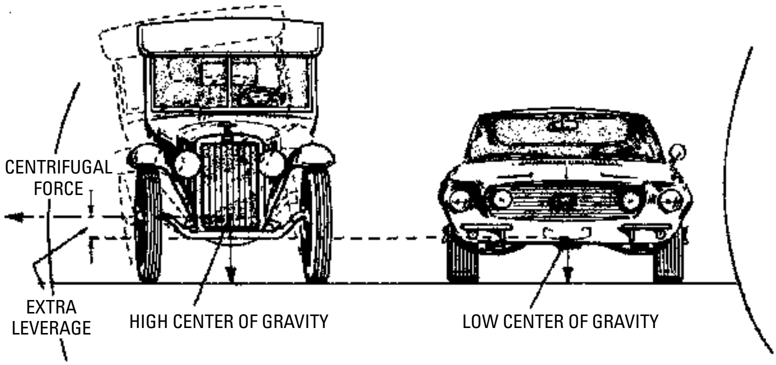


Figure 1-19 Comparison of the height of the center of gravity in an earlier model automobile (left) and later model (right).

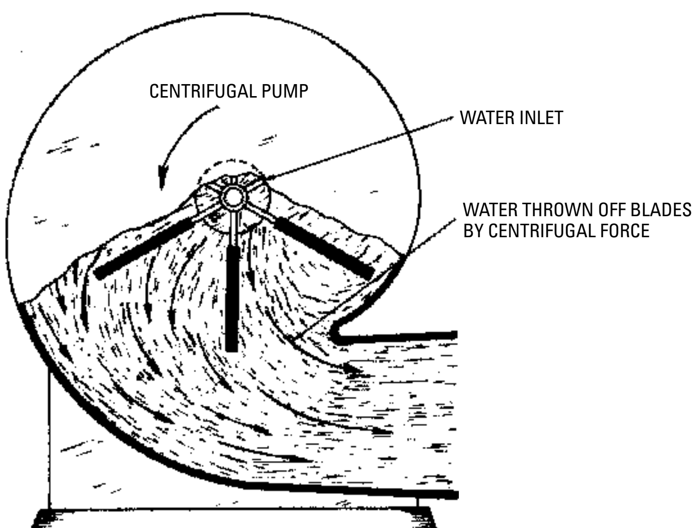


Figure 1-20 The use of centrifugal force in the basic operation of a centrifugal pump.

Centripetal Force

The force that tends to move rotating bodies toward the center of rotation is called *centripetal force*. Centripetal force resists centrifugal force, and the moving body revolves in a circular path when these opposing forces are equal—that is, the system is in a *state of equilibrium* (see Figure 1-21).

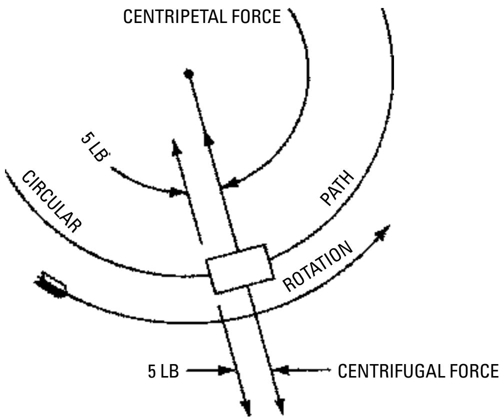


Figure 1-21 The state of equilibrium between centrifugal and centripetal force.

If a body *O* (see Figure 1-22) is acted upon by two directly opposed forces *OA* and *OC*, those forces are equal. If it is also acted upon by another pair of directly opposed forces *OB* and *OD*, the various forces balance and the resultant reaction on the body *O* is zero (that is, the body remains in a state of rest).

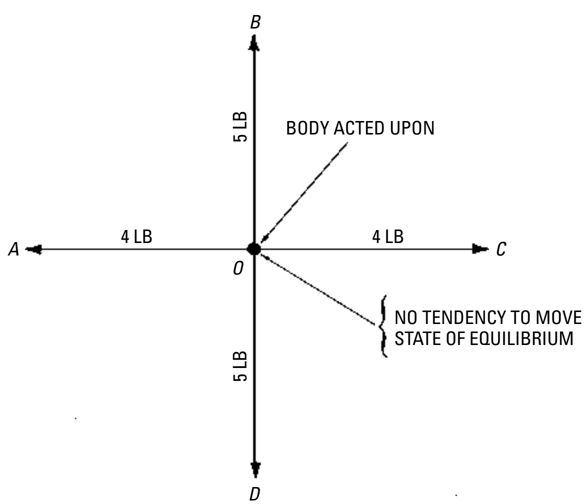


Figure 1-22 State of equilibrium existing as a resultant of directly opposed forces.

Force

A force is completely defined only when its *direction, magnitude*, and *point of application* are defined. All three of these requirements can be represented by a line or vector, so that its direction, length, and location correspond to given conditions.

As shown in Figure 1-23, a force of 4000 pounds can be represented by drawing a line to a convenient scale (1 inch = 1000 pounds), which requires a line *AB* 4 inches in length, drawn in the direction of and to the point where the force is applied. Note that the arrowhead is placed at the point where the force is applied.

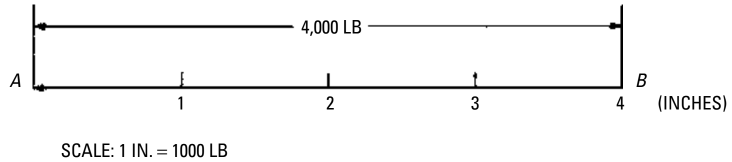


Figure 1-23 A line or vector is used to represent a force and its intervals, its direction, and its point of application. The arrowhead indicates the point of application of the force.

Resultant of Directly Opposed Forces

If the lines *OA* and *OB* (see Figure 1-24) are used to represent two directly opposed forces acting on the point *O*, and the forces *OA* and *OB* are equal to 4000 pounds and 2000 pounds, respectively, these opposed forces can be represented by a single line *OC* or force, which is equal to 2000 pounds (4000 – 2000). Thus, the resultant of forces *OA* and *OB* is a single force *OC*. The broken line in the illustration indicates the subtraction of the smaller force *OB*.

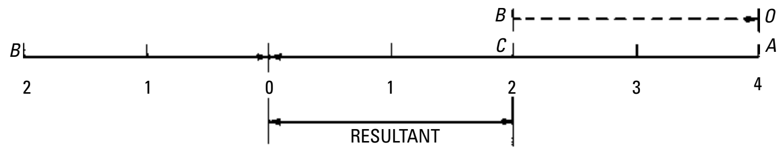


Figure 1-24 Diagram used to determine the resultant of two directly opposed forces.

Resultant of Forces at an Angle

If two forces *OA* and *OB* are acting on a common point *O*, an angle is formed (see Figure 1-25) in which the two forces can be

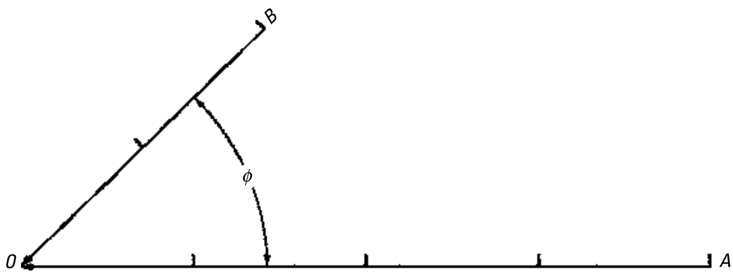


Figure 1-25 Diagram of two forces acting on a common point at an angle to each other.

represented by the lines *OA* and *OB* whose lengths represent 4000 pounds and 2000 pounds, respectively.

To determine the direction and intensity of the *resultant* force, a parallelogram of force can be constructed (see Figure 1-26). The parallelogram can be constructed from the diagram in Figure 1-25. The broken line *BC* is constructed parallel to line *OA*, and the broken line *AC* is drawn parallel to line *OB*. The diagonal *OC* represents the direction and intensity (by measuring its length) of the resultant force that is equivalent to the forces *OA* and *OB*.

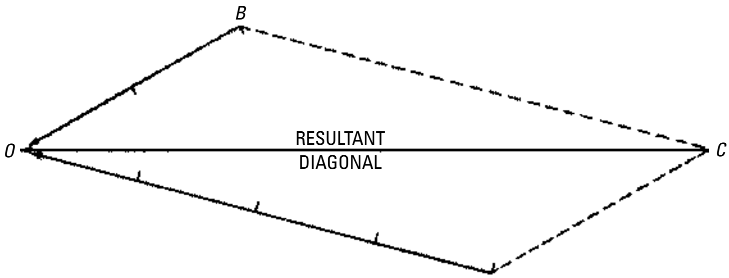


Figure 1-26 Determining the resultant of two angular forces by the parallelogram-of-forces method.

Components of a Force

The *components of a force* can be determined by reversing the process of determining the resultant of two forces. A component of force is a single force that was used to compound the resultant force derived by the parallelogram-of-forces principle.

For example, the reaction caused by the thrust of a connecting rod on the crank pin (see Figure 1-27) may be considered. The thrust can be divided into two component forces.

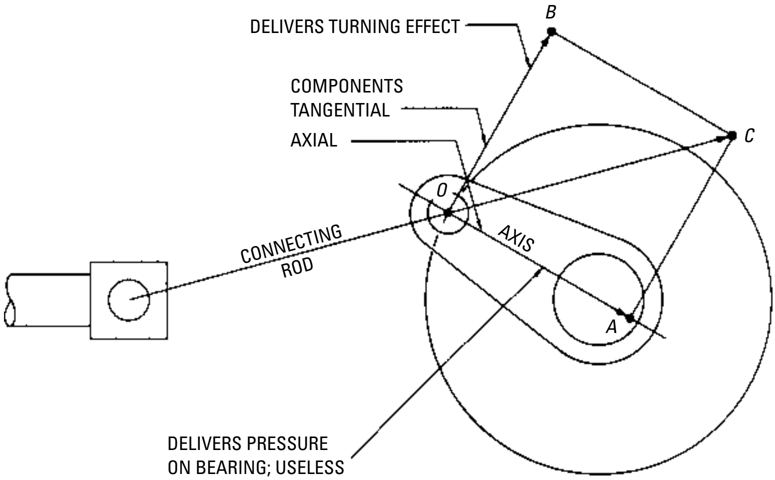


Figure 1-27 Determining the components of a force by means of the parallelogram-of-forces method.

One component force acts in a direction tangent to the circle described by the crank pin, which causes the crank to turn. The other component force acts in the direction of the axis of the crank arm, which causes the shaft to press against its bearing. A diagram (see Figure 1-27) can be constructed to determine the components of a force.

From point *O*, project a line *OC* equal in length to the thrust of the connecting rod (see Figure 1-27). Complete the parallelogram of forces to obtain points *B* and *A*, their lengths *OB* and *OA* representing the components of force in direction and intensity.

Motion

Motion is usually described as a change in position in relation to an assumed fixed point. Motion is strictly a relative matter because there can be no motion unless some point or object is regarded as stationary (see Figure 1-28).

As shown in Figure 1-28, the man is rowing the boat at a speed of 4 miles per hour against a current flowing at 2 miles per hour in the opposite direction. The boat is moving at 4 miles per hour with

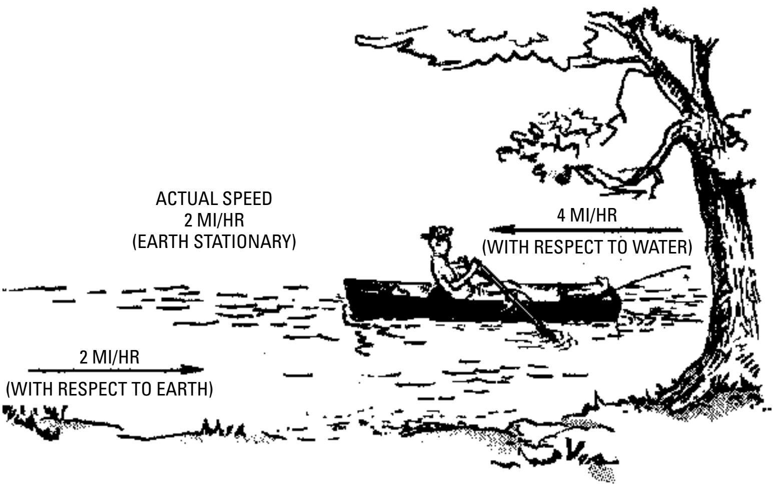


Figure 1-28 Motion.

respect to the water, and the water is moving at 2 miles per hour with respect to the Earth.

The familiar example of the ferryboat crossing the river, pointing upstream to counteract the motion of the water, is used to illustrate *apparent* and *actual* motion (see Figure 1-29). The line *OA* represents the apparent motion (both distance and direction) of the boat. However, regarding the Earth as stationary, the line *OB* represents the actual motion of the boat. If the water is regarded as stationary, the boat is moving in the direction represented by the line *OA*.

Newton's Laws of Motion

The noted physicist, Sir Isaac Newton, announced the three laws of motion as follows:

- *First Law of Motion*—If a body is at rest, it tends to remain at rest. If a body is in motion, it tends to remain in motion in a straight line until acted upon by a force.
- *Second Law of Motion*—If a body is acted on by several forces, it tends to obey each force as though the other forces do not exist, whether the body is at rest or in motion.
- *Third Law of Motion*—If a force acts to change the state of a body with respect to rest or motion, the body offers a resistance

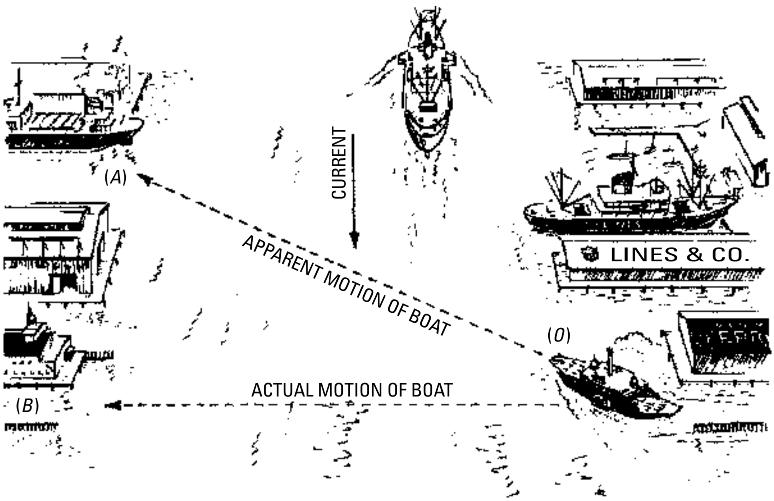


Figure 1-29 Apparent and actual motion.

that is equal and directly opposed to the force. In other words, to every action there is an equal and opposite reaction.

Types of Motion

The rate of change of position in relation to time is termed *velocity*. Velocity is also the rate of motion in a given direction (as the rotation of a sphere) in relation to time. The rate of increase in velocity or the average increase of velocity in a given unit of time is called *acceleration*.

A train traveling at a rate of 30 miles per hour is an example of *linear* velocity. A line shaft rotating at a rate of 125 revolutions per minute is an example of *rotary* velocity. Figure 1-30 shows linear motion and rotary motion.

Tangential motion is the equivalent of rotary motion, but is regarded as moving in a straight line or tangential direction. Tangential motion or velocity is used in belting calculations. As shown in Figure 1-31, the circumference of a 1-foot diameter pulley is 3.1416 feet. Thus, for each revolution of the pulley, the belt travels the tangential equivalent distance *AB*, or 3.1416 feet.

Example

If a 4-foot diameter pulley is rotating at 100 rpm, what is the tangential speed of the belt? The calculation is as follows:

$$\text{tangential speed} = \text{circumference} \times \text{rpm}$$

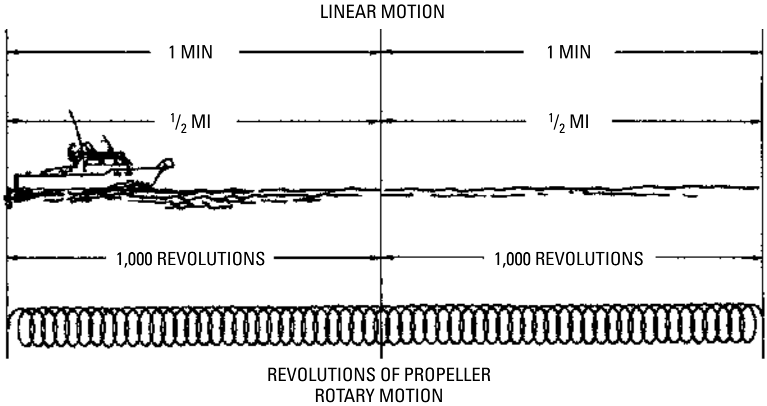


Figure 1-30 Linear motion and rotary motion.

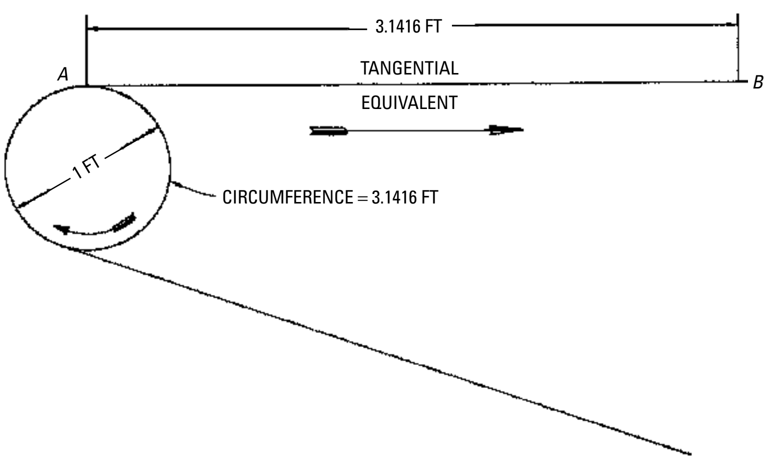


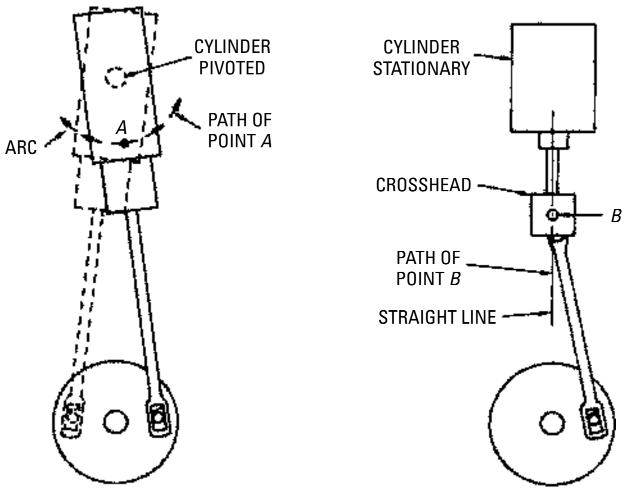
Figure 1-31 The tangential equivalent distance of rotary motion.

$$\text{tangential speed} = 4 \times 3.1416 \times 100$$

$$\text{tangential speed} = 12.566 \times 100$$

$$\text{tangential speed} = 1256.6 \text{ feet per minute}$$

Vibrating motion that describes a path similar to the arc of a circle is called *oscillating* motion. A familiar example of oscillating motion is the pendulum of a clock. A vibrating motion that makes a path similar to a straight line is called *reciprocating* motion. The movement of the crosshead of an engine is an illustration of reciprocating motion. Figure 1-32 shows oscillating and reciprocating motion.



(A) Oscillating engine. (B) Reciprocating engine.

Figure 1-32 Oscillating type of engine (left) and reciprocating type of engine (right).

The oscillating-type engine (see Figure 1-32) is sometimes used on board ship as a capstan engine. It can be noted that the to-and-fro path of point *A* is similar to the arc of a circle whose center point is the center point of the pivot about which the cylinder oscillates. In the right-hand diagram, note that the point *B* on the crosshead moves up and down or reciprocates in a straight line path.

The movement of a point through equal space in equal intervals of time is called *constant* motion. The movement of a point through unequal spaces in equal intervals of time is called *variable* motion. Figure 1-33 illustrates both constant motion and variable motion.

In the movements of the crank pin and piston of an engine (see Figure 1-33), the rate of motion from the position of the crank pin at the beginning of the stroke (position *A*) is constant as it rotates to position *B*. This means that it passes through equal arcs in equal intervals of time. Perpendiculars from points 1, 2, 3, and so on, locate the corresponding positions *a*, *b*, *c*, and so on, of the piston. As shown in the diagram, the traversed spaces (*Aa, ab,* and so on) are

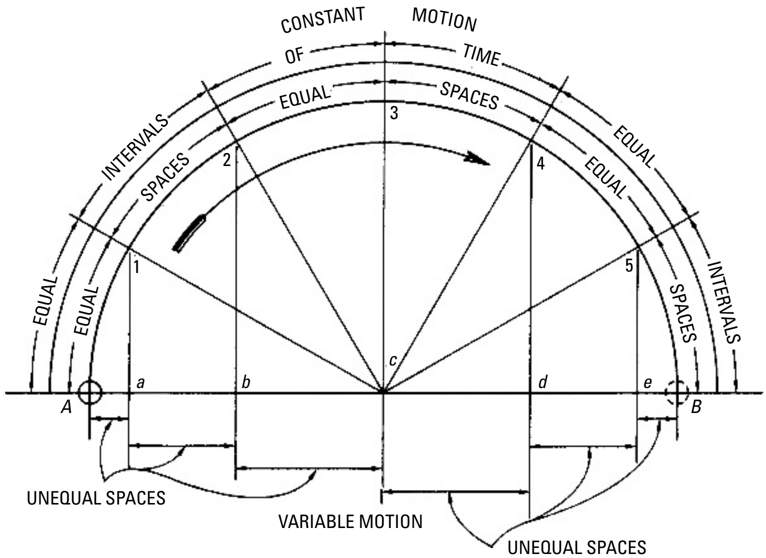


Figure 1-33 Constant motion and variable motion.

unequal. Therefore, the motion is variable. The diagram represents the true relation where there is no distortion, as with a Scotch-yoke mechanism. However, when a connecting rod is used, there is distortion caused by the angularity of the connecting rod.

Momentum

The power of a body to overcome resistance by means of its motion is termed *momentum*. Momentum is the quantity of motion in a moving body.

Momentum is measured by multiplying the quantity of matter in a body by its velocity. A numerical value of momentum can be expressed as the force (in pounds) steadily applied that can stop a moving body in 1 second. Therefore, momentum is equal to the mass of a body multiplied by its velocity in feet per second or:

$$\text{momentum} = \frac{\text{weight}}{32.16} \times \text{velocity (ft/s)}$$

Following is the formula for determining momentum:

$$M = \frac{WV}{g}$$

in which the following is true:

W is the weight (in pounds)
V is velocity (in feet per second)
g is attraction caused by gravity (32.16)

Inertia
The property of matter that causes a body to tend to remain at rest (if it is already at rest); or to keep moving in the same direction unless affected by an outside force (if it is moving), is called *inertia* (symbol I). This gives rise to two states of inertia known as *static inertia* and *dynamic inertia* (see Figure 1-34).

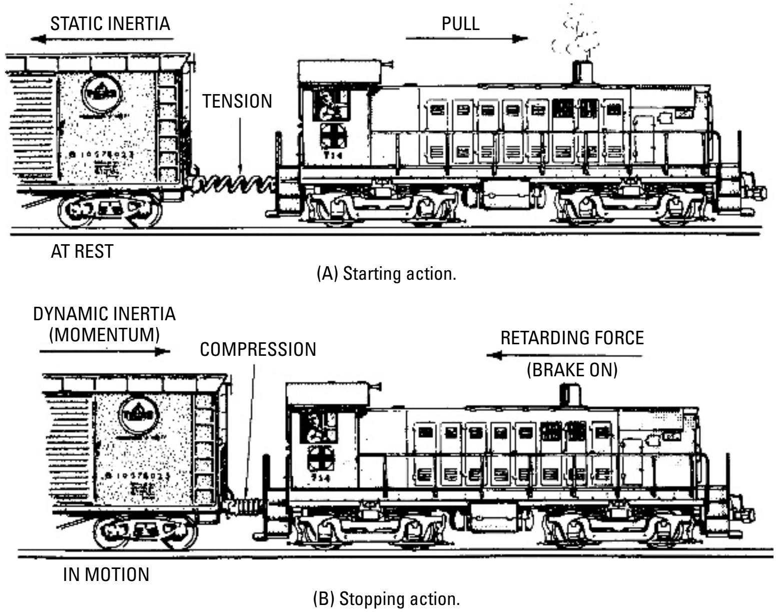


Figure 1-34 Static inertia with respect to a body at rest (top) and dynamic inertia with respect to a body in motion (bottom).

Friction
The resistance to motion of two moving objects that touch is called *friction*. Friction is caused partially by the natural adhesion of one body to another. However, its chief cause is the roughness of surfaces that are in contact. Even a glossy, polished surface is not smooth when viewed with a powerful magnifying glass or microscope.

Coefficient of Friction

The ratio of the force required to slide a body along a horizontal plane surface to the weight of the body is the *coefficient of friction*. The coefficient of friction is equivalent to the tangent of the *angle of repose*.

The angle of repose is the largest angle with the horizontal at which a mass of material (such as an embankment or pile of coal) can remain at rest without sliding. This angle varies with different materials.

Laws of Friction

The first laws of friction were given by Morin in about 1830, but they have been modified by later experiments. As summarized by Kent, the laws of friction are as follows:

- Friction varies approximately as the normal pressure with which the rubbing surfaces are pressed together.
- Friction is approximately independent of the area of the surfaces, but it is slightly greater for smaller surfaces than for larger surfaces.
- Friction decreases with an increase in velocity, except at an extremely low velocity and with soft surfaces.

As applied to lubricated surfaces, the laws of friction for *perfect lubrication* (surfaces completely separated by a film of lubricant) are as follows:

- The coefficient of friction is independent of the materials making up the surfaces.
- The coefficient of friction varies directly with the viscosity of the lubricant, which varies inversely with the temperature of the lubricant.
- The coefficient of friction varies inversely as the unit pressure and varies directly as the velocity.
- The coefficient of friction varies inversely as the mean film thickness of the lubricating medium.
- Mean film thickness varies directly with velocity and inversely as the temperature and unit pressure.

As applied to *imperfect lubrication*, that is, surfaces partially separated (which may range from nearly complete separation to nearly complete contact) by a film of lubricant, the laws of friction are as follows:

- The coefficient of friction increases with an increase in pressure between the surfaces.
- The coefficient of friction increases with an increase in relative velocity between the surfaces.

Machinery cannot be operated without lubrication (notwithstanding the alleged antifriction metals) because of the tiny irregularities in a smooth metal surface. A lubricant is used to keep the rubbing parts separated by a thin film of oil, thus preventing actual contact so far as possible.

Work and Power

The expenditure of energy to overcome resistance through a certain distance is *work*. It is difficult to understand horsepower without an understanding of the difference between work and power (see Figure 1-35). *Power* is the rate at which work is done (that is, work divided by the time in which it is done).

The standard unit for measuring work is the *foot-pound* (ft-lb). The foot-pound is the amount of work that is done in raising a

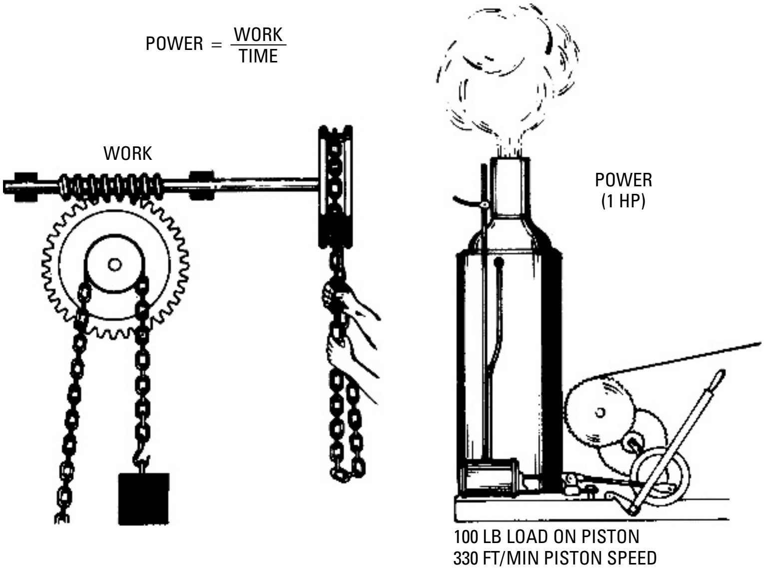


Figure 1-35 The difference between work (left) and power (right).

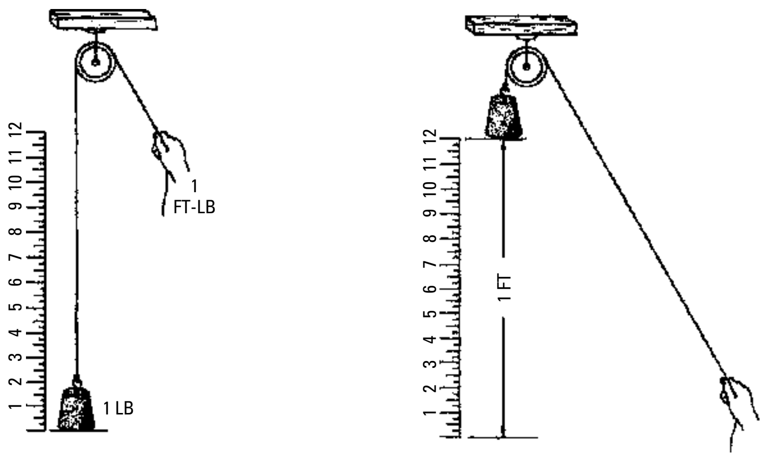


Figure 1-36 One foot-pound.

weight of 1 pound through a distance of 1 foot, or in overcoming a pressure of 1 pound through a distance of 1 foot (see Figure 1-36).

James Watt is believed to have adopted the term *horsepower*. He used it for his steam engine, to represent the power or capacity of a strong London draft-type horse for doing work during a short time interval. The term was used as a power rating for his steam engines. The present standard unit for measuring power is horsepower (*hp*). It is defined as 33,000 foot-pounds per minute. In other words, one horsepower is required to raise a weight of the following:

- 33,000 lb a height of 1 foot in one minute
- 3300 lb a height of 10 feet in one minute
- 33 lb a height of 1000 feet in one minute
- 3.3 lb a height of 10,000 feet in one minute
- 1 lb a height of 33,000 feet in one minute

A formula that is generally used to calculate engine horsepower is as follows:

$$\text{hp} = \frac{2\ \text{PLAN}}{33{,}000}$$

in which the following is true:

P is the mean effective pressure in psi
L is the length of stroke, in feet

A is the area of piston, in square inches ($0.7854 \times d^2$)
N is the number of revolutions per minute (rpm)

Since the stroke of an engine is usually given in inches rather than in feet, and the revolutions per minute are given rather than the piston speed, the previous formula involves extra calculations for these items, as well as the extra multiplication and division introduced because of the constants. Therefore, the formula can be reduced to its lowest terms, as follows:

$$\begin{aligned} \text{hp} &= \frac{2\ \text{PLAN}}{33{,}000} \\ &= \frac{2 \times P \times \dfrac{L}{12} \times (0.7854 \times d^2) \times N}{33{,}000} \\ &= \frac{0.1309 \times PLD^2N}{33{,}000} \\ &= 0.000003967\ PLD^2N \end{aligned}$$

Thus, the constant 0.000004 can be used for most calculations. By changing the order of the factors, the formula is simplified to:

$$hp = 0.000004\ d^2LNP$$

According to its definitions and the manner in which it is derived, the various types of horsepower are *nominal*, *indicated*, *brake*, *effective*, *hydraulic*, *boiler*, and *electrical*. Figure 1-37 shows the various types of horsepower.

Basic Machines

For many years the basic mechanical contrivances that enter into the composition or formation of machines were referred to as *mechanical powers*. Since these mechanical contrivances are regarded in a more static than dynamic sense (that is, the consideration of opposing forces in equilibrium rather than tending to produce motion), it is more correct to refer to them as *basic machines*. Strictly speaking, the term *power* is a dynamic term relating to the time rate of doing work. When the elements of a machine are in equilibrium, no work is done. Therefore, it is incorrect to refer to the basic machines as mechanical powers.

It should be understood that the action of all the basic machines depends on the principle of work, which is: The applied force,

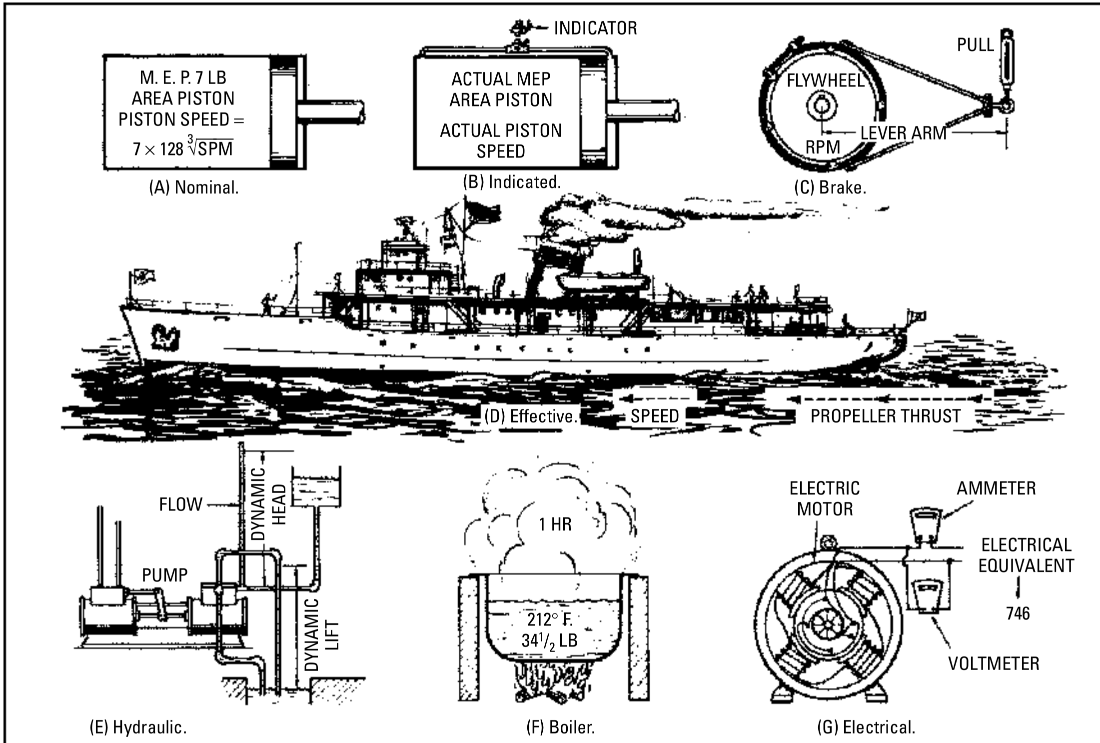


Figure 1-37 Various types of horsepower.

multiplied by the distance through which it moves, equals the resistance overcome, multiplied by the distance through which it is overcome.

Following are the basic machine:

- Lever
- Wheel and axle
- Pulley
- Inclined plane
- Screw
- Wedge

These machines can be reduced further to three classes of machines, as follows:

- A solid body turning on an axis
- A flexible cord
- A hard and smooth inclined surface

The *Principle of Moments* is important in studying the basic machines. This important principle can be stated as follows: "When two or more forces act on a rigid body and tend to turn it on an axis, equilibrium exists if the sum of the moments of the forces which tend to turn the body in one direction equals the sum of the moments of those forces which tend to turn the body in the opposite direction about the same axis.

Lever

A lever is a bar of metal, wood, or other substance that is used to exert a pressure or to sustain a weight at one point in its length by receiving a force at a second point, and is free to turn at a third or fixed point called the *fulcrum*. Its application is based on the Principle of Moments. The following general rule can be applied to all classes of levers.

Rule: The force P, multiplied by its distance from the fulcrum F, is equal to the load W, multiplied by its distance from the fulcrum.

Thus, the formula for calculation involving the three classes of levers is:

$$F \times \text{distance} = W \times \text{distance}$$

As shown in Figure 1-38, there are three classes of levers.

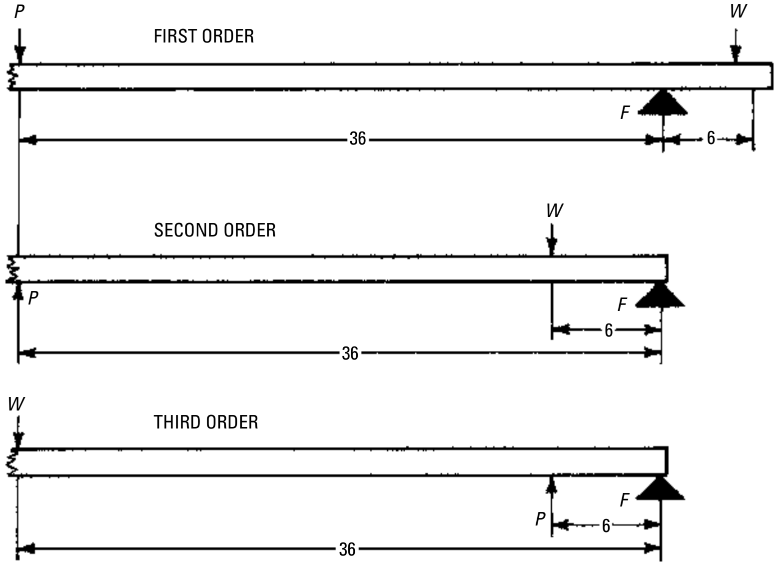


Figure 1-38 The three classes of levers.

Problem

What force P is required at a point 3 feet from the fulcrum F to balance a weight of 112 pounds applied at a point 6 inches from the fulcrum?

Solution

The distances or lengths of the levers are 3 feet and 6 inches, respectively. Since the distances must be of the same denomination, the 3 feet must be reduced to inches (3 × 12), or 36 inches. Then, applying the rule:

$$P \times 36 = 112 \times 6$$

$$P = \frac{112 \times 6}{36}$$

$$= 18.67 \text{ lb}$$

Wheel and Axle

A comparison of the wheel and axle with the first-order lever (see Figure 1-38) indicates that they are similar in principle. The same

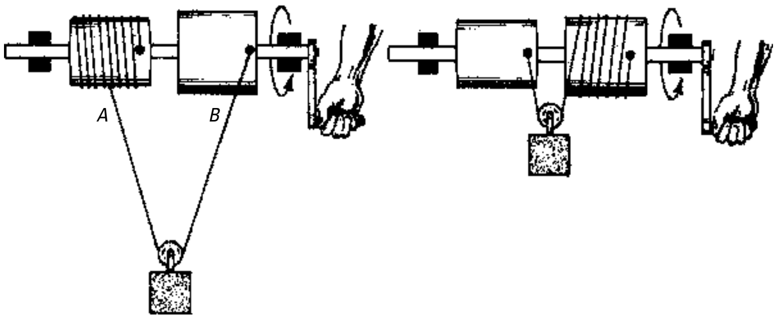


Figure 1-39 The principle of the differential hoist, cranking clockwise to lift the weight (left), and the lifting operation completed (right).

formula can be used for calculations involving the wheel and axle. Figure 1-39 shows the Chinese wheel and axle. This is a modification of the wheel and axle and can be used to obtain extreme leverage. This is also the basic principle of the differential hoist. As the crank is turned clockwise, the cable winds onto drum *B* and unwinds from drum *A*. Since drum *B* is larger in diameter, the length of cable between the two drums is gradually taken up, lifting the load. Thus, if the difference in the diameters of the two drums is small, an extreme leverage is obtained, enabling heavy weights to be lifted with little effort. Also, the load remains suspended at any point, because the difference in diameters of the two drums is too small to overbalance the friction of the parts.

Pulley

The two types of pulleys are *fixed* and *movable*. No mechanical advantage is obtained from the fixed pulley. Its use is important in accomplishing work that is appropriate (raising water from a well, for example).

The movable pulley, by distributing its weight into separate portions, is attended by mechanical advantages proportional to the number of points of support. As illustrated in Figure 1-40, the relation between the force applied and the load lifted is changed by the various basic pulley combinations. Of course, an even greater range may be obtained by additional pulleys, but there is a practical limit to which this is mechanically expedient. The following rule states the relation between force and load.

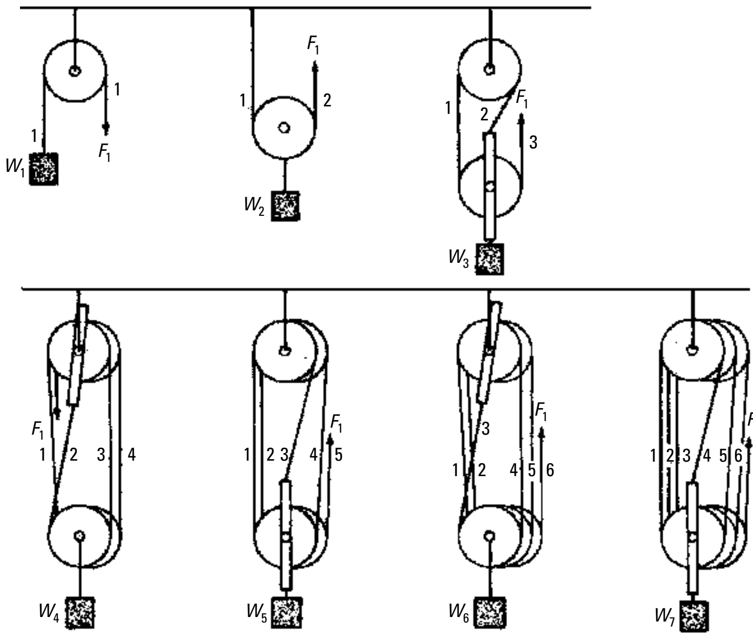


Figure 1-40 Relation between force applied and load lifted in the various basic pulley combinations.

Rule: The load W that can be lifted by a combination of pulleys is equal to the force F times the number of ropes supporting the lower or movable block.

Inclined Plane

If a sloping path or incline is substituted for a direct upward line of ascent, a given weight can be raised by a smaller weight. Thus, the inclined plane is a basic machine, because a lesser force can be applied to lift a load (see Figure 1-41).

Rule: As the applied force P is to the load W, so is the height H to the length of the inclined plane L.

Thus, the calculation is:

$$\text{force} : \text{load} = \text{height} : \text{length of plane}$$

Problem

What force P is required to lift a load of 10 pounds if the height is 2 feet and the plane is 12 feet in length?

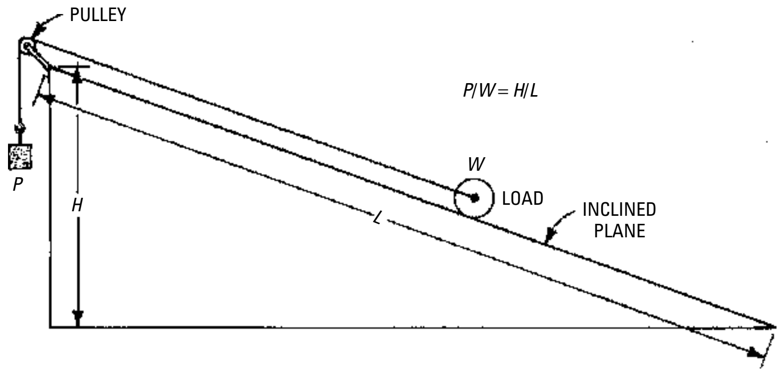


Figure 1-41 Inclined plane. A smaller weight (P) can be used to lift a load or weight (W), because the load is partially supported by the inclined plane.

Solution

Substituting in the previous equation:

$$P : 10 = 2 : 12$$

$$P \times 12 = 2 \times 10$$

$$P = \frac{10 \times 2}{12} = \frac{20}{12} = 1^{2}/_{3}$$

Screw

This type of basic machine is merely an inclined plane wrapped around a cylinder. The screw is used to exert a severe pressure through a small space. Since it is subjected to a high loss from friction, the screw usually exerts a small amount of power in itself, but a large amount of power may be derived when combined with the lever or wheel.

Rule: As the applied force P is to the load W, so is the pitch to the length of thread per turn.

Thus, the calculation is:

$$\text{applied force } P : \text{load } W = \text{pitch} : \text{length of thread per turn}$$

Problem

If the pitch or distance between threads is $^{1}/_{4}$ inch and a force P of 100 pounds is applied, what load of weight W can be moved by the screw if the length of thread per turn of the screw is 10 inches?

Solution
Substituting in the above equation:

$$100 : \text{load } W = \tfrac{1}{4} : 10$$
$$\text{load } W \times \tfrac{1}{4} = 10 \times 100$$
$$\text{load } W = \frac{10 \times 100}{\tfrac{1}{4}}$$
$$= 4000 \text{ lb}$$

Wedge

The wedge is virtually a pair of inclined planes that are placed back-to-back or in contact along their bases (see Figure 1-42).

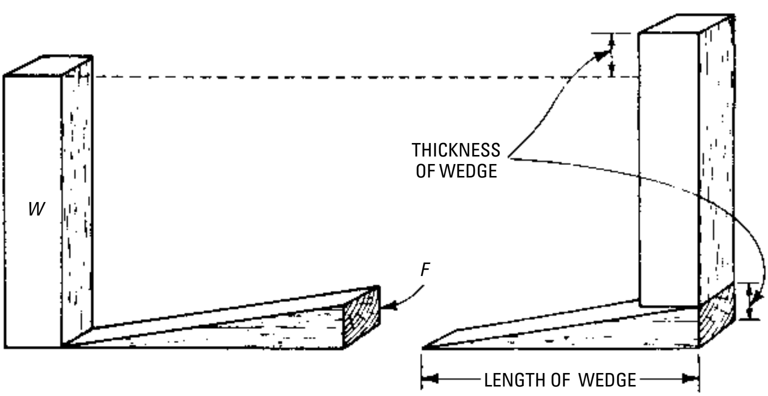


Figure 1-42 Application of a wedge (P) to raise a heavy load or weight (W).

Rule: As the applied force P is to the load W, so is the thickness of the wedge to its length.

Thus, the calculation is:

$$\text{applied force } P : \text{load } W = \text{thickness of wedge} : \text{length of wedge}$$

Problem
What applied force P is required to raise a load W of 2000 pounds, using a wedge that is 4 inches in thickness and 20 inches in length?

Solution

Substituting in the equation:

$$P\,(\text{applied force}) : 2000 = 4 : 20$$

$$P \times 20 = 4 \times 2000$$

$$P = \frac{4 \times 2000}{20}$$

$$= 400 \text{ lb}$$

Water

In the study of hydraulics and pumps, it is important that water and its characteristics be understood. Water is a most remarkable substance. By definition, water is a compound of hydrogen and oxygen in the proportion of 2 parts by weight of hydrogen to 16 parts by weight of oxygen.

The behavior of water under the influence of temperature is extraordinary. When subjected to low temperatures, water is converted to a solid (ice), which, because of its peculiar characteristic of expanding during its change of state, causes burst pipes and other types of damage. At higher temperatures, water is converted to a gas (steam). Thus, water is used as a medium for developing power (as in steam for a steam engine).

At maximum density (39.1°F) water expands as heat is added and it also expands slightly as the temperature drops from this point, as shown in Figure 1-43. Water freezes at 32°F and boils at 212°F, when the barometer reads 29.921 inches of mercury, which is the standard atmosphere. The equivalent of 29.921 inches of mercury is 14.696 psi.

Water contains approximately 5 percent air by volume (see Figure 1-44), mechanically mixed with it. This is the reason that steam engines that condense moisture should have air pumps attached to the condenser. Otherwise, the necessary vacuum cannot be maintained.

In the operation of steam heating plants, air is liberated when the water boils and passes into radiators with the steam. Therefore, automatic air valves must be provided to rid the system of the air. If automatic air valves are not provided (or if they become clogged because of corrosion), radiators may become air-bound and ineffective.

The boiling point of water rises as the pressure increases. Thus, the boiling point is 212°F for standard atmospheric pressure at sea level. The boiling point is 327.8°F at 100 pounds (absolute) pressure.

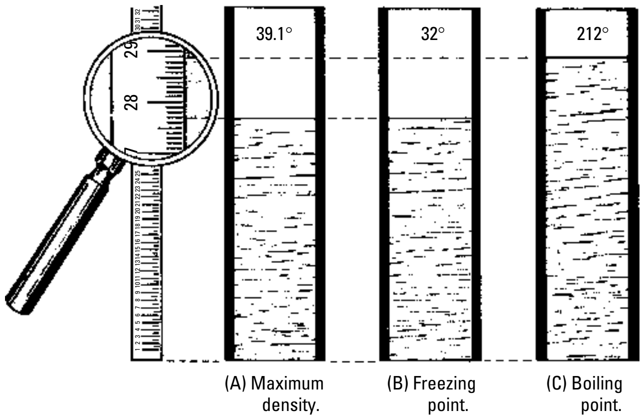


Figure 1-43 A remarkable property of water—expansion at temperatures both above and below its temperature at point of maximum density (39.1°F). (A) If one pound of water is placed in a cylinder having a cross-sectional area of 1 square inch at 39.1°F, the water rises to a height of 27.68 inches; (B) as the temperature drops to 32°F, the water rises to a height of 27.7 inches; and (C) as the temperature is increased to 212°F, the water rises to a height of 28.88 inches in the tube.

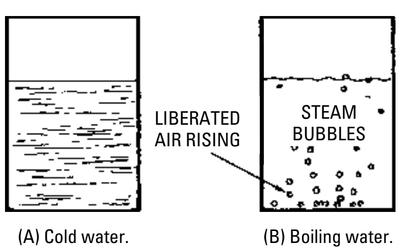


Figure 1-44 Boiling of water to liberate air that is mechanically mixed in the water.

Figure 1-45 shows water boiling (as in a tea kettle) with the addition of heat. If the vessel were closed, the water would continue to boil, causing the pressure to rise. If no more heat is added when the pressure reaches 100 pounds, for example, the water would cease to boil and the pressure would remain constant if no heat were lost. The temperature of the water, steam, and pressure are said to be in a *state of equilibrium*. The least variation in temperature (either upward or downward) destroys the state of equilibrium and causes a change. By permitting some of the confined steam to escape (see Figure 1-46), the water can be made to boil again. This is because of the reduction in pressure, which causes the equilibrium of the system

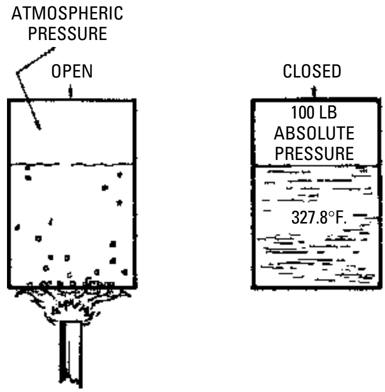


Figure 1-45 The effect of pressure on the temperature at which water boils: (a) at atmospheric pressure; (b) at 100 pounds (absolute pressure).

to be disturbed. The water (containing excess heat) immediately begins to boil and tends to keep the pressure constant. If the process is continued, a gradual reduction in temperature and pressure results until all of the heat originally introduced into the system is used up.

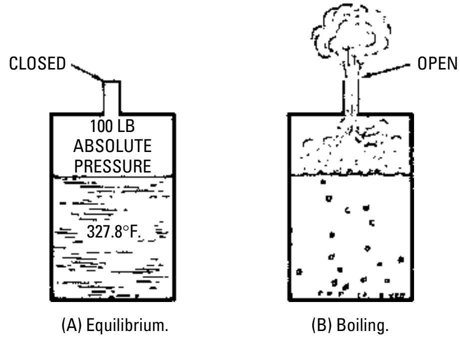


Figure 1-46 State of equilibrium (left) between temperature and pressure. The equilibrium is upset (right) by reducing the pressure, resulting in boiling.

The boiling point of water is lowered as the elevation increases, because of the lower pressure of the atmosphere. At an elevation of 5000 feet, water boils at 202°F. Eggs cannot be boiled at high altitudes. Baking of cakes and bread sometimes presents a problem at high altitudes.

It is not essential that water be hot before it can be brought to a boil. For example, water at 28-inch vacuum pressure boils at 100°F. However, if the vacuum pressure is increased to 29.74 inches, the water boils at 32°F (see Figure 1-47).

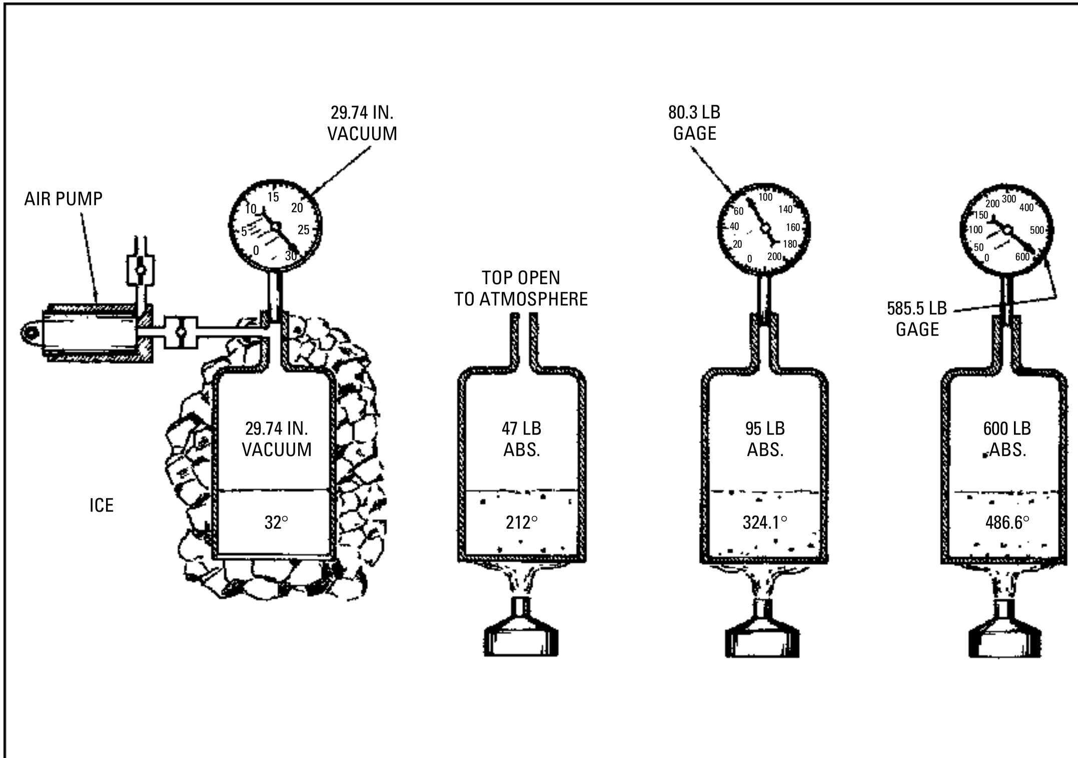


Figure 1-47 The boiling point (temperature) of water varies with a change in pressure. Entirely different values are obtained for other liquids.

For efficient operation of boilers, the water used must be as pure as possible. Impure water often contains ingredients that form scale, which is precipitated on heating and adheres to the heating surfaces of the boilers. Scale in boilers may be rock-hard in nature; or it may be soft, greasy, or powdery in nature, depending upon its chemical and mechanical composition or formation.

Scale is an extremely poor conductor of heat, which results in a wasting of fuel and in overheating of the metal in the heating surface. Boilers should be cleaned frequently and, in most instances, special chemical treatment should be applied to the feed-water before it passes into the boiler.

The basic operation of a hot-water heating system is dependent upon that property of water that causes expansion and contraction because of the rise or fall of temperature, respectively. In a U-shaped glass tube, for example (see Figure 1-48), water poured into the tube rises to the same level in each leg of the tube, because the water is at the same temperature in each leg of the tube. When the water is heated in one leg of the tube and cooled in the other, as shown, the hot water in the heated leg of the tube expands and rises above the level *AB,* while the cold water in the opposite leg contracts and recedes below the normal level *AB*.

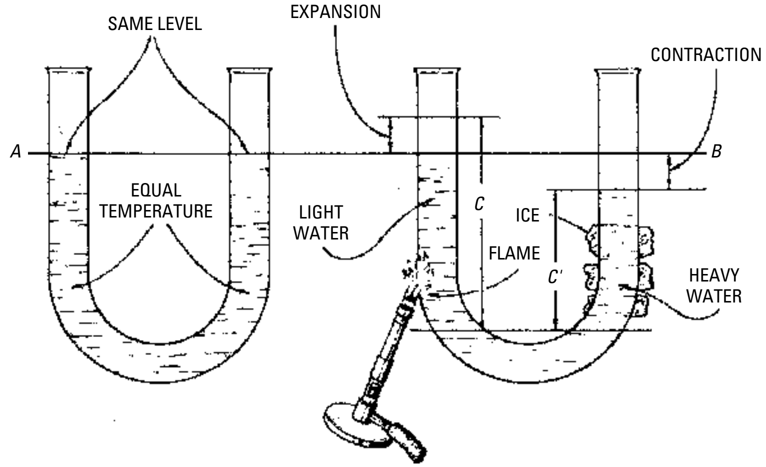


Figure 1-48 Expansion and contraction of water with variation in temperature, resulting in a change in weight per unit volume.

Equilibrium can occur within the tube even though the water is at different levels, because the longer column *C* (see Figure 1-48), consisting of expanded and lighter water, weighs the same as the shorter column consisting of contracted and heavier water.

In the hot-water heating system, the weight of the hot and expanded water in the upflow column *C* (see Figure 1-49), being less than that of the cold and contracted water in the downflow column, upsets the equilibrium of the system and results in a continuous circulation of water, as indicated by the arrows. This type of circulation is known as *thermocirculation*.

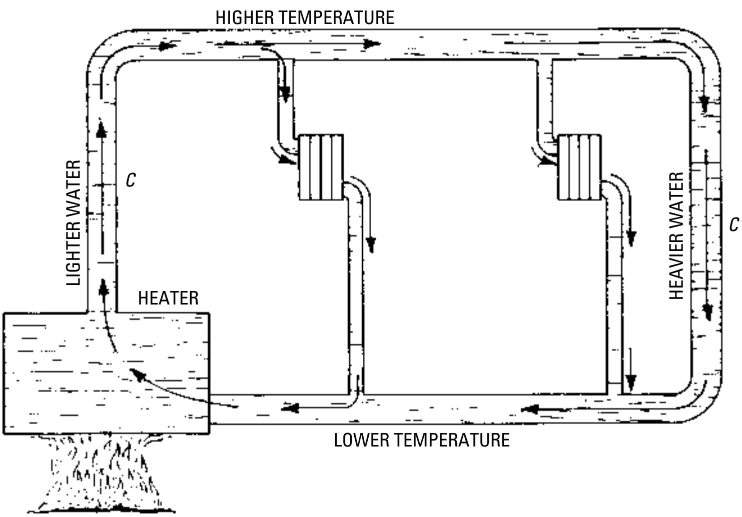


Figure 1-49 Thermocirculation in a hot-water heating system.

In Figure 1-50, there is no circulation of water even though heat is applied. If this should happen in a boiler, practically no generation of steam would result, except for a film of steam that separates the water from the heating surface. The latter surface becomes red-hot and the boiler may be damaged or destroyed. Such a situation is known as the *spheroidal state* (see Figure 1-51). As in the illustration, a small quantity of water poured on a red-hot plate separates into drops and moves all around the plate, being supported by a thin film of steam. Since the water, after steam has formed, is not in contact with the plate, there is practically no cooling effect on the plate.

Figure 1-52 shows cooling by re-evaporation. Some regard re-evaporation as a loss, which, in fact, is incorrect. Since the area of the indicator diagram from point *L* (see Figure 1-52) to a point of release is increased, re-evaporation represents a gain.

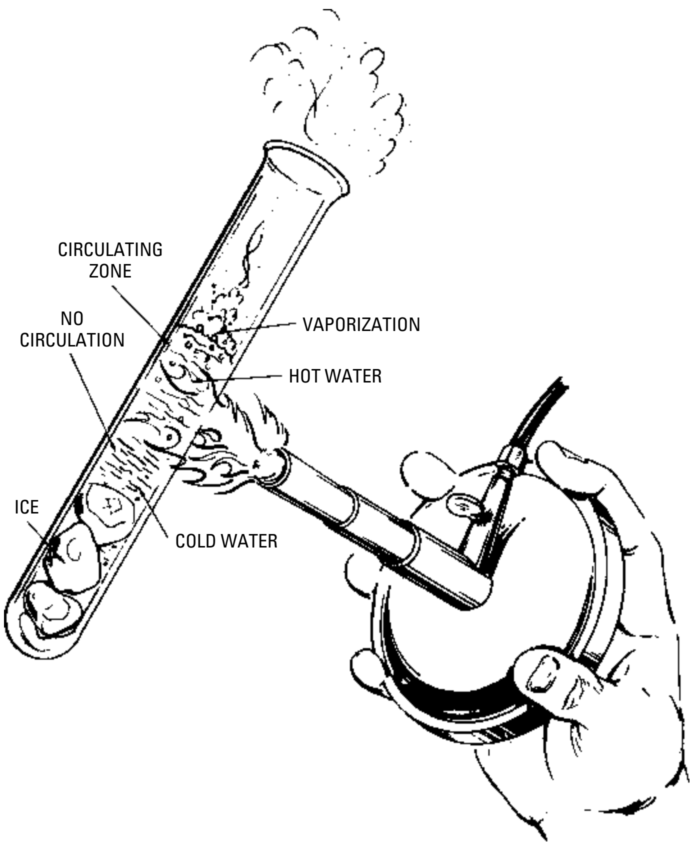


Figure 1-50 Experiment illustrating effect of no circulation. If ice is placed in the bottom of the test tube and heat is applied near the surface of the water, the water boils at that point. However, the heat does not melt the ice, because the cold water around the ice is heavier than the hot water at the top, which prevents thermocirculation. If the heat is applied at the bottom of the tube, the ice melts and all the water is vaporized if the heat is applied long enough.

The reason that the loss concept is incorrect is that it is the cost of re-evaporation that is a loss, and not the re-evaporation process itself. That is, re-evaporation robs the cylinder walls of a quantity of heat corresponding to the latent heat of re-evaporation. This additional cooling of the cylinder walls increases condensation during the first portion of the stroke, which is the loss. Since this loss exceeds

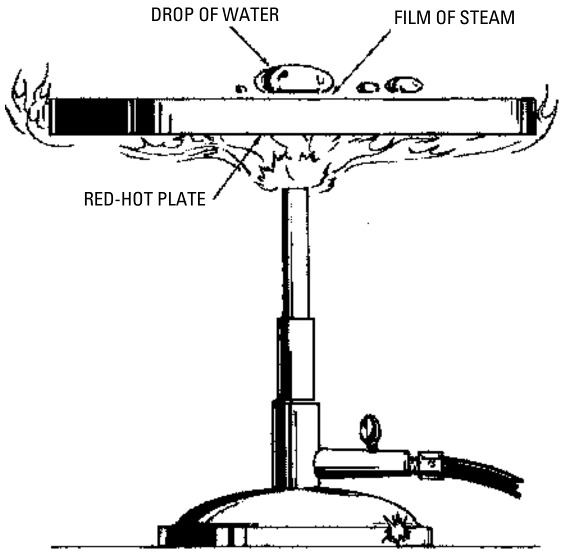


Figure 1-51 The spheroidal state in which a drop of water on a red-hot plate changes to steam.

the gain because of evaporation, re-evaporation is erroneously considered a loss.

The U.S. gallon of water weighs 8.33111 pounds only at the standard temperature of 62°F. At any other temperature reading, its weight is different. For calculations at most temperature readings, the weight of a gallon of water is considered to be $8\frac{1}{3}$ pounds, which is near enough in most instances. However, it should be understood that this is an approximate value. For precision calculations, the weight of a gallon of water at the given temperature should be used. Table 1-4 shows the weight of water per cubic foot at various temperatures. Table 1-5 shows the relative volume of water at various temperatures compared with its volume at 4°C.

Properties of Water with Respect to Pump Design

Experience in the design of pumps has shown that water is nearly an unyielding substance when it is confined in pipes and pump passages, which necessitates substantial construction for withstanding the pressure (especially from periodic shocks or water hammer). Accordingly, in pump design, a liberal factor of safety should be used.

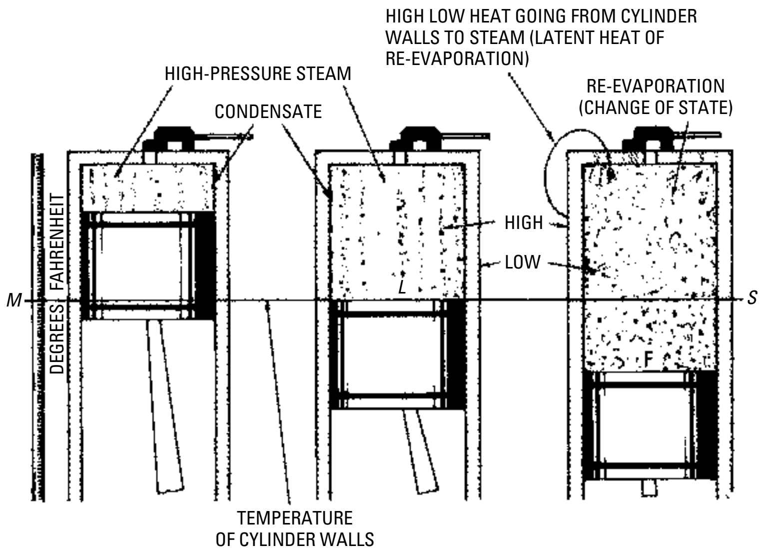


Figure 1-52 A cylinder in a steam engine, illustrating the cooling action by change of state. The line (MS) represents the average temperature of the cylinder walls. In actual operation, when steam is admitted to the cylinder and during a portion of its stroke, its temperature is higher than that of the cylinder walls (left). If the point (L) is assumed to be the position of the piston at equal temperatures (center), condensation takes place. As the piston advances beyond point (L), the temperature of the steam is lower than that of the cylinder walls. The excess heat in the cylinder walls causes the condensate to boil (that is, re-evaporation occurs), which robs the cylinder walls of some of their heat.

Pressure at Different Depths

The pressure of water varies with the head. This is equal to 0.43302 psi for each foot of static head. Thus, a head of 2.31 feet exerts a pressure of 1 psi (2.31×0.43302), as shown in Table 1-6.

Compressibility of Water

Water is only slightly compressible. According to Kent, its compressibility ranges from 0.00004 to 0.000051 inch for one atmosphere of pressure, decreasing as temperature increases. For each 1 cubic foot, distilled water diminishes in volume from 0.0000015 to 0.0000013 inches. Water is so incompressible that, even at a depth of 1 mile, 1 cubic foot of water weighs approximately $^1/_2$ pound more than at the surface.

Table 1-4 Weight of Water per Cubic Foot at Various Temperatures

Temp., °F	*Lb.per cu. ft.*	*Temp., °F*	*Lb.per cu. ft.*	*Temp., °F*	*Lb.per cu. ft.*	*Temp., °F*	*Lb.per cu. ft.*
32	60.41	66	62.32	100	61.99	134	61.48
33	62.41	67	62.32	101	61.98	135	61.46
34	62.42	68	62.31	102	61.96	136	61.44
35	62.42	69	62.30	103	61.95	137	61.43
36	62.42	70	62.30	104	61.94	138	61.41
37	62.42	71	62.29	105	61.93	139	61.39
38	62.42	72	62.28	106	61.91	140	61.37
39	62.42	73	62.27	107	61.90	141	61.36
40	62.42	74	62.26	108	61.89	142	61.34
41	62.42	75	62.25	109	61.87	143	61.32
42	62.42	76	62.25	110	61.86	144	61.30
43	62.42	77	62.24	111	61.84	145	61.28
44	62.42	78	62.23	112	61.83	146	61.26
45	62.42	79	62.22	113	61.81	147	61.25
46	62.41	80	62.21	114	61.80	148	61.23
47	62.41	81	62.20	115	61.78	149	61.21
48	62.41	82	62.19	116	61.77	150	61.19
49	62.41	83	62.18	117	61.75	151	61.17
50	62.40	84	62.17	118	61.74	152	61.15
51	62.40	85	62.16	119	61.72	153	61.13
52	62.40	86	62.15	120	61.71	154	61.11
53	62.39	87	62.14	121	61.69	155	61.09
54	62.39	88	62.13	122	61.68	156	61.07
55	62.38	89	62.12	123	61.66	157	61.05
56	62.38	90	62.11	124	61.64	158	61.03
57	62.38	91	62.10	125	61.63	159	61.01
58	62.37	92	62.08	126	61.61	160	60.99
59	62.37	93	62.07	127	61.60	161	60.97
60	62.36	94	62.06	128	61.58	162	60.95
61	62.35	95	62.05	129	61.56	163	60.93
62	62.35	96	62.04	130	61.55	164	60.91
63	62.34	97	62.02	131	61.53	165	60.89
64	62.34	98	62.01	132	61.51	166	60.87
65	62.33	99	62.00	133	61.50	167	60.85

(*continued*)

Table 1-4 (*continued*)

Temp., °F	*Lb.per cu. ft.*	*Temp., °F*	*Lb.per cu. ft.*	*Temp., °F*	*Lb.per cu. ft.*	*Temp., °F*	*Lb.per cu. ft.*
168	60.83	193	60.28	230	59.42	480	50.00
169	60.81	194	60.26	240	59.17	490	49.50
170	60.79	195	60.23	250	58.89	500	48.78
171	60.77	196	60.21	260	58.62	510	48.31
172	60.75	197	60.19	270	58.34	520	47.62
173	60.73	198	60.16	280	58.04	530	46.95
174	60.71	199	60.14	290	57.74	540	46.30
175	60.68	200	60.11	300	57.41	550	45.66
176	60.66	201	60.09	310	57.08	560	44.84
177	60.64	202	60.07	320	56.75	570	44.05
178	60.62	203	60.04	330	56.40	580	43.29
179	60.60	204	60.02	340	56.02	590	42.37
180	60.57	205	59.99	350	55.65	600	41.49
181	60.55	206	59.97	360	55.25	610	40.49
182	60.53	207	59.95	370	54.85	620	39.37
183	60.51	208	59.92	380	54.47	630	38.31
184	60.49	209	59.90	390	54.05	640	37.17
185	60.46	210	59.87	400	53.62	650	35.97
186	60.44	211	59.85	410	53.19	660	34.48
187	60.42	212	59.82	420	52.74	670	32.89
188	60.40	214	59.81	430	52.33	680	31.06
189	60.37	216	59.77	440	51.87	690	28.82
190	60.35	218	59.70	450	51.28	700	25.38
191	60.33	220	59.67	460	51.02	706.1	19.16
192	60.30			470	50.51		

Table 1-5 Expansion of Water

°C	*°F*	*Volume*	*°C*	*°F*	*Volume*	*°C*	*°F*	*Volume*
4	39	1.00000	35	95	1.00586	70	158	1.02241
5	41	1.00001	40	104	1.00767	75	167	1.02548
10	50	1.00025	45	113	1.00967	80	176	1.02872
15	59	1.00083	50	122	1.01186	85	185	1.03213
20	68	1.00171	55	131	1.01423	90	194	1.03570
25	77	1.00286	60	140	1.01678	95	203	1.03943
30	86	1.00425	65	149	1.01951	100	212	1.04332

Air

Air is a gas that is a mixture of 23.2 percent (by weight) oxygen, 75.5 percent nitrogen, and 1.3 percent argon. Other substances present in the air or atmosphere in small amounts are 0.03 to 0.04 percent carbonic acid, or carbon dioxide, 0.01 percent krypton, and small amounts of several other gases. The air or atmosphere is a mixture of the following gases by volume: 21.0 percent oxygen, 78.0 percent nitrogen, and, 0.94 percent argon.

The term *free air* refers to the air at atmospheric pressure. It does not refer to air under identical conditions. Barometer and temperature readings vary with the altitude of a locality and at different times. Thus, free air is not necessarily the air at sea level conditions—or an absolute pressure of 14.7 psi at a temperature of 60°F. It is correct to refer to the air at atmospheric condition at the point where a compressor is installed as free air.

The average condition of the atmosphere in a temperate climate is referred to as *normal air*. This term is used to indicate air with 36 percent relative humidity at 68°F.

Humidity

Water vapor is always present in the atmosphere. The actual quantity of water present in the air is referred to as *absolute humidity*, and it is usually expressed as grains of moisture per cubic foot of air. A *grain* is $^1/_{7000}$ (0.00014285) part of 1 pound. The temperature of the air determines the amount of water that the air is capable of holding—the warmer the air, the more moisture it can hold. For example, the air at 80°F can hold nearly twice the moisture as it can hold at 60°F.

The actual amount of moisture in the air as compared with the maximum amount of moisture that the air is capable of holding at a given temperature, expressed as a percentage, is called the *relative humidity*. Two thermometers (a wet-bulb and a dry-bulb thermometer) are required to determine relative humidity. This is a form of *hydrometer* and it consists of two thermometers mounted side by side; the bulb of one thermometer is kept moist by means of a loose cotton wick tied around its bulb, the lower end of the wick dipping into a vessel that contains water. The wet bulb is cooled by evaporation of water from the bulb. Therefore, the wet-bulb thermometer indicates a lower temperature reading than the dry-bulb thermometer (the difference depending on the rate of evaporation, which, in turn, is determined by the amount of water vapor in the atmosphere). If the air is saturated with moisture, its relative humidity is 100 percent. Air at the same temperature, but holding one-half the saturation amount, has a relative humidity of 50 percent. A table

Table 1-6 Pound per Square Inch to Feet (Head) of Water (Based on Water at Its Greatest Density)

Pressure, Pounds Per Square Inch	*Feet Head*	*Pressure, Pounds Per Square Inch*	*Feet Head*	*Pressure, Pounds Per Square Inch*	*Feet Head*	*Pressure, Pounds Per Square Inch*	*Feet Head*	*Pressure, Pounds Per Square Inch*	*Feet Head*	*Pressure, Pounds Per Square Inch*	*Feet Head*	*Pressure, Pounds Per Square Inch*	*Feet Head*
1	2.31	53	122.43	105	242.55	157	382.67	209	482.79	261	602.91	365	843.15
2	4.62	54	124.74	106	244.86	158	364.98	210	485.10	262	605.22	370	854.70
3	6.93	55	127.05	107	247.17	159	367.29	211	487.41	263	607.53	375	856.28
4	9.23	56	129.36	108	249.48	160	369.60	212	489.72	264	609.84	380	877.80
5	11.55	57	131.67	109	251.79	161	371.91	213	492.03	265	612.15	385	889.35
6	13.86	58	133.98	110	254.10	162	374.22	214	494.04	266	614.46	390	900.90
7	16.17	59	136.29	111	256.41	163	375.53	215	496.65	267	616.77	395	912.45
8	18.48	60	138.60	112	258.72	164	378.84	216	498.96	268	619.08	400	924.00
9	20.79	61	140.91	113	261.03	165	381.15	217	501.27	269	621.39	405	931.55
10	23.10	62	143.22	114	263.34	166	383.45	218	503.58	270	623.70	410	947.10
11	25.41	63	145.53	115	265.65	167	385.77	219	505.89	271	626.01	415	958.65
12	27.72	64	147.84	116	267.96	168	388.08	220	508.20	272	628.32	420	970.20
13	30.03	65	150.15	117	270.27	169	390.39	221	510.51	273	630.63	425	981.75
14	32.34	66	152.46	118	272.58	170	392.70	222	512.82	274	632.94	430	993.30
15	34.65	67	154.77	119	274.89	171	395.01	223	515.13	275	635.25	435	1004.85
16	36.96	68	157.08	120	277.20	172	397.32	224	517.44	276	637.56	440	1016.40
17	39.27	69	159.39	121	279.51	173	399.63	225	519.75	277	639.87	445	1027.95
18	41.58	70	161.70	122	281.82	174	401.94	226	522.06	278	642.18	450	1039.50
19	43.89	71	164.01	123	284.13	175	404.25	227	524.37	279	644.49	455	1051.06
20	46.20	72	166.32	124	286.44	176	406.56	228	526.65	280	646.80	460	1062.60
21	48.51	73	168.83	125	288.75	177	408.87	229	528.99	281	649.11	465	1074.15
22	50.82	74	170.94	126	291.06	178	411.18	230	531.30	282	851.42	470	1085.70
23	53.13	75	173.25	127	293.37	179	413.49	231	533.61	283	653.73	475	1097.25
24	55.44	76	175.56	128	295.68	180	415.80	232	535.92	284	655.04	480	1106.80

25	57.75	77	177.87	129	297.99	181	418.11	233	538.23	285	668.35	485	1120.35
26	60.06	78	180.18	130	300.30	182	420.42	234	540.54	286	660.66	490	1131.90
27	62.37	79	182.49	131	302.61	183	422.73	235	542.85	287	662.97	495	1143.45
28	64.68	80	184.80	132	304.92	184	425.04	236	545.16	288	665.28	500	1155.00
29	66.99	81	187.11	133	307.23	185	427.35	237	547.47	289	667.59	525	1212.75
30	69.30	82	189.42	134	309.54	186	429.66	238	549.78	290	669.90	550	1270.50
31	71.61	83	191.73	135	311.85	187	431.97	239	552.09	291	672.21	575	1328.25
32	73.92	84	194.04	136	314.16	188	434.28	240	554.40	292	674.52	600	1386.00
33	76.23	85	196.35	137	316.47	189	436.59	241	556.71	293	676.83	625	1443.75
34	78.54	86	198.55	138	318.78	190	438.90	242	559.02	294	679.14	650	1501.50
35	80.85	87	200.97	139	321.09	191	441.21	243	561.33	295	681.45	675	1559.25
36	83.18	88	203.28	140	323.40	192	443.52	244	563.64	296	683.76	700	1617.00
37	85.47	89	205.59	141	325.71	193	445.83	245	565.95	297	686.07	725	1674.75
38	87.78	90	207.90	142	328.02	194	448.14	246	568.26	298	688.38	750	1732.60
39	90.09	91	210.21	143	330.33	195	450.45	247	570.57	299	690.69	775	1790.25
40	92.40	92	212.52	144	332.64	196	452.76	248	572.88	300	693.00	800	1848.00
41	94.71	93	214.83	145	334.95	197	455.07	249	575.19	305	704.55	825	1905.75
42	97.02	94	217.14	146	337.26	198	457.38	250	577.50	310	716.10	850	1963.60
43	99.33	95	219.45	147	339.57	199	459.69	251	579.81	315	727.55	875	2021.25
44	101.64	96	221.76	148	341.88	200	462.00	252	582.12	320	739.20	900	2079.00
45	103.95	97	224.07	149	344.19	201	484.31	253	584.43	325	750.75	925	2136.75
46	106.26	98	226.38	150	345.50	202	466.62	254	586.74	330	762.30	950	2194.50
47	108.57	99	228.69	151	348.81	203	468.93	255	589.05	335	773.85	975	2252.25
48	110.88	100	231.00	152	351.12	204	471.24	256	591.36	340	785.40	1000	2310.00
49	113.19	101	233.31	153	353.43	205	473.55	257	593.67	345	796.95	1500	3465.00
50	115.50	102	235.62	154	355.74	206	476.86	258	595.98	350	808.50	2000	4620.00
51	117.81	103	237.93	155	358.05	207	478.17	259	598.29	355	820.05	3000	6930.00
52	120.12	104	240.24	156	380.36	208	480.48	260	600.60	360	831.60		

can be used to determine the percentage of relative humidity after the wet-bulb and dry-bulb readings have been obtained.

Weight of Air

Pure air (at 32°F and a barometric pressure of 14.696 psi) weighs 0.08071 pounds per cubic foot. The weight and volume of air change with variations in temperature and pressure (Table 1-7).

Table 1-7 Volume and Weight of Air at Atmospheric Pressure for Different Temperatures

Temperature °F	*Volume of 1 Pound of Air (cu.ft.)*	*Weight per Cubic Foot (lbs.)*	*Temperature °F*	*Volume of 1 Pound of Air (cu.ft.)*	*Weight per Cubic Foot (lbs.)*
0	11.57	0.0864	325	19.76	0.0508
12	11.88	0.0842	350	20.41	0.0490
22	12.14	0.0824	375	20.96	0.0477
32	12.39	0.0807	400	21.69	0.0461
42	12.64	0.0791	450	22.94	0.0436
52	12.89	0.0776	500	24.21	0.0413
62	13.14	0.0761	600	26.60	0.0376
72	13.39	0.0747	700	29.59	0.0338
82	13.64	0.0733	800	31.75	0.0315
92	13.89	0.0720	900	34.25	0.0292
102	14.14	0.0707	1000	37.31	0.0268
112	14.41	0.0694	1100	39.37	2.0254
122	14.66	0.0682	1200	41.84	0.0239
132	14.90	0.0671	1300	44.44	0.0225
142	15.17	0.0659	1400	46.95	0.0213
152	15.41	0.0649	1500	49.51	0.0202
162	15.67	0.0638	1600	52.08	0.0192
172	15.92	0.0628	1700	54.64	0.0183
182	16.18	0.0618	1800	57.14	0.0175
192	16.42	0.0609	2000	62.11	0.0161
202	16.67	0.0600	2200	67.11	0.0149
212	16.92	0.0591	2400	72.46	0.0138
230	17.39	0.0575	2600	76.92	0.0130
250	17.89	0.0559	2800	82.64	0.0121
275	18.52	0.0540	3000	87.72	0.0114
300	19.16	0.0522			

Volumetric expansion = linear expansion.

Moisture in the air has an adverse effect on an air compressor. The efficiency of the air compressor is reduced because the presence of water vapor in the air being compressed increases the total heating capacity of the air. This is due to the latent heat of the water vapor. The increased temperature increases the pressure and power required for compression.

Summary

The three states in which matter may exist are known as solid, liquid, and gas. Water is a familiar example of a substance that exists in each of the three states of matter as ice, water, and steam, respectively.

Energy is the capacity for doing work and for overcoming resistance. The two types of energy are potential and kinetic.

The two types of heat are sensible and latent. The effect of heat is produced by the accelerated vibration of molecules. Heat is transferred from one body to another by radiation, conduction, and convection.

Pressure (P) is a force exerted against an opposing body, or a thrust distributed over a surface. Pressure is considered to be distributed over a unit area of the surface.

Atmospheric pressure is caused by the weight of the Earth's atmosphere. At sea level it is equal to about 14.69 psi. The pressure of the atmosphere does not remain constant at a given location, because weather conditions vary continually.

Pressure measured above that of atmospheric pressure is termed gage pressure. Pressure measured above that of a perfect vacuum is termed absolute pressure.

The barometer is used to measure atmospheric pressure. The barometer reading is expressed in inches of mercury. At standard atmospheric pressure, the barometer reads approximately 30 inches of mercury. The barometer reading in inches of mercury can be converted to psi by multiplying the barometer reading by 0.49116.

The force that tends to draw all bodies in the Earth's sphere toward the center of the Earth is known as gravity. The rate of acceleration of gravity is approximately 32 feet per second per second. Centrifugal force tends to move a rotating body away from its center of rotation. Centripetal force tends to move a rotating body toward its center of rotation.

A force is defined completely only when its direction, magnitude, and point of application are defined. All these factors can be represented by a line or vector with an arrowhead.

Motion is described as a change in position in relation to an assumed fixed point. Motion is strictly a relative matter. Velocity is the rate of change of position in relation to time, and acceleration is the rate of increase or average increase in velocity in a given unit of time.

The resistance to motion of two moving objects that touch is called friction. The ratio of the force required to slide a body along a horizontal plane surface to the weight of the body is called the coefficient of friction.

The expenditure of energy to overcome resistance through a distance is work. The standard unit for measuring work is the foot-pound (ft-lb). The foot-pound is the amount of work that is done in raising 1 pound a distance of 1 foot, or in overcoming a pressure of 1 pound through a distance of 1 foot.

Power is the rate at which work is done, or work divided by the time in which it is done. The standard unit for measuring power is the horsepower (hp), which is defined as 33,000 foot-pounds per minute. The formula that can be used to calculate engine horsepower is as follows:

$$hp = \frac{2\ PLAN}{33{,}000}$$

The basic machines are lever, wheel and axle, pulley, inclined plane, screw, and wedge. The Principle of Moments is important in studying the basic machines.

An important property of water is that it varies in weight (pound per unit volume) with changes in temperature, giving rise to circulation in boilers and heating systems. A U.S. gallon of water (231 cubic inches) weights 8.33111 pounds at 62°F.

Air is a gas that is a mixture of 23.2 percent (by weight) oxygen, 75.5 percent nitrogen, and 1.3 percent argon. Other substances present are 0.03 to 0.04 percent carbonic acid, or carbon dioxide, 0.01 percent krypton, and small quantities of several other gases. Air is a mixture (by volume) of 21.0 percent oxygen, 78.0 percent nitrogen, and 0.94 percent argon.

Humidity is the water vapor that is always present in the atmosphere. The actual quantity of water present is absolute humidity, and it is usually expressed as grains of moisture per cubic foot of air. A grain is $^1/_{7000}$ part of one pound. The actual amount of moisture in the air as compared with the maximum amount of moisture that the air is capable of holding, expressed as a percentage, is called relative humidity.

Review Questions

1. What is the definition of *matter*?
2. What are the three states of matter?

3. What is the definition of *energy*?
4. What are the two forms of energy?
5. State the Law of Conservation of Energy.
6. What are the two forms of heat?
7. What is the unit of heat?
8. What is meant by the *specific heat* of a substance?
9. What are the three methods of transferring heat?
10. What is meant by *pressure*?
11. What is the value for standard atmospheric pressure?
12. What is the difference between *gage pressure* and *absolute pressure*?
13. How is atmospheric pressure measured?
14. What is the definition of *gravity*?
15. What is the difference between *centrifugal force* and *centripetal force*?
16. What is the definition of *motion*?
17. Explain the difference between *momentum* and *inertia*.
18. What is *friction*, and what is its cause?
19. Explain the difference between *work* and *power*.
20. What is the standard unit of work? Of power?
21. State the Principle of Moments.
22. What elements are found in air?
23. What is the definition of *humidity*?
24. What is *inertia*?
25. What did Joule's experiment reveal?
26. What is the difference between *latent heat* and *sensible heat*?
27. What are some of the disadvantages of expansion and contraction caused by changes in temperature?
28. What does a *barometer* measure?
29. What is meant by *state of equilibrium*?
30. What are Newton's three laws of motion?
31. What are the two states of inertia?
32. What does *coefficient of friction* mean?
33. What are the three laws of friction?
34. What does the term *fulcrum* mean?

35. What is the *point of maximum density* of water?
36. What does a gallon of water weigh?
37. How compressible is water?
38. What is the weight of pure air at 32°F and a barometric pressure of 14.696 pounds?
39. How is relative humidity found?
40. What causes the efficiency of an air compressor to decrease?