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FUNDAMENTALS OF REFRIGERATION

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FOREWORD

This text book on Fundamentals of Refrigeration was compiled for use by the Marine Engineering Course trainees of the Training Department, SEAFDEC.

Since this has been prepared as part of a more comprehensive study on refrigeration, only a general review of the basic physics required for further study of the subject is contained herein. Other parts of the text book will be issued in the very near future.

For subsequent revision of the text suggestions and comments from readers would be greatly appreciated.

In addition, the author wishes to thank Miss Barbara Mountfield for her assistance in the compilation of the present text book.

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1. Force

A force is defined as a push or a pull. It is anything that has a tendency to set a body in motion, to bring a moving body to rest, or to change the direction of motion. A force may also change the size or shape of a body. That is, the body may be twisted, bent, stretched, compressed, or otherwise distorted by the action of a force.

The most familiar force is weight. The weight of a body is a measure of the force exerted on the body by the gravitational pull of the earth as shown in Fig. 1. There are many forces other than the force of gravity, but all forces are measured in weight units. Although the most commonly used unit of force measure is kilogram, any unit of weight may be used, and the particular unit used at any time will usually depend on the magnitude of the force to be measured.

2. Pressure

Pressure is the force exerted per unit of area. It may be described as a measure of the intensity of a force at any given point on the contact surface. Whenever a force is evenly distributed over a given area, the pressure at any point on the contact surface is the same and can be calculated by dividing the total force exerted by the total area over which the pressure is applied. This relationship is expressed by the following equation:

$$P = \frac{F}{A} \tag{1}$$

where P = the pressure expressed in unit of F per unit of A
F = the total force in any unit of force
A = the total area in any unit of area.

As indicated by equation (1), pressure is measured in unit of force per unit of area. Pressures are most frequently given in kilogram per square centimeter, abbreviated kg/cm^2, or pounds per square inch, abbreviated psi. However, pressure, like force, as a matter of convenience and depending on the magnitude of the pressure, may be stated in terms of other units of force and area.

2.1 Atmospheric Pressure

The earth is surrounded by the atmosphere or air which extends upward from the surface of the earth to distance of about 80 km. or more. Air has weight and, because of its weight, exerts a pressure on the surface of the earth. The pressure exerted by the atmosphere is known as atmospheric pressure.

The weight of a column of air having a cross section of 1 cm^2 and extending from the surface of the earth at sea level to the upper limits of the atmosphere is 1.033 kg. Therefore, the pressure on the surface of the earth at sea level resulting from the weight of the atmosphere is 1.033 kg/cm^2. This is understood to be the normal or standard atmospheric pressure at sea level and is sometimes referred to as a pressure of one atmosphere. Actually, the pressure of the atmosphere does not remain constant, but will usually vary somewhat from hour to hour depending upon the temperature, water vapour content and several other factors.

2.2 Barometers

Barometers are instruments used to measure the pressure of the atmosphere and are of several types. A simple barometer which measures atmospheric pressure in terms of height of a column of mercury can be constructed by filling with mercury a glass tube 920 mm or more long and closed at one end. The mercury is held in the tube by placing the index finger over the open end of the tube while the tube is inverted in an open dish of mercury. When the finger is removed from the tube, the level of the mercury in the tube will fall, leaving an almost perfect vacuum at the closed end. The pressure exerted downward by the atmosphere on the open dish of mercury will cause the mercury to rise into the tube to a height depending upon the amount of the pressure exerted. The height of the mercury column in the tube is the measure of the pressure exerted by the atmosphere and is read in milimeters of mercury column (abbreviated Hg.)

The normal pressure of the atmosphere at sea level (1.033 kg/cm^2) pressing down on the dish of mercury will cause the mercury in the tube to rise to a height of 760 mm as shown in Fig. 2. A column of mercury 760 mm high is, then, a measure of a pressure equivalent to 1.033 kg/cm^2. This means that a pressure of 1.033 kg/cm^2 is equivalent to a pressure of 760 mm Hg.

2.3 Pressure Gages

Pressure gages are instruments used to measure the fluid pressure inside a closed vessel. Pressure gages commonly used in the refrigeration systems are of two types: (1) manometer and (2) bourdon tube gauge.

2.3.1 Manometers

The manometer type gage utilizes a column of liquid to measure the pressure, the height of the column indicating the magnitude of the pressure. The liquid used in manometers is usually either water or mercury. When mercury is used the instrument is know as a mercury manometer or mercury gage, and when water is used, the instrument is a water manometer or water gauge. The simple barometer described above is also a manometer type instrument.

A simple mercury manometer, illustrated in Figs. 3a, 3b, and 3c, consists of a U-shaped glass tube open at both ends and partially filled with mercury. When both arms of the U-tube are open to the atmosphere, the atmospheric pressure is exerted on the mercury in both arms of the tube and the height of the two mercury columns is the same. The height of the two mercury columns at this position is marked as the zero point of the scale and the scale is calibrated in milimeters to read the deviation of the mercury columns from the zero condition in either direction. Fig. 3a shows that the height of the mercury columns is the same.

To use this gage, one side of the U-tube is connected to a vessel containing fluid whose pressure is to be measured. The pressure in the vessel, acting on one arm of the tube, is balanced by the atmospheric pressure exerted on the open arm of the tube. If the pressure in the vessel is greater than that of the atmosphere, the level of the mercury on the vessel side of the U-tube is depressed while the level of the mercury on the open side of the tube is raised an equivalent amount as shown in Fig. 3b. Conversely, Fig. 3c shows the case where the pressure in the vessel is lower than that of the atmosphere. In either case, the difference in the heights of the two mercury columns is a measure of the pressure difference between the pressure of the fluid in the vessel and the pressure of the atmosphere.

In Fig. 3b, the level of mercury is 50 mm below the zero point in the side of the U-tube connected to the vessel and 50 mm above the zero point in the open arm of the tube. This indicated that the pressure in the vessel exceeds the pressure of the atmosphere by 100 mm Hg. In Fig. 3c, it is similarly indicated that the pressure in the vessel is below than that of the atmosphere by 100 mm Hg. Pressures below atmospheric pressure are usually called "vacuum" pressures and may be read as "milimeters of mercury vacuum".

Manometers using water as the measuring fluid are particularly useful for measuring very small pressures, because owing to the difference in the density of mercury and water, pressures so slight that they will not visibly affect the height of a mercury column will produce easily detectable variations in the height of a water column. Atmospheric pressure, which will support a column of mercury 760 mm high, will lift a column of water to a height of approximately 10,336 mm.

Table 1. gives the conversion of pressures.

2.3.2 Bourdon Tube Gages

Gages of the manometer type are not practical for measuring pressures above 1 kg/cm^2, because of the excessively long tube required. These gauges are limited to the measurement of relatively small pressures in air ducts, etc.

Gages of the bourdon tube type are widely used to measure the higher pressures in refrigeration work. The actuating mechanism of the bourdon tube gage is illustrated in Fig. 4. The bourdon tube itself is a curved, metallic tube which tends to straighten as the fluid pressure in the tube increases and to curl tighter as the pressure decreases. Any change in the curvature of the tube is transmitted through a system of gears to the pointer.

Bourdon tube gages are very strong and will measure pressures either above or below atmospheric pressure. Those designed to measure pressures above atmospheric are known as "pressure" gages, and are generally calibrated in kg/cm^2, whereas those designed to read pressures below atmospheric are called "vacuum" gages and are usually calibrated in mm of mercury. Bourdon tube gages designed to measure pressures both above and below atmospheric in a single gage are called "compound" gages.

2.4 Absolute and Gage Pressures

Absolute pressure is understood to be the "total" or the "true" pressure of a fluid, whereas gage pressure is the pressure as indicated by a gage.

It is important to understand that gages are calibrated to read zero at atmospheric pressure and that neither the manometer nor the bourdon tube gage measures the "Total" or "True" pressure of the fluid in a vessel: both measure only the difference in pressure between the total pressure of the fluid in the vessel and the atmospheric pressure.

When the fluid pressure is greater than the atmospheric pressure the absolute pressure of the fluid in the vessel is determined by adding the atmospheric pressure to the gage pressure. When the fluid pressure is less than atmospheric, the absolute pressure of the fluid is found by subtracting the gage pressure from the atmospheric pressure.

3. Work

Work is done when a force acting on a body moves the body through a distance. The amount of work done is the product of the force and the distance through which the force acts.

This relationship is shown by the following equation:

$$W = F \times S \qquad (2)$$

where F = the force applied in any unit of force
S = the distance through which the force acts in any linear unit
W = the work done expressed in unit of force and linear measure.

The work done is always expressed in the same unit terms used to express the magnitude of the force and distance. For instance, if the force is expressed in kilograms and the distance in meters, the work done is expressed in kg-m.

4. Power

Power is the rate of doing work. That is, it is the work done divided by the time needed to do the work.

The unit of power is the horsepower or kilowatt. One horsepower is defined as the power required to do the work at the rate of 75 kg-m/sec. One horsepower corresponds to 0.936 $\overline{KW}$. Therefore, the power required in horsepower may be found by the following equation:

$$HP = \frac{W}{75 \times t} \qquad (3)$$

where HP = the horsepower
W = the work done in kg-m
t = the time in seconds.

5. Energy

Energy is described as the ability to do work. The amount of energy required to do a given work is always equal to the work done. The amount of energy a body possesses is equal to the amount of work a body can do in passing from one condition or position to another.

Energy may be possessed by a body in either or both of two basic kinds : (1) kinetic and (2) potential.

5.1 Kinetic Energy

Kinetic energy is the energy a body possesses as a result of its motion or velocity. For instance, a hammer swinging through an arc, and the moving parts of machinery all have kinetic energy by virtue of their motion.

The amount of kinetic energy a body possesses is a function of its mass and velocity and may be determined by the following equation:

$$K = \frac{M \times V^2}{2\ g} \qquad (4)$$

where K = the kinetic energy in kg-m
M = the weight of the body in kg
V = the velocity in m per second
g = gravitational constant $9.8 m/s^2$

5.2 Potential Energy

Potential energy is the energy a body possesses because of its position or configuration. The amount of work a body can do in passing from a giving position or condition to some reference position or condition is a measure of the body's potential energy. For example, the driving head of a pile driver has potential energy of position when raised to some distance above the top of a piling. If released, the driving head can do the work of driving the piling. A compressed steel spring or a stretched rubber band possesses potential energy of configuration. Both the steel spring and the rubber band have the ability to do work because of their tendency to return to their initial condition.

The potential energy of a body may be evaluated by the following equation:

$$P = M \times Z \qquad (5)$$

where P = the potential energy in kg-m
M = the weight of the body in kg
Z = the vertical distance above some datum or reference.

5.3 Energy as Stored Work

Before a body can possess energy, work must be done on the body. The work which is done on a body to give the body its motion, position or configuration is stored in the body as energy. Hence energy is stored work. For instance, the work must be done to stretch the rubber band, to compress the steel spring, or to raise the driving head of a pile driver to a position above the piling. In any case, the potential energy stored is equal to the work done.

The amount of energy a body possesses can be ascertained by determining the amount of work done on the body to give the body its motion, position, or configuration. For example, assume that the driving head of the pile driver weighing 100 kg is raised to a position 2 m above the top of a piling. The work done in raising the driving head is 200 kg-m. Therefore, 200 kg-m of energy are stored in the driving head in its raised position and, when released, neglecting friction, the driving head will do 200 kg-m of work on the piling.

5.4 Law of Conservation of Energy

The first law of thermodynamics states that the amount of energy is constant. None can be either created or destroyed. Energy is expended only in the sense that it is converted from one form to another.

5.5 Form of Energy

All energy, as mentioned above, can be classified as being either of the two basic kinds, kinetic or potential. However, energy may appear in any one of several different forms, such as mechanical energy, electrical energy, chemical energy, heat energy, etc. and is readily converted from one form to another. Electrical energy, for instance, is converted into heat energy in an electric toaster, heater, or range. Electric energy is converted into mechanical energy, in electrical motors, solenoids, and other electrically operated mechanical devices. Mechanical energy, chemical energy and heat energy are converted into electrical energy in the generator, battery and thermocouple, respectively. Chemical energy is converted into heat energy in chemical reactions such as combustions and oxidation.

6. Matter and Molecules

Everything in the universe that has weight or occupies space is composed of molecules. Molecules are made up of smaller particles called atoms. Atoms are composed of still smaller particles known as electrons, protons, neutrons, etc. The molecule is the smallest, stable particle of matter into which a particular substance can be subdivided and still retain the identity of the original substance.

It is assumed that the molecules that make up a substance are held together by forces of mutual attraction known as cohesion. The molecules are not tightly packed together. There is a certain amount of space between them and they are relatively free to move about. The molecules are further assumed to be in a state of rapid and constant vibration or motion, the rate and extent of the vibration or movement being determined by the amount of energy they possess.

6.1 Internal Energy

It has been previously stated that energy is required to do work or to cause motion of any kind. Molecules can also move about only if they possess energy. Hence, a body has internal energy as well as external energy. Whereas a body has external energy because of its velocity, position, or configuration in relation to some reference condition, it also has internal energy as a result of the velocity, position, and configuration of the molecules of the materials which make up the body.

The molecules of any material may possess energy of both kinds, kinetic and potential. The total internal energy of a material is the sum of its internal kinetic and potential energies. This relationship is shown by the equation:

$$U = K + P \qquad (6)$$

where U = the total internal energy
K = the internal kinetic energy
P = the internal potential energy

6.1.1 Internal Kinetic Energy

Internal kinetic energy is the energy of molecular motion or velocity. When heat energy flowing into a material increases the internal kinetic energy, the velocity or motion of the molecules is increased. The increase in the molecular velocity is always accompanied by an increase in the temperature of the material. Hence, a material's temperature is, in a sense, a measure of the average velocity of the molecules which make up the material. The more kinetic energy the molecules have, the greater is their movement and the faster they move. The more rapid the motion of the molecules, the hotter is the material and the greater its internal kinetic energy. It follows, then that if the internal kinetic energy of the material is diminished by the removal of heat, the motion of the molecules will be slowed down of retarded and the temperature of the material will be decreased.

6.1.2 Internal Potential Energy

Internal potential energy is the energy of molecular separation or configuration. It is the energy the molecules have as a result of their position in relation to one another. The greater the degree of molecular separation, the greater is the internal potential energy. When a material expands or changes its physical state with the addition of energy, a rearrangement of the molecules takes place, which increases the distance between them. Inasmuch as the molecules are attracted to one another by forces which tend to pull them together, internal work must be done in order to separate further the molecules against their attractive forces. An amount of energy equal to the amount of internal work done must flow into the material. This energy is set up in the material as an increase in the potential energy. It is 'stored' energy which is accounted for by the increase in the mean distance between the molecules. The source of this energy is the heat energy supplied.

It is important to understand that in this instance the energy flowing into the material has no effect on molecular velocity (internal kinetic energy); only the degree of molecular separation (the internal potential energy) is affected.

6.2 States of Matter

Matter can exist in three different phases or states of aggregation: solid, liquid, or vapor or gas. For example, water is a liquid, but this same substance can exist as ice, which is a solid, or as steam, which is a vapor or gas.

6.2.1 Effect of Heat on the State

Many materials, under the proper conditions of pressure and temperature, can exist in any and all of the three physical states of matter. The addition or removal of heat can bring about a change in the physical state of the material as well as a change in its temperature. That heat can bring about a change in the physical state of a material is evident from the fact that many materials will become molten when sufficient heat is applied. Furthermore, the phenomenon of melting ice and boiling water is familiar to everyone. Each of these changes in the physical state is brought about by the addition of heat.

6.2.2 Solid State

A material in the solid state has a relatively small amount of internal potential energy. The molecules of the material are rather closely bound together by each other's attractive forces and by the force of gravity. Hence, a material in the solid state has a rather rigid molecular structure in which the position of each molecule is more or less fixed and the motion of the molecules is limited to a vibratory type of movement which, depending upon the amount of internal kinetic energy the molecules possess, may be either slow or rapid. Because of its rigid molecular structure, a solid tends to retain both its size and its shape. A solid is not compressible and will offer considerable resistance to any effort to change its shape.

6.2.3 Liquid State

The molecules of a material in the liquid state have more energy than those of material in the solid state and they are not so closely bound togther. Their great energy allows them to overcome each other's attractive forces to some extent and to have more freedom to move about. They are free to move over and about one another in such a way that the material is said to "flow". Although a liquid is non-compressible and will retain its size, because of its fluid molecular structure, it will not retain its shape, but will assume the shape of any containing vessel.

6.2.4 Vapor or Gaseous State

The molecules of a material in the state of vapour or gas have even a greater amount of energy than those of a material in the liquid state. They have sufficient energy to overcome all restraining forces. They are no longer bound by each other's attractive forces, neither are they bound by the force of gravity. Consequently, they fly about at high velocities, continually colliding with each other and with the walls of the container. For this reason, a gas will retain neither its size nor its shape. It is readily compressible and will completely fill any container regardless of size. Further, if the gas is not stored in a sealed container, it will escape from the container and be diffused into the surrounding air.

7. Temperature

Temperature is a property of matter and a measure of the level of heat intensity or the thermal pressure of a body. A high temperature indicates a high level of heat intensity or thermal pressure, and the body is said to be hot. Likewise, a low temperature indicates a low level of heat intensity or thermal pressure, and the body is said to be cold.

7.1 Thermometers

The most common instrument for measuring temperature is the thermometer. The operation of most thermometers depends upon the property of a liquid to expand or contract as its temperature is increased or decreased, respectively. Because of their low freezing temperatures and relatively constant coefficients of expansion, alcohol and mercury are the liquids most frequently used in thermometers. The mercury thermometer is the more accurate of the two because its coefficient of expansion is more constant through a greater temperature range than is that of alcohol. However, the mercury thermometer has the disadvantage of being more expensive and more difficult to read. Alcohol is cheaper and can be colored for easy visibility. Two temperature scales are in common use today. Those are the Fahrenheit scale and the Centrigrade scale.

7.1.1 Centigrade Scale

The point at which water freezes under atmospheric pressure is taken as the arbitrary zero point on the Centigrade scale, and the point at which water boils is designated as 100. The distance on the scale between these two points is divided into one hundred equal units called degrees, so that the distance between the freezing and boiling points of water on the Centigrade scale is 100^{o}. Water freezes at 0^{o} Centigrade ($0^{o}C$) and boils at 100^{o} Centigrade ($100^{o}C$).

7.1.2 Fahrenheit Scale

On the Fahrenheit scale, the point at which water freezes is marked as 32, and the point at which water boils 212. Thus, there are 180 units between the freezing and boiling points of water.

7.1.3 Temperature Conversion

Temperature readings on one scale can be converted to readings on the other scale by using the following equations:

$$^{\circ}F = {^{\circ}C} \times \frac{9}{5} + 32 \quad (7)$$

$$^{\circ}C = ({^{\circ}F} - 32) \times \frac{5}{9} \quad (8)$$

It has been noted that the difference between the freezing and boiling points of water on the Fahrenheit scale is 180, whereas the difference between the two points on the Centigrade scale is only 100. Therefore, 100 Centigrade degrees are equivalent to 180 Fahrenheit degrees. This establishes a relationship such that $1^{\circ}C$ equals $9/5^{\circ}F$ ($1.8^{\circ}F$) and $1^{\circ}F$ equals $5/9^{\circ}C$ ($0.555^{\circ}C$). This is shown graphically in Fig. 5. Since $0^{\circ}C$ on the Fahrenheit scale is $32^{\circ}F$ below the freezing point of water, it is necessary to add $32^{\circ}F$ to the Fahrenheit equivalent after converting from Centigrade. Likewise, it is necessary to subtract $32^{\circ}F$ from a Fahrenheit reading before converting to Centigrade. Table 2 shows conversions of temperature readings for Fahrenheit and Centigrade scales.

7.2 Absolute Temperature

Temperature readings from either the Fahrenheit or Centigrade scales are taken with reference to arbitrarily selected zero points. When it is desired to know only the change in temperature that occurs during a process or the temperature of a substance in relation to some known reference point, such readings are entirely adequate. However, when temperature readings are to be applied in equations dealing with certain fundamental laws, it is necessary to use temperature readings whose reference point is the true or absolute zero of temperature. Experiments have indicated that such a point, known as absolute zero, exists at approximately $-460^{\circ}F$ or $-273^{\circ}C$ (Fig. 5).

Temperature readings in reference to absolute zero are designated as absolute temperatures and may be in either Fahrenheit or Centigrade degrees. A temperature reading on the Fahrenheit scale can be converted to absolute temperature by adding 460° to the Fahrenheit reading. The resulting temperature is in degrees Rankine ($^{\circ}R$). Likewise, Centigrade temperatures can be converted to absolute temperatures by adding 273° to the Centigrade reading. The resulting temperature is stated in degrees Kelvin ($^{\circ}K$).

In converting to or from absolute temperatures, the following equations will apply:

$$^{o}K = 273^{o} + {}^{o}C \qquad (9)$$

$$^{o}C = {}^{o}K - 273^{o} \qquad (10)$$

$$^{o}R = 460^{o} + {}^{o}F \qquad (11)$$

$$^{o}F = {}^{o}R - 460^{o} \qquad (12)$$

where K = absolute temperature in degrees Kelvin
C = temperature in degrees Centigrade
R = absolute temperature in degrees Rankine
F = temperature in degree Fahrenheit.

8. Heat

Heat is a form of energy. This is evident from the fact that heat can be converted into other forms of energy and that other forms of energy can be converted into heat. Heat is almost universally accepted as internal or molecular energy. On the other hand, heat is defined as energy in transition from one body to another as a result of a difference in temperature between the two bodies. Both these concepts of heat will be used in refrigeration.

8.1 Heat Quantity

A thermometer measures only the intensity of heat and not the quantity. However, in working with heat, it is often necessary to determine heat quantity. Obviously, some unit of heat quantity measure is required. Heat can be measured only by measuring the effects it has on a material, such as the change in temperature, colour, size, etc. The most universally used unit of heat measure is kilocalorie (Kcal) and British thermal unit (Btu). One Kcal is defined as the quantity of heat required to change the temperature of 1 kg of water $1^{o}C$. This quantity of heat, if added to 1 kg of water, will raise the temperature of water $1^{o}C$. Similarly, one Btu changes the temperature of 1 lb of water $1^{o}F$.

The relation between 1 Kcal and 1 Btu is shown as follows:

$$1 \text{ Kcal} = 3.97 \text{ Btu} \qquad (13)$$

$$1 \text{ Btu} = 0.252 \text{ Kcal} \qquad (14)$$

8.2 Specific Heat

The specific heat of a material is defined as the quantity of heat required to change the temperature of 1 kg of the material $1^{o}C$. Therefore, specific heat of water is defined as 1 Kcal/kg/^{o}C or 1 cal/g/^{o}C or 1 Btu/lb/^{o}F. The specific heat of aluminium is 0.21 cal/g/^{o}C whereas that of water is 1 cal/g/^{o}C. This means that 1 cal/g/^{o}C is required to raise the temperature of 1 g of water 1^{o}C, whereas only 0.21 cal is necessary to raise the temperature of 1 g of aluminium 1^{o}C.

The specific heat of a material in the solid state is approximately one-half of that of the same material in the liquid state. Therefore, the specific heat of ice is 0.5 cal/g/^{o}C, whereas that of water is 1 cal/g/^{o}C. The specific heat of raw fish is 0.88 cal/g/^{o}C. Table 3 shows the specific heat of some foods.

8.3 Calculation of Heat Quantity

The puantity of heat which must be added to or removed from a material in order to change its temperature can be calculated by the following equation:

$$Q = MC\ (t_2 - t_1) \qquad (15)$$

where Q = the quantity of heat either absorbed or rejected by the material in cal
M = the weight of the material in g
C = the specific heat of the material in cal/g/^{o}C
t_1 = the initial temperature in ^{o}C
t_2 = the final temperature in ^{o}C

The specific heat of gases, however, varies due to their volume and pressure. The specific heat while the volume of the gas remains constant in known as the constant volume specific heat (C_v). Similarly, the specific heat while the gas expands at a constant pressure is called the constant pressure specific heat (C_p). The constant pressure specific heat is always greater than the constant volume specific heat.

8.4 Two Kinds of Heat

Heat has the ability to bring about a change in the physical state of a material as well as the ability to cause a change in its temperature. This heat is classified into two kinds: sensible heat and latent heat.

8.4.1 Sensible heat

When heat, either absorbed or rejected by a material, causes a change in the temperature of the material, the heat transferred is defined as sensible heat. The term "sensible" is applied to this heat, because the change in temperature can be perceived through the sense of touch and measured with a thermometer.

8.4.2 Latent heat

When heat, either absorbed or rejected by a material, brings about a change in the physical state of the material, the heat is defined as latent heat. The term "latent" is derived from a Latin word meaning hidden. It is applied to this special kind of heat, because this heat is hidden in a material without having any effect on the temperature of the material.

When the change of phase occurs in either direction between the solid and the liquid phases, the heat involved is known as the latent heat of fusion. When the change occurs between the liquid and vapor phases, the heat involved is the latent heat of vaporization.

8.5 Mechanical Energy Equivalent of Heat

Normally the external energy of a body is expressed in mechanical energy units (work), whereas the internal energy of a body is expressed in heat energy units. The mechanical energy of the work done on a body may be converted to the internal energy of the body. For example, the head of a nail struck by a hammer will become warm as a part of the mechanical energy of the hammer blow is converted to the internal kinetic energy of the nail head.

Since heat energy is often converted into mechanical energy (work) and vice versa, and since it is often desirable to express both the internal and external energies of a body in terms of the same energy unit, a factor which can be used to convert from one unit to the other is useful. It has been determined by experiment that one Kcal of heat energy is equivalent to 427 kg-m of the mechanical energy, that is, one kcal is the amount of heat energy required to do 427 kg-m of work. This quantity is known as the mechanical energy equivalent of heat and is usually presented in equations by the symbol J.

Expressed as equations, these relationships become:

$$Q = \frac{W}{J} \qquad (16)$$

and

$$W = J \times Q \qquad (17)$$

where Q = the quantity of heat energy in kcal
W = mechanical energy or work in kg-m
J = the mechanical energy equivalent of heat in kg-m/Kcal.

To convert energy in kcal into energy in kg-m, the energy in kcal is multiplied by 427 and to convert energy in kg-m into energy in kcal, the energy in kg-m is divided by 427. In the case of the calculation of the energies in Btu or in foot-pounds, the above equation can also be used, but in such a case J must be 778 ft-lb.

9. Heat Transfer

As it has been stated, the prime purpose of refrigeration is to produce a desired temperature within a specific area by transferring unwanted heat to a location where it is not undesirable. To understand how these processes are carried on, it is necessary to have a working knowledge of heat flow, how heat may be transferred, and how heat enters a refrigerated space.

9.1 Direction and Rate of Heat Flow

Heat will flow from one body to another when a difference in temperature exists between the two bodies. If the temperature of the two bodies is the same, there is no transfer of heat. Heat always flows down the temperature scale from a high temperature to a low temperature, from a hot body to a cold body, and never in the opposite direction. This states the second law of thermodynamics.

Since heat is energy and can not be destroyed, if heat is to leave one body of material, it must flow into and be absorbed by another body of material whose temperature is below that of the body being cooled. The rate of heat transfer between two bodies is always directly proportional to the difference in temperature between the two bodies.

9.2 Methods of Heat Transfer

The transfer of heat from one body to another occurs in three ways: (1) Conduction (2) Convection, and (3) Radiation.

9.2.1 Conduction

Heat transfer by conduction occurs when energy is transmitted by direct contact between the molecules of a single body or between the molecules of two or more bodies in good thermal contact with each other. The rate of heat transfer by conduction, as previously stated, is in direct proportion to the difference in temperature between the high and low temperature bodies. However, all materials do not conduct heat at the same rate. Some materials, such as metals, conduct heat very readily, whereas others, such as glass, wood, and cork, offer considerable resistance to the conduction of heat. Therefore, for any given temperature difference, the rate of heat flow by conduction through different materials of the same length and cross section will vary with the particular ability of the various materials to conduct heat.

The relative capacity of a material to conduct heat is known as its conductivity. Materials which are good conductors of heat have a high conductivity, whereas materials which are poor conductors have a low conductivity and are used as heat insulators. In general, solids are better conductors of heat than liquids, and liquids are better conductors than gases. This is accounted for by the difference in the molecular structure. Since the molecules of a gas are widely separated the transfer of heat by conduction, that is, from molecule to molecule is difficult.

The Table 4 gives the conductivity of some materials.

9.2.2 Convection

Heat transfer by convection occurs when heat moves from one place to another by means of currents which are set up within some fluid medium. These currents are known as convection currents and result from the change in density which is brought about by the expansion of the heated portion of the fluid. When any portion of a fluid is heated, it expands and its volume per unit of weight increases. Thus, the heated portion becomes lighter, rises to the top, and is immediately replaced by a cooler, heavier portion of the fluid.

For example, assume that a tank of water is heated on the bottom at the center as shown in Fig. 6. The heat from the flame is conducted through the bottom of the tank to the water inside. As the water adjacent to the heat source absorbs heat, its temperature increases and it expands. The heated portion of water being lighter than the surrounding water, rises to the top and is replaced by cooler, more dense water pushing in from the sides. As this sequence continues, the heat is distributed throughout the entire mass of the water by means of the convection currents established within the mass.

There are two kinds of convection, that is, natural and forced convection. Natural convection means that the heated portion of the fluid moves naturally by the difference of heat. Forced convection means that the movement of heat is forced artificially by a fan or the like.

9.2.3 Radiation

Heat transfer by radiation occurs in the form of a wave motion similar to light waves wherein the energy is transmitted from one body to another without the need for intervening matter. Heat energy transmitted by wave motion is called radiation energy.

It is assumed that the molecules of a body are in rapid vibration and that this vibration sets up a wave motion in the ether surrounding the body. Thus, the internal molecular energy of the body is converted into radiant energy waves. When these energy waves are intercepted by another body of matter, they are absorbed by that body and are converted into its internal molecular energy.

The earth receives heat from the sun by radiation. The energy of the sun's molecular vibration is imparted in the form of radiant energy waves to the ether of interstellar space surrounding the sun. The energy waves travel across billions of miles of space and impress their energy upon the earth and upon any other material body which intercepts their path. The radiant energy is absorbed and transformed into internal molecular energy, so that the vibratory motion of the hot body (the sun) is reproduced in the cooler body (the earth).

When the temperature of a body is greater than that of its surroundings, it will give off more heat by radiation than it absorbes. This means that it loses energy to its surroundings and its internal energy decreases. If the temperature of the body is below that of its surroundings, it absorbs more radiant energy than it loses and its internal energy increases.

Heat transfer through a vacuum is impossible by either conduction or convection, since these processes by their very nature require that matter should be the transmitting media. Radiant energy, on the other hand, is not dependent upon matter as a medium of transfer and therefore can be transmitted through a vacuum. Furthermore, when radiant energy is transferred from a hot body to a cold body through some intervening media such as air the temperature of the intervening media is inaffected by the passage of the radiant energy.

When radiant energy waves strike a material body, they may be reflected, refracted or absorbed by it, or they may pass through it to some other substance beyond. A highly transparent material such as glass or air will allow most of the radiant energy to pass through to the materials beyond, whereas opaque materials such as wood, metal or cork cannot be penetrated by radiant energy waves and none will pass through. The amount of radiant energy which is either reflected or absorbed by a material depends upon the nature of the material's surface, that is, its texture and its colour.

9.3 Steady and Unsteady Heat Flow

Heat flow within one body or between different bodies always occurs owing to the difference in heat. Heat flows from a high temperature body to a low temperature body, and never vice versa.

In heat flow, when the temperature difference between the high temperature body and the low temperature body is constant, the amount of heat flow per unit time is also constant without relation to time. This is designated as steady heat flow. On the contrary, when the temperature difference decreases as heat flows, the amount of heat flow per unit time decreases as time passes. This is called unsteady heat flow.

To keep the temperature of frozen food at -20°C, which is stored at -20°C in the cold storage, by cooling with the refrigerant at -25°C is considered as steady heat flow. However, to cool fish at -10°C in the freezing room by the refrigerant at -30°C reduces by degrees the temperature of the fish lower. This is considered as unsteady flow.

In refrigeration, unsteady heat flow is dealt with as steady heat flow by considering the average value of temperature difference per unit time. That is, unsteady heat flow may be calculated as the approximate value of steady flow by calculating the average value of the heat flow measured per unit time.

10. Enthalpy and Entropy

10.1 Enthalpy

Enthalpy is defined as the total heat which must be transferred to the material to bring the material to the specified condition from some initial condition arbitrarily taken as the zero point of enthalpy. Enthalpy is shown in cal/g, but in engineering it is shown in Kcal/kg or Btu/lb. The zero point of enthalpy for water and its vapor, steam, is taken as water at 0°C under atmospheric pressure.

The enthalpy of 1 kg of water at 30°C is the total amount of heat which must be transferred to the water in order to raise the temperature of the water from 0°C to 30°C. Hence, based on the assumption that the enthalpy of water is zero at 0°C the enthalpy of water at 30°C is 30 Kcal/kg. In the case of refrigerants, however the standard datum is choses as 0°C in the metric system and as -40°F in the Btu system, respectively. Enthalpy of liquid at the respective temperatures is determined as 100 Kcal/kg in the metric system and 0 Btu/lb in the Btu system.

Methematically, enthalpy is expressed:

$$h = U + \frac{PV}{J} \qquad (18)$$

where h = the specific enthalpy in Kcal/kg
U = the specific internal energy in Kcal/kg
P = the pressure in kg/cm^2 ab
V = the specific volume in cm^3
J = the mechanical energy equivalent of heat

All the heat transferred to a fluid is not necessarily stored in the fluid as an increase in the internal energy of the fluid. In many cases, some part or all of the heat transferred to the fluid passes through the fluid and leaves the fluid as work. The part of the transferred energy which is stored in the fluid as an increase in the internal energy is represented by the term U, whereas the part of the transferred heat which leaves the fluid as work is represented by the term PV/J. Although the energy represented by the term PV/J does not increase the internal energy of the fluid and is not stored in the fluid, it nevertheless represents energy which must be transferred to the fluid in order to bring the fluid to the specified condition from the initial condition at the arbitrarily selected zero point of enthalpy. Furthermore, even though the external work energy is not stored in the fluid, it must pass back through the fluid and be given up by the fluid as the fluid returns to the initial condition.

10.2 Entropy

Entropy is an expression of the total heat transferred to the material per degree of absolute temperature to bring the material to that condition from some initial condition taken as the zero entropy. Since it is not possible to calculate the absolute value of entropy, entropy values like those of enthalpy are based on an arbitrarily selected zero point. The zero points of entropy and enthalpy are the same for any one fluid. Hence, for water and its vapour, steam, the zero point of entropy is taken as water at $0^{o}C$. In the case of refrigerants, the standard datum of entropy is chosen as $0^{o}C$ in the metric system and as $-40^{o}F$ in the Btu system, respectively. Entropy of a liquid at the respective temperatures is determined as 1.00 $Kcal/kg^{o}K$ in the metric system and 0 $Btu/lb^{o}R$ in the Btu system.

The heat energy transferred during a process can be expressed as the product of the change in entropy and the average absolute tembera-ture. Mathematically, the relationship is expressed by the following equations:

$$\Delta Q = \Delta S \times Tm \qquad (19)$$

$$\Delta S = \frac{\Delta Q}{Tm} \qquad (20)$$

$$Tm = \frac{\Delta Q}{\Delta S} \qquad (21)$$

where ΔQ = the heat energy transferred in Kcal (Btu)
ΔS = the change in entropy in $Kcal/kg/^{o}K$ ($Btu/lb/^{o}R$)
Tm = the average absolute temperature in ^{o}K (^{o}R)

Fig. 7 shows the relationship mentioned above. This is, the heat energy Δ Q (fluctuation in heat amount) is determined by the product of Δ S and Tm. Likewise, heat energy Q required in the change of entropy from S1 to S2 is given as the area, A-B-S2-S1. This is called "entropy diagram" being broadly used for determining the change in the amount of heat in the refrigeration cycle.

11. Refrigerating Capacity

11.1 Ton of Refrigeration

The capacity of refrigerating systems is given as ton of refrigeration (RT). One ton of refrigeration is the capacity of one ton of water at 0°C to be changed into ice at 0°C per 24 hours. The change of water at 0°C into ice at 0°C can be done by absorbing heat equivalent to the heat of fusion from the water. The heat of fusion is 79.6 Kcal per one Kg of water so that one ton of refrigeration is 79600 Kcal per 24 hours or 3320 Kcal per hour.

In the Btu system, which is employed in the United Stated of America and some other countries, 2,000 lb corresponds to one ton, and the heat of fusion of 1 lb of ice is 144 Btu. Therefore, one ton of refrigeration is 288,000 Btu per 24 hours or 12,000 Btu per hour. This corresponds to 3,024 Kcal per hour, because one Btu is equal to 0.252 Kcal.

11.2 Ton of Ice Making

Apart from this ton of refrigeration, which denotes the capacity of the refrigeration system, the ton of ice-making is also used. When an ice making plant is called a 30-ton ice making plant, it means that the plant has the capacity to produce 30 tons of ice per day. The capacity needed for ice making may be as follows: 1) the cooling capacity needed for cooling the water for making ice down to the temperature of 0°C; 2) the capacity necessary for changing the water at 0°C to ice at 0°C; 3) the capacity necessary for cooling the ice at 0°C to the approximate temperature of the brine which is used for cooling the ice; 4) the capacity needed for cooling the heat transmitted from the outside of the ice making plant. The heat which is transmitted from the outside is assumed to be 20% of the sum of capacities 1), 2), and 3).

For example, the capacity to produce one ton of ice from water at 30°C may be calculated as follows:

Heat to be removed for cooling the water from 30^{o}C to 0^{o}C		30,000 Kcal
Heat to be removed for changing the water at 0^{o}C into ice at 0^{o}C		79,600 "
Heat for cooling the ice from 0^{o}C to -9^{o}C		4,500 "
	sub total	114,100 Kcal
Heat transmitted from the outside	114,100 x 0.2 =	28,800 "
	total	136,900 Kcal

This total heat converted into ton of refrigeration is:

$$\frac{136,900}{79,600} = 1.72 \text{ RT}$$

APPENDIX

(Tables)

Table 1. Conversion Table of Pressures

Bar	Kg/cm^2	lb/in^2	Atm standard	Mercury Column (0^oC)		Water Column (15^oC)	
				m	in	m	in
1.0000	1.0197	14.50	0.9869	0.7500	29.53	10.21	401.80
0.9807	1.0000	14.22	0.9678	0.7354	28.96	10.01	394.0
0.06895	0.07031	1.00	0.06804	0.5171	2.036	0.7037	27.70
1.0133	1.0333	14.70	1.0000	0.7600	29.92	10.34	407.2
1.3333	1.3596	19.34	1.316	1.0000	39.37	13.61	535.7
0.03386	0.03453	0.4912	0.03342	0.0254	1.00	0.3456	13.61
0.09998	0.09991	1.421	0.0967	0.0967	2.893	1.000	39.37
0.002489	0.002538	0.03610	0.002456	0.002456	0.07349	0.0254	1.00

Table 2. Equivalent Temperature Readings for Fahrenheit and Centigrade Scales.

FAHRENHEIT DEGREES	CENTIGRADE DEGREES	FAHRENHEIT DEGREES	CENTIGRADE DEGREES	FAHRENHEIT DEGREES	CENTIGRADE DEGREES	FAHRENHEIT DEGREES	CENTIGRADE DEGREES
-459.4	-273.	- 21.	- 29.4	17.6	- 8.	56.	13.3
-436.	-270.	- 20.2	- 29.	18.	- 7.8	57.	13.9
-418.	-260.	- 20.	- 28.9	19.	- 7.2	57.2	14.
-400.	-240.	- 19.	- 28.3	19.4	- 7.	58.	14.4
-382.	-230.	- 18.4	- 28.	20.	- 6.7	59.	15.
-364.	-220.	- 18.	- 27.8	21.	- 6.1	60.	15.6
-346.	-210.	- 17.	- 27.2	21.2	- 6.	60.8	16.
-328.	-200.	- 16.6	- 27.	22.	- 5.6	61.	16.1
-310.	-190.	- 16.	- 26.7	23.	- 5.	62.	16.7
-292.	-180.	- 15.	- 26.1	24.	- 4.4	62.6	17.
-274.	-170.	- 14.8	- 26.	24.8	- 4.	63.	17.2
-256.	-160.	- 14.	- 25.6	25.	- 3.9	64.	17.8
-238.	-150.	- 13.	- 25.	26.	- 3.3	64.4	18.
-220.	-140.	- 12.	- 24.4	26.6	- 3.	65.	18.3
-202.	-130.	- 11.2	- 24.	27.	- 2.8	66.	18.9
-184	-120.	- 11.	- 23.9	28.	- 2.2	66.2	19.
-166.	-110.	- 10.	- 23.3	28.4	- 2.	67.	19.4
-148.	-100.	- 9.4	- 23.	29.	- 1.7	68.	20.
-139.	- 95.	- 9.	- 22.8	30.	- 1.1	69.	20.6
-130.	- 90.	- 8.	- 22.2	30.2	- 1.	69.8	21.
-121.	- 85.	- 7.6	- 22.	31.	- 0.6	70.	21.1
-112.	- 80.	- 7.	- 21.7	32.	0.	71.	21.7
-103.	- 75.	- 6.	- 21.1	33.	+ 0.6	71.6	22.
- 94.	- 70.	- 5.8	- 21.	33.8	1.	72.	22.2
- 85.	- 65.	- 5.	- 20.6	34.	1.1	73.	22.8
- 76.	- 60.	- 4.	- 20.	35.	1.7	73.4	23.
- 67.	- 55.	- 3.	- 19.4	35.6	2.	74.	23.3
- 58.	- 50.	- 2.2	- 19.	36.	2.2	75.	23.9
- 49.	- 45.	- 2.	- 18.9	37.	2.8	75.2	24.
- 40.	- 40.	- 1.	- 18.3	37.4	3.	76.	24.4
- 39.	- 39.4	- 0.4	- 18.	38.	3.3	77.	25.
- 38.2	- 39.	0.	- 17.8	39.	3.9	78.	25.6
- 38.	- 38.9	+ 1.	- 17.2	39.2	4.	78.8	26.
- 37.	- 38.3	1.4	- 17.	40.	4.4	79.	26.1
- 36.4	- 38.	2.	- 16.7	41.	5.	80.	26.7
- 36.	- 37.8	3.	- 16.1	42.	5.6	80.6	27.
- 35.	- 37.2	3.2	- 16.	42.8	6.	81.	27.2
- 34.6	- 37.	4.	- 15.6	43.	6.1	82.	27.8
- 34.	- 36.7	5.	- 15.	44.	6.7	82.4	28.
- 33.	- 36.1	6.	- 14.4	44.6	7.	83.	28.3
- 32.8	- 36.	6.8	- 14.	45.	7.2	84.	28.9
- 32.	- 35.6	7.	- 13.9	46.	7.8	84.2	29.
- 31.	- 35.	8.	- 13.3	46.4	8.	85.	29.4
- 30.	- 34.4	8.6	- 13.	47.	8.3	86.	30.
- 29.2	- 34.	9.	- 12.8	48.	8.9	87.	30.6
- 29.	- 33.9	10.	- 12.2	48.2	9.	87.8	31.
- 28.	- 33.3	10.4	- 12.	49.	9.4	88.	31.1
- 27.4	- 33.	11.	- 11.7	50.	10.	89.	31.7
- 27.	- 32.8	12.	- 11.1	51.	10.6	89.6	32.
- 26.	- 32.2	12.2	- 11.	51.8	11.	90.	32.2
- 25.6	- 32.	13.	- 10.6	52.	11.1	91.	32.8
- 25.	- 31.7	14.	- 10.	53.	11.7	91.4	33.
- 24.	- 31.1	15.	- 9.4	53.6	12.	92.	33.3
- 23.8	- 31.	15.8	- 9.	54.	12.2	93.	33.9
- 23.	- 30.6	16.	- 8.9	55.	12.8	93.2	34.
- 22.	- 30.	17.	- 8.3	55.4	13.	94.	34.4

Table 2. (cont'd) Equivalent Temperature Readings for Fahrenheit and Centigrade Scales.

FAHRENHEIT DEGREES	CENTIGRADE DEGREES	FAHRENHEIT DEGREES	CENTIGRADE DEGREES	FAHRENHEIT DEGREES	CENTIGRADE DEGREES	FAHRENHEIT DEGREES	CENTIGRADE DEGREES
95.	35.	134.	56.7	172.4	78.	211.	99.4
96.	35.6	134.6	57.	173.	78.3	212.	100.
96.8	36.	135.	57.2	174.	78.9	213.	100.6
97.	36.1	136.	57.8	174.2	79.	213.8	101.
98.	36.7	136.4	58.	175.	79.4	214.	101.1
98.6	37.	137.	58.3	176.	80.	215.	101.7
99.	37.2	138.	58.9	177.	80.6	215.6	102.
100.	37.8	138.2	59.	177.8	81.	216.	102.2
100.4	38.	139.	59.4	178.	81.1	217.	102.8
101.	38.3	140.	60.	179.	81.7	217.4	103.
102.	38.9	141.	60.6	179.6	82.	218.	103.3
102.2	39.	141.8	61.	180.	82.2	219.	103.9
103.	39.4	142.	61.1	181.	82.8	219.2	104.
104.	40.	143.	61.7	181.4	83.	220.	104.4
105.	40.6	143.6	62.	182.	83.3	221.	105.
105.8	41.	144.	62.2	183.	83.9	222.	105.6
106.	41.1	145.	62.8	183.2	84.	222.8	106.
107.	41.7	145.4	63.	184.	84.4	223.	106.1
107.6	42.	146.	63.3	185.	85.	224.	106.7
108.	42.2	147.	63.9	186.	85.6	224.6	107.
109.	42.8	147.2	64.	186.8	86.	225.	107.2
109.4	43.	148.	64.4	187.	86.1	226.	107.8
110.	43.3	149.	65.	188.	86.7	226.4	108.
111.	43.9	150.	65.6	188.6	87.	227.	108.3
111.2	44.	150.8	66.	189.	87.2	228.	108.9
112.	44.4	151.	66.1	190.	87.8	228.2	109.
113.	45.	152.	66.7	190.4	88.	229.	109.4
114.	45.6	152.6	67.	191.	88.3	230.	110.
114.8	46.	153.	67.2	192.	88.9	231.	110.6
115.	46.1	154.	67.8	192.2	89.	231.8	111.
116.	46.7	154.4	68.	193.	89.4	232.	111.1
116.6	47.	155.	68.3	194.	90.	233.	111.7
117.	47.2	156.	68.9	195.	90.6	233.6	112.
118.	47.8	156.2	69.	195.8	91.	234.	112.3
118.4	48.	157.	69.4	196.	91.1	235.	112.8
119.	48.3	158.	70.	197.	91.7	235.4	113.
120.	48.9	159.	70.6	197.6	92.	236.	113.3
120.2	49.	159.8	71.	198.	92.2	237.	113.9
121.	49.4	160.	71.1	199.	92.8	237.2	114.
122.	50.	161.	71.7	199.4	93.	238.	114.4
123.	50.6	161.6	72.	200.	93.3	239.	115.
123.8	51.	162.	72.2	201.	93.9	240.	115.6
124.	51.1	163.	72.8	201.2	94.	240.8	116.
125.	51.7	163.4	73.	202.	94.4	241.	116.1
125.6	52.	164.	73.3	203.	95.	242.	116.7
126.	52.2	165.	73.9	204.	95.6	242.6	117.
127.	52.8	165.2	74.	204.8	96.	243.	117.2
127.4	53.	166.	74.4	205.	96.1	244.	117.8
128.	53.3	167.	75.	206.	96.7	244.4	118.
129.	53.9	168.	75.6	206.6	97.	245.	118.3
129.2	54.	168.8	76.	207.	97.2	246.	118.9
130.	54.4	169.	76.1	208.	97.8	246.2	119.
131.	55.	170.	76.7	208.4	98.	247.	119.4
132.	55.6	170.6	77.	209.	98.3	248.	120.
132.8	56.	171.	77.2	210.	98.9	249.	120.6
133.	56.1	172.	77.8	210.2	99.	249.8	121.

Table 3. Specific Heat of Some Foods

Name of food	Specific heat	
	Above thr freezing point	Below the freezing point
Raw fish	0.82	0.41
Dry fish	0.56	0.34
Lobster	0.81	0.42
Oyster	0.85	0.42
Cod	0.76	
Beef	0.70 - 0.84	0.38 - 0.43
Pork	0.48 - 0.54	0.30 - 0.32
Ham	0.58 - 0.63	0.34 - 0.36
Butter	0.33	0.25
Egg	0.74	0.40
Water	1	0.5

Table 4. Conductivity of Some Materials

Material	Conductivity (kcal/m-h-^{o}C)
Aluminium	175
Steel	48
Cast iron	42
Copper	330
Tin	58
Concrete	0.7
Asphalt	0.56
Seawater	0.495
Fish	0.327
Beef tallow	0.15
Lard	0.513

APPENDIX

(Figures)

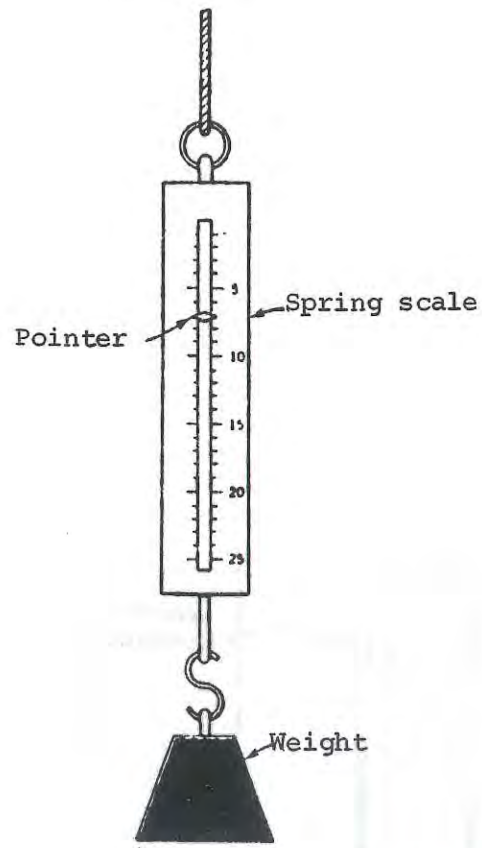

Fig. 1 Because of gravity, the suspended weight exerts a downward force.

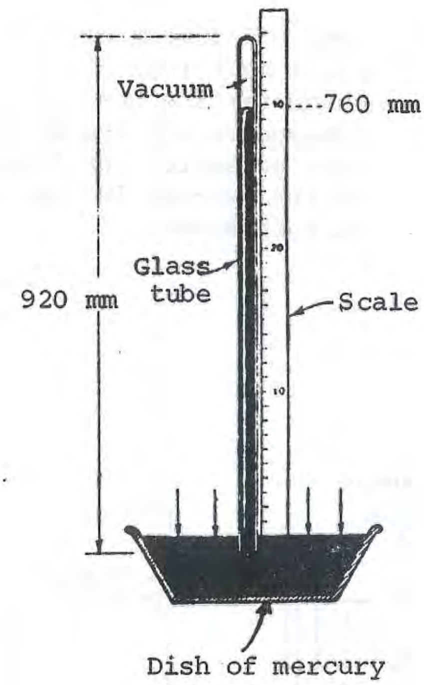

Fig. 2 The pressure exerted by the weight of the atmosphere on the open dish of mercury causes the mercury to stand up into the tube. The magnitude of the pressure determines the height of the mercury column.

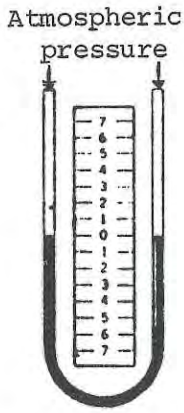

Fig. 3a Simple U-tube manometer. Since both legs of the manometer are open to the atmosphere and are at the same pressure, the level of the mercury is the same in both sides.

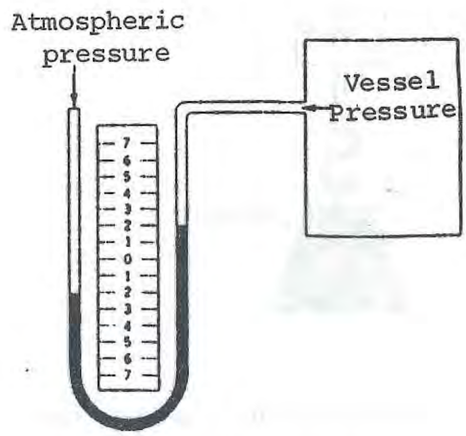

Fig. 3c Manometer indicates that the vessel pressure is less than the atmospheric pressure.

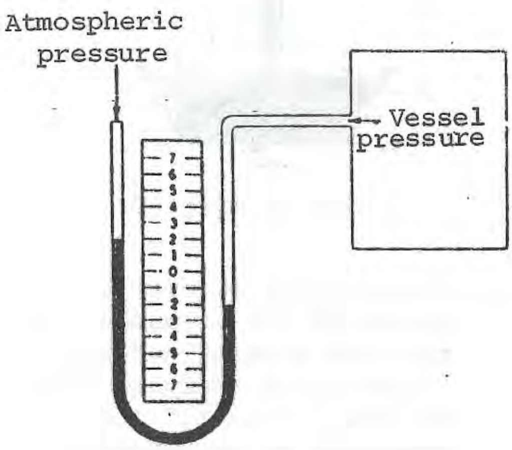

Fig. 3b Simple manometer indicates that the vessel pressure exceeds the atmospheric pressure.

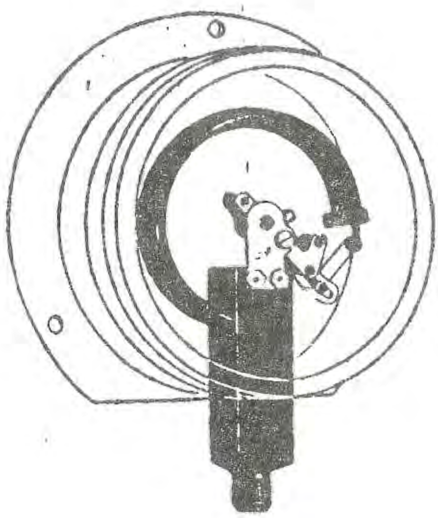

Fig. 4 Bourdon tube gage mechanism.

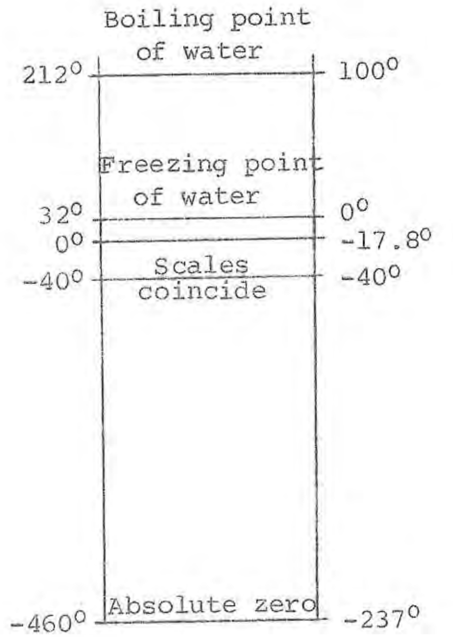

Fig. 5 Comparison of Fahrenheit and Centigrade temperature scales.

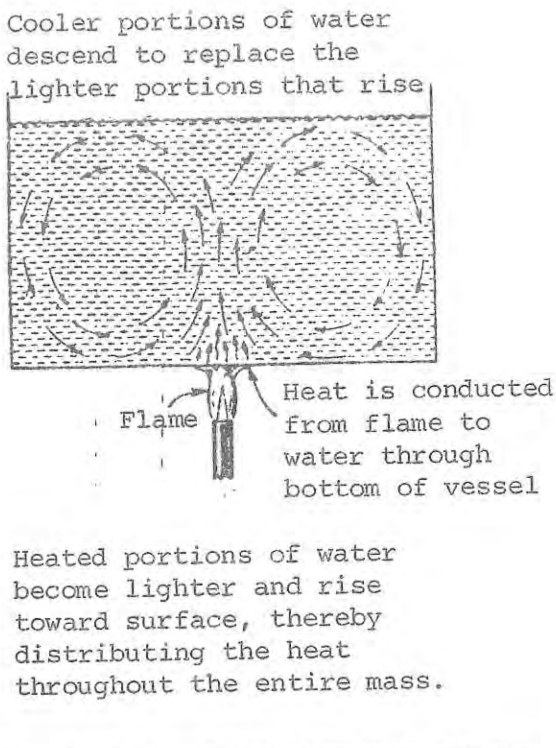

Fig. 6 Convection currents set up in a vessel of water when the vessel is heated at bottom center.

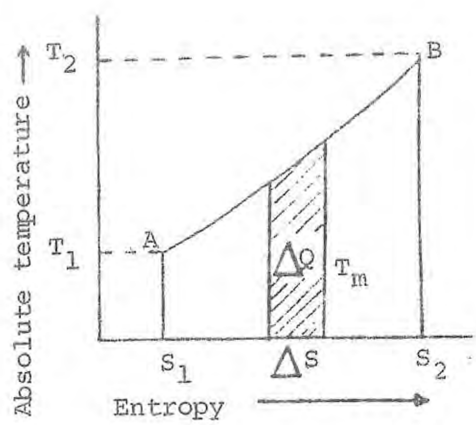

Fig. 7 Relationship between temperature and entropy.