PRINCIPLES OF REFRIGERATION – PART 4

By: Ralph C. Downing
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INTRODUCTION

Refrigeration is the process of taking heat from someplace where it isn't wanted and disposing of it somewhere else. This process can be as simple as placing a dish of strawberries in a snowbank or as complicated as a huge compressor with all of its surrounding auxiliary equipment and controls. In any case, the principles are the same, although the refrigerant used and method of handling it may be different. In the following discussion, a simple mechanical system is assumed with a closed cycle; that is, one in which the refrigerant is recovered and used again.

REFRIGERANT

Theoretically, anything which is capable of accepting heat at one place, carrying it to another place and releasing it there is a refrigerant. Factually, relatively few substances are used as refrigerants for reasons that will appear later. These materials include water and ammonia and several halogenated products, such as R-11, R-12, R-22, R-502, etc.

WHAT IS HEAT OR COLD?

Heat is a form of energy and is related to motion and velocity of atoms and molecules. Addition of heat causes molecules to move faster and causes atoms and other particles making up the molecule to increase their movement and motion. Cold might be thought of as an absence of heat. It is used in a qualitative sense as in saying that some object is colder than another one, but it is not used quantitatively. Rather than evaluate the amount of cold added to an object it is customary to determine how much heat has been removed from it.

There are several different units of heat. Most commonly used however are the British Thermal Unit, or Btu, and the calorie. A Btu is defined as the amount of heat necessary to raise the temperature of one pound of water one degree Fahrenheit at temperatures near its freezing point, see Figure 2F53. A calorie is the amount of heat necessary to raise one gram of water one degree Centigrade. At high temperatures and pressures more than one Btu is required to raise the temperature of one pound of water by 1° F but this does not affect definition or size of the Btu or calorie.

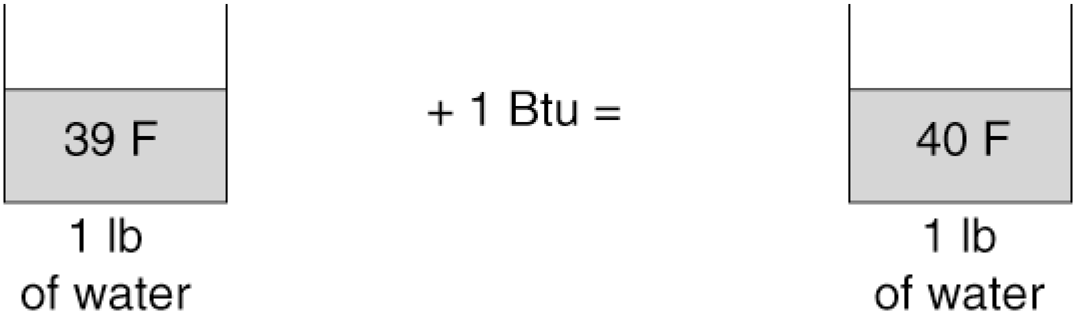

FIGURE 2F53 The British thermal unit or Btu is defined as the amount of heat needed to raise the temperature of one pound of water one degree F.

The absolute amount of heat energy that a molecule contains is difficult to determine, so a reference point is used instead. The reference point usually selected in this country is a value of 0° for the heat content of liquid at -40° F. In Europe, the reference point usually selected is a value of 100 calories per gram for saturated vapor at 0° C . Other reference points could easily be used and sometimes are. Since all refrigeration work involves changes in heat content, the absolute value or reference point is of little importance.

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TEMPERATURE

Temperature is an indication of the level of heat energy but not of total amount of heat or amount of material that might be present. For example, if a temperature of 100°F is indicated in connection with R-12, it immediately projects a situation where gas or liquid contains more heat energy than it would, for instance, if a temperature of 0°F was present. However, merely quoting temperature is no indication of the number of pounds of R-12 that might be present and, therefore, total amount of heat that might be involved in any situation.

Two temperature scales are in general use — the Celsius scale is used in most parts of the world and in scientific work, and the Fahrenheit scale in the U.S., England, Canada, and a few other parts of the former British Empire. The Celsius scale is gradually replacing Fahrenheit throughout the world and in time will probably be used everywhere.

MOVING HEAT

As illustrated in Figure 2F54, heat can flow only from a higher to a lower temperature. So, in producing refrigeration by removing heat from something, it is necessary to have something else at a lower temperature. This "something else", or refrigerant, can be a gas, liquid, solid, or a combination of these states. Cold air is frequently used as a secondary refrigerant in freezing foods, for example. Liquid brines are often used in many kinds of refrigeration applications. Solid carbon dioxide has been used as a refrigerant for many years. The most common method of refrigeration, however, involves evaporation of a liquid to a vapor followed by reclamation of the vapor with a compressor and condenser.

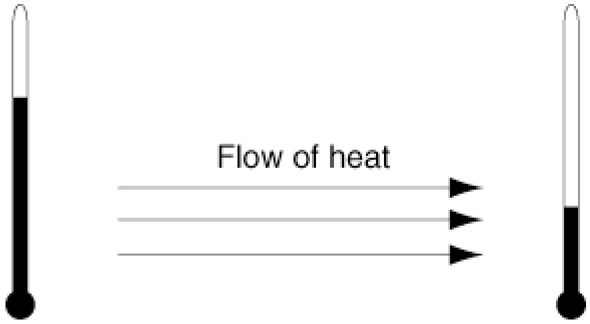

FIGURE 2F54 Heat can flow only from a higher to a lower temperature. The rate of heat transfer depends on the difference in temperature.

CHANGE OF STATE

An evaporating liquid makes a good refrigerant for two reasons:

a. A large amount of heat is involved, and;

b. During evaporation, its temperature remains constant

Heat involved in changing from a liquid to a vapor is called latent heat of vaporization. At first analysis, it may seem odd that a gas contains more heat than a liquid. However, when it is considered that a pound of material is used as a reference point in both cases, and that a pound of gas takes up much more space than a pound of liquid, it may seem more reasonable. Molecules in the gas state have higher velocities and higher amounts of energy bound up in the atoms than molecules in the liquid state.

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For example, the enthalpy or heat content of saturated vapor of R-12 at 40° F is listed in tables of properties as 81.44 Btu/lb. At the same temperature, heat content of liquid R-12 is 17.27 Btu/lb. The difference between these two numbers, or 64.17 Btu/lb, is the amount of heat necessary to cause one pound of liquid to change into one pound of vapor at 40° F. If liquid R-12 were at a temperature of 0° F. liquid heat content would have been 8.52 Btu/lb and it would have required 68.75 Btu/lb to change R-12 liquid to vapor. When this change of state or vaporization, occurs in the evaporator of a refrigeration machine or in some similar piece of apparatus, most of the heat needed to change liquid to vapor is taken from the material to be cooled. This withdrawal of heat causes such material to become colder but its temperature can never go below that of evaporating liquid.

Melting of ice is another change of state that has been used for centuries as a means of refrigeration. As a general rule, the amount of heat involved in changing from a solid to a liquid is quite a bit less than in changing from a liquid to a vapor. With ice and water, however, latent heat of fusion or of melting is quite large—amounting to 144 Btu/lb. The temperature at which the process occurs, 32°F. is very convenient for the storage of foods and other perishables. Melting of ice has been a standard method of refrigeration for so long that it has been perpetuated in modern practice as a "ton" of refrigeration. This is an amount of heat equivalent to that required to melt one ton of ice in 24 hours. A ton of refrigeration equals 2,000 pounds times 144 Btu/lb per 24 hours, 288,000 Btu/24 hours, 12,000 Btu/hr, or 200 Btu/ min. Notice that "pounds" have disappeared from units since the "ton" is a measure of capacity and can be produced by different refrigerants with a correspondingly different number of pounds.

The three states of matter, solid, liquid, and gas, have different appearances and properties, and can easily be distinguished visually. For instance, ice looks different from water and water can easily be distinguished from water vapor. From the standpoint of energy, the principal difference between the three states is the amount of heat contained in each molecule. Heat is required to cause a solid to change to liquid and more heat is necessary to cause the liquid to change into gas. Most of this added heat goes into increased activity in atoms making up a molecule and in the molecule itself. This ability to accept heat and conversely to release it under other circumstances is important in refrigeration.

HEAT CAPACITY

Heat can be added to or removed from solids, liquids, or gases, without causing a change of state. When no change of state is involved, removing or adding heat causes only a change in temperature. A Btu has been defined as amount of heat necessary to cause a change in temperature of 1°F for one pound of water. Temperature change depends on amount of heat and material involved. If 10 Btus of heat are removed from one pound of water, its temperature would drop 10°. If 10 Btus were removed from 1/2 pound of water, its temperature would drop 20°F. This relationship between heat, quantity of material, and temperature is called heat capacity, or specific heat. Units are measured in Btus/ (lb) (°F) in the refrigeration industry in this country, calories/ (gram) (°C) in most other countries. The numerical figure is the same with either set of units.

Heat capacity is the change in heat content or enthalpy for one pound of material for one degree of temperature change. For water, the heat capacity is 1. Heat capacity of nearly all other liquids is less than 1. For example, heat content or enthalpy of liquid R-12 at 100°F is 31.100 Btu/lb. At a temperature of 99°F, heat content is 30.859. The difference between these two numbers is heat capacity and is 0.241 Btu/(lb) (°F). Thus, the amount of heat required to change the temperature of liquid R-12 by one °F is only about 25% of the amount required to change water temperature 1°F. Other liquids have different values. For example, alcohol is 0.55, olive oil is 0.47 Btu/(lb) (°F), etc. Solid materials also have their individual heat capacities, depending not only on material nature, but also on how it is "packed"—that is, finely ground, small pieces, large sections, etc.

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Heat capacity is usually considered to be independent of temperature. This means that a single value of heat capacity is used to calculate heat changes over quite a wide range of temperatures. In most cases, this assumption is perfectly satisfactory and valid. For example, the heat capacity of fresh, lean beef is listed as 0.77 Btu/lb °F at temperatures above freezing. Accordingly, to find the amount of heat that must be removed when cooling beef from, say 100°F to 40°F, this same value for the specific heat of beef could be used throughout the entire temperature range. Heat involved in this example would be simply the temperature difference times heat capacity, or 60 times 0.77 equals 46.2 Btu/lb of beef .

In reality, specific heat does change with temperature and in some cases the difference may be appreciable. Specific heat of R-12 at 100°F was shown to be 0.241. At 0°F the value is 8.521 – 8.305 = 0.216 Btu/(lb) (°F). In this example, the difference is not great, but at higher temperatures heat capacity may change more rapidly.

SENSIBLE HEAT

Heat capacity of a material is a measure of change in sensible heat. For example, the heat capacity of liquid R-12 at 100°F is 0.241 Btu/(lb) (°F). Amount of heat that must be added to raise the temperature to 110°F is (0.241) (10) = 2.41 Btu/lb. The sensible heat of R-12 has been increased by 2.41 Btu/lb. Changes in heat content or enthalpy that do not involve a change of state are usually accompanied by a change in temperature. Since changes in temperature can be detected by one of the senses, the associated heat change is called sensible heat.

Sensible heat as contrasted with latent heat:

Sensible heat as contrasted with latent heat:	
Sensible Heat:	Change in heat content or enthalpy
	Change in temperature
	No change of state
Latent Heat:	Change in heat content or enthalpy
	No change in temperature
	Change of state (solid to liquid or liquid to vapor)

VAPOR PRESSURE

Two kinds of pressure are of interest in refrigeration, vapor pressure and gas pressure.

Vapor pressure is pressure associated with any liquid as long as some vapor is present. With respect to pressure, a liquid is said to have one degree of freedom. This means that when a temperature is specified, vapor pressure will have a definite and unchangeable value. For instance, the vapor pressure of R-12 at 70°F is 84.9 psia. As long as both liquid and vapor are present this pressure will exist regardless of whether the R-12 is in a cylinder, as Figure 2F55 illustrates receiver, storage tank, coil or anywhere else.

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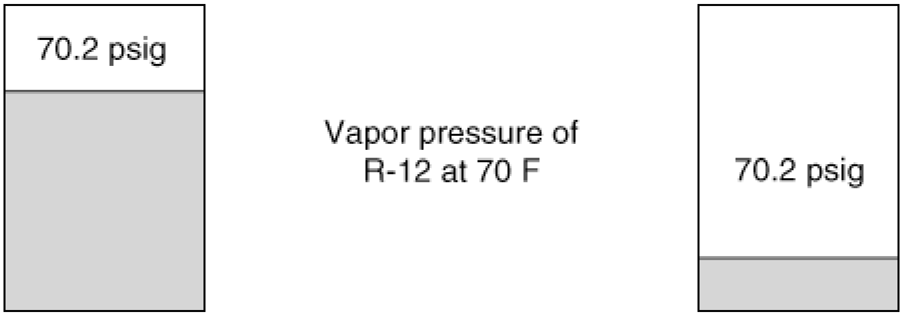

FIGURE 2F55 The vapor pressure at a given temperature is the same regardless of the relative amounts of liquid and vapor.

The relative amounts of liquid and vapor will not make any difference. A cylinder can be nearly full or nearly empty but the pressure will be the same as long as a little bit of liquid is present. Note that if there is no vapor present, that is, if cylinder or container is entirely filled with liquid, hydrostatic pressure develops and will be much higher than vapor pressure. Development of hydrostatic pressure can be very dangerous and great care should be used to be sure that this condition does not exist.

A gas is said to have two degrees of freedom, that is, two properties must be known before pressure is fixed. The two properties that are ordinarily considered with pressure are temperature and gas density or specific volume. As a good approximation, pressure is directly related to amount of gas present. For instance, if a cylinder contains air at a pressure of 100 pounds per square inch absolute, the pressure can be increased to 200 pounds psia by putting twice as much air in it. Assume a container with a volume of one cubic foot is filled with R-12 at 70°F to a pressure of 15 psia. From tables of properties for R-12 specific volume of the gas under these conditions is 3.0657 cubic feet per pound. Specific volume is the reciprocal of density or:

$$\text{Specific volume, cu ft / lb} = \frac{1}{\text{Density, lb / cu ft}}$$

Resulting density would be 1/3.0657, or 0.326 lb/cubic foot. To further illustrate, enough R-12 gas is added to increase container pressure to 30 psia. Referring again to tables. . .at a temperature of 70°F, specific volume is 1.4976 cu ft/lb, or 0.668 lb of R-12 in the same one cubic foot container. In doubling the pressure, weight of gas in the cylinder has been doubled. The fact that the weight of R-12 necessary to double the pressure was a little more than twice as many pounds is an indication that R-12 is not quite a perfect gas.

SATURATION VS. SUPERHEAT

Saturated vapor is vapor that is in equilibrium with or associated with liquid. Tables of refrigerant properties include data for saturated vapor. This data is for 100% vapor in a condition where liquid could also exist. Liquid is changed into vapor by adding the latent heat of vaporization. If more heat is added to saturated vapor it becomes superheated, that is, it has a higher heat content than when it is in a saturated condition. Addition of more heat has caused the gas to move into a region where liquid can no longer exist. Addition of heat causes temperature to rise above that for saturated vapor assuming that pressure remains the same.

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At 20°F vapor pressure of R-12 is 21.0 psig or 35.7 psia. Latent heat or enthalpy is:

Enthalphy of saturated vapor = 79.385 Btu/lb

Enthalpy of saturated liquid = 12.863 Btu/lb

Latent heat = 66.522 Btu/lb

Assume that enough heat is added to the gas to raise its temperature to 50° F. Since the gas is still in a coil or pipe without any obstruction, such as a valve or orifice, its pressure is the same throughout. From tables or a chart, the enthalpy of R-12 gas at 50° F and a pressure of 35.7 psia is 83.911 Btu/lb. Accordingly superheating to 50°F has added 4.526 Btu to the heat content of each pound.

SATURATION VS. SUBCOOLING

In tables of properties for refrigerant liquids, it is assumed that the liquid is saturated, that is, in equilibrium with its vapor. In most cases, this is true, but in some refrigeration applications, the liquid may become subcooled. The temperature of the liquid may be reduced below that associated with pressure in tables of properties. In this case, pressure on the liquid is higher than vapor pressure. Properties of liquids in this region are not usually well known. However, the change in enthalpy or heat content with pressure is very slight over a reasonably small range of temperature so that the enthalpy of a subcooled liquid can be assumed to be the same as that of saturated liquid at subcooled temperature.

BOILING VS. EVAPORATION

The normal boiling point of a liquid is the temperature at which its vapor pressure is equal to one atmosphere. One atmosphere is defined as a pressure of 14.7 pounds per sq in absolute or 29.92 inches of mercury. This is essentially the pressure of atmosphere at sea level. Boiling is the rapid change from liquid to vapor. This change occurs so rapidly that it is visible. Bubbles of vapor formed below the surface of the liquid rise and escape as vapor. If the liquid is in an open dish, boiling takes place when vapor pressure is equal to atmospheric pressure. It is necessary for pure vapor to be present just above the surface of the liquid if true boiling point is to be observed. In an open dish, vapor that is formed during boiling becomes dispersed in the air easily since pressure of escaping vapor and atmospheric pressure is the same. If atmospheric pressure is less than one atmosphere, the boiling point of the liquid in an open dish will be less than atmospheric boiling point. For example, water has a boiling point of 212° F when pressure is 14.7 psia. At an altitude of about 10,000 feet above sea level average atmospheric pressure is only 9.7 psia. Temperature at which water has a vapor pressure of 9.7 psia is about 192° F and this is its boiling point under these conditions.

In a closed system such as a cylinder or a refrigeration system, atmospheric boiling point has no significance. It is just another point on a pressure temperature curve. For example, vapor pressure of R-12 at -22° F is about 1 atmosphere. This temperature is considered the normal or atmospheric boiling point. However, R-12 liquid will boil at any other temperature if proper pressure is maintained. If vapor pressure of R-12 is maintained at about 10 psia its boiling point is approximately -37°F. If pressure was maintained at 50 psia, boiling point would be about 38°F. At each temperature, saturated liquid and saturated vapor have definite properties of pressure and density and heat content or enthalpy. A certain definite quantity of heat is required to cause the change from liquid to vapor. It is called the latent heat of vaporization for that particular temperature.

Boiling and evaporation describe the same process. They both refer to change from liquid to vapor. About the only difference is rate at which the change occurs. In boiling, the rate is rapid and formation of bubbles and agitation of liquid can be observed. In evaporation, the rate may be slower and there may be no visible liquid agitation. In addition, boiling occurs at a constant temperature as long as pressure remains constant. On the other hand, evaporation can take place at almost any temperature below the boiling point.

Water in an open pan will evaporate at ordinary temperatures, absorbing heat from the air as it does so. If pan is warmed with a burner so that heat is added at a faster rate than from air alone, evaporation is faster. At the same time the temperature rises. The limiting point is boiling point when vapor pressure equals atmospheric pressure. The temperature no longer rises no matter how fast heat is added as long as some liquid remains.

The same pressure-temperature relationships apply to both boiling and evaporating. In some areas, water is cooled by putting it in a canvas bag or in a porous earthen jar. Water seeps through the bag or sides of jar and evaporates on the outside. The temperature of the water inside depends on pressure of water vapor in equilibrium with water on outside surface of bag or jar. If air movement around the bag is slow so that considerable water vapor builds up, the temperature will be only moderately reduced. If air is blown past the bag so that water vapor is carried away and vapor pressure of the water, therefore, lowered, the temperature of water inside will be lowered.

A similar effect is found with refrigerants. For instance, if R-12 liquid is put in a glass jar with a narrow opening and a thermometer is inserted in the liquid, the ordinary atmospheric boiling point will be observed. Pure R-12 vapor will be above the surface of the liquid at atmospheric pressure. However, if liquid R-12 is placed in a porous paper cup so that vapors can seep through the sides, vapor on the outside will be mixed with air, pressure of vapor in equilibrium with liquid inside will be less than one atmosphere and temperature of the liquid will be lower than its normal boiling point.

EVAPORATING TEMPERATURE

In a mechanical refrigeration system, the temperature at which the refrigerant evaporates is determined by pressure maintained by compressor. The compressor draws vapor out of evaporator. If vapor is removed faster than liquid entering evaporator can evaporate or change from liquid to vapor, the pressure is lowered. When pressure becomes less, boiling point or evaporating temperature is also lowered in accordance with pressure-temperature relationship for the particular refrigerant in question. For example, assume that in an R-12 system, the compressor is controlled to start operating when pressure reaches 14 psig (28.7 psia), and stop operating at 12.9 psig (27.6 psia). Corresponding evaporating temperatures for liquid refrigerant would be 9°F and 7°F for an average evaporating temperature of about 8°F. Whether the compressor is controlled directly by changes in pressure or, as is more common, by changes in temperature, the result is maintenance of a reasonably constant pressure in evaporator.

Pressure maintained in evaporator directly governs the temperature of evaporating refrigerant but does not indicate capacity for removing heat. Capacity depends on amount of refrigerant evaporated which, in turn, depends on compressor size and ability to remove refrigerant vapors from the evaporating area.

LATENT HEAT

The only source of cooling in the refrigeration cycle comes from absorption of heat when liquid evaporates. Heat necessary to cause liquid to change into vapor comes from the load or from material that is being cooled. As an example, the following latent heat can be obtained from a table of properties for R-12, assuming that evaporation takes place at 0°F in this instance.

Enthalpy of saturated vapor at 0°F = 77.271 Btu/lb

Enthalpy of saturated liquid at 0°F = 8.521 Btu/lb

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Latent Heat of Vaporization at 0°F = 68.750 Btu/lb

NET REFRIGERATION

Not all of the latent heat of vaporization is available for cooling work. Some of it must be used to cool liquid refrigerant itself from condensing temperature down to that at which vaporization takes place. The amount of heat that must be removed from the liquid can also be calculated from tables of properties. The following example assumes that liquid R-12 enters evaporator at 100°F:

Enthalpy of liquid at 100°F = 31.100 Btu/lb

Enthalpy of liquid at 0°F = 8.521 Btu/lb

Heat to be removed from liquid = 22.579 Btu/lb

As Figure 2F58 illustrates, the useful amount of cooling work or net refrigerating effect, is the difference between latent heat of vaporization and amount of heat that has to be removed from the liquid to cool it from condensing temperature to evaporating temperature.

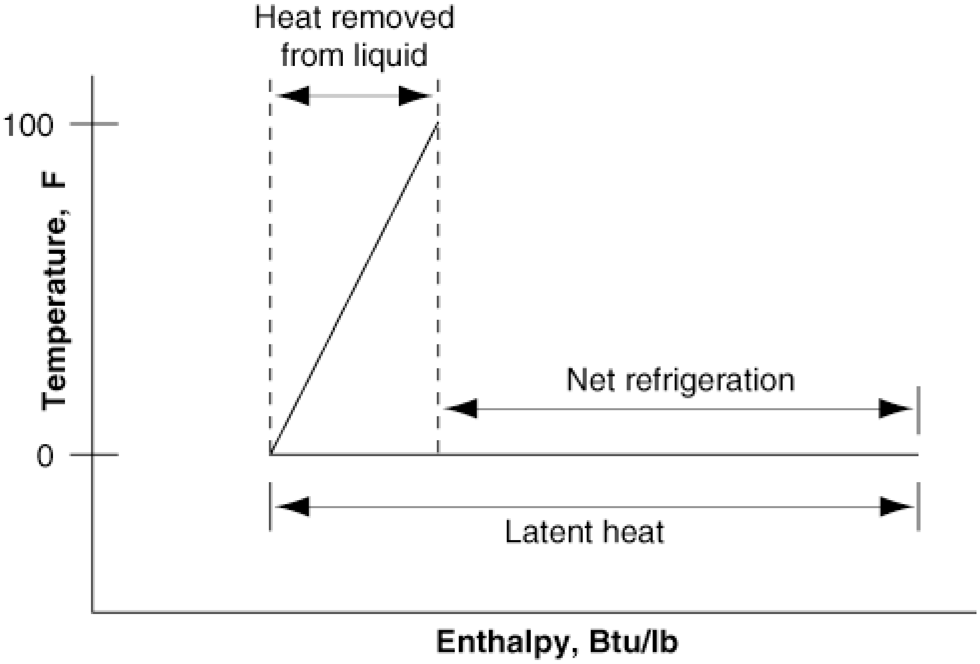

FIGURE 2F58 The amount of cooling that a refrigerant can do is equal to the latent heat of vaporization minus the heat taken up in cooling the liquid.

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Latent heat of vaporization at 0° F = 68.750 Btu/lb

Heat removed from liquid = 22.579 Btu/lb

Net refrigerating effect = 46.171 Btu/lb

Assuming that vapor is saturated when it leaves the evaporator, every pound of refrigerant in a system is able to remove 46 Btu from the load or contribute 46 Btu of cooling to the system's capacity.

SUPERHEAT IN THE EVAPORATOR

As mentioned above, the only source of cooling in the refrigeration cycle is heat required to change refrigerant from the liquid to vapor state. However, a little bit more cooling can be squeezed out of the system by taking advantage of cold vapor before it leaves evaporator.

In a refrigeration system, pressure throughout the low side is essentially the same. In practice, there is a slight drop in pressure in going from coil or evaporator to compressor. The size of this drop in pressure can be important as far as system capacity is concerned. However, in order to illustrate the ability of refrigerant to carry heat, this pressure drop can be ignored. Superheat means that the gas contains more heat than it does when in a saturated condition. Enthalpy or heat content of R-12 saturated vapor at 0°F has been noted previously as being 77.271 Btu/lb. At this temperature, vapor pressure of R-12 is 9.15 psig and gas will be at this pressure throughout suction line.

Assume that gas picks up enough additional heat while in evaporator to cause a temperature rise of 20° F. Heat content of the gas at this point can be determined, in tables of properties or from pressure-enthalpy charts, to contain 80.161 Btu/lb at a temperature of 20° F and a pressure of 9.15 psig. The difference between this value and the heat content of saturated vapor is 2.89 Btu/lb. Since the gas is still in evaporator, this additional amount of heat is extracted from the load so total net refrigerating effect when gas is superheated by 20° F is 46.17 plus 2.89 or 49.06 Btu/lb. It is evident that superheating gas while it is in evaporator is helpful and contributes to an increase in system capacity.

Another effect of superheating refrigerant gas is to cause an increase in specific volume which tends to cause a reduction in compressor output. This effect may also slightly reduce net gain in capacity due to increased heat content of superheated vapor.

MORE SUPERHEAT

After leaving evaporator area, refrigerant gas usually is still cooler than ambient air or whatever other material the suction line is exposed to. If there is a difference of temperatures, heat will flow from higher temperature to lower temperature and refrigerant gas will become more superheated as it flows through suction line. See Figure 2F59. The only advantage gained from adding heat to refrigerant gas is assurance that liquid refrigerant does not reach compressor cylinders and cause damage to valves. This isn't very likely with hermetic compressors, since refrigerant vapor enters the motor housing and does not go directly into compressor cylinders. Adding more superheat to vapor than is necessary is harmful for two reasons:

a. Specific volume of the gas is increased and this has a direct effect on reducing compressor capacity.

b. Temperature of the gas is increased. An increase in the temperature of suction gas usually means that temperature of gas leaving compressor will also be higher.

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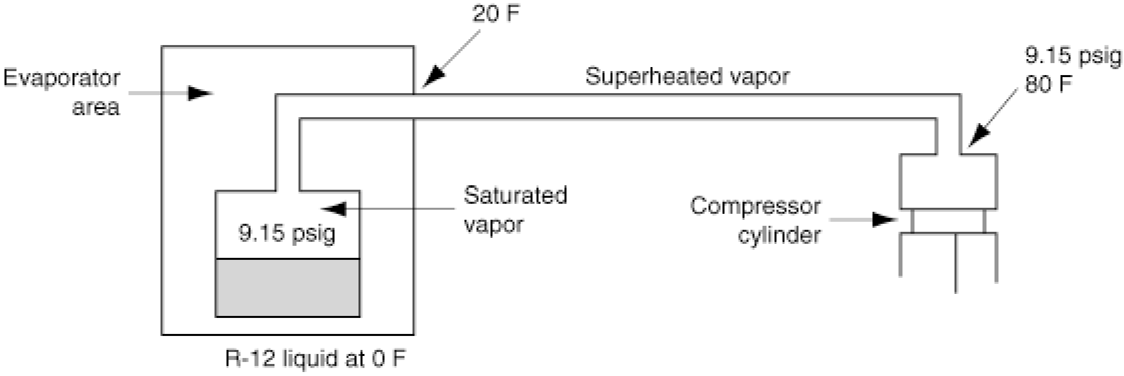

FIGURE 2F59 Refrigerant vapor is saturated in the evaporator but becomes more and more superheated as it flows toward the compressor. The pressure stays essentially the same (except for a slight drop due to the resistance developed by a gas flowing in a pipe.)

For these two reasons, adding superheat to refrigerant vapor is undesirable unless:

a. Heat added to gas is taken from someplace where resulting cooling is of value, or

b. Some superheat is necessary to prevent liquid from entering compressor cylinders.

The change in specific volume of R-12 at various different superheat temperatures is illustrated below. It is assumed that vapor is saturated at 0°F and that pressure stays constant at 9.15 psig, its normal for 0°F.

Temperature of Gas(°F)	**Specific Volume (cu ft./lb)**
0	1.61
20	1.69
40	1.78
60	1.86
80	1.94
100	2.02

In many cases, it is desirable to insulate the suction line to keep refrigerant as cool as possible on its way back to compressor.

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REFRIGERANT-COOLED MOTOR

Most smaller compressors are currently being built with the motor inside compressor shell to eliminate the need for a gas-tight seal around shaft connecting motor with compressor. Refrigerant gas is circulated around the motor in order to help keep it cool. High temperatures are often mentioned as one of the worst enemies of operating refrigeration equipment as far as long life and smooth operation are concerned. It seems certain that cool running motors will give better performance and longer operating life than those operating in higher temperature ranges. Three factors that influence motor cooling are:

a. Temperature of incoming refrigerant vapor,

b. Heat capacity of the vapor,

c. Vapor flow rate.

The lower the temperature of the refrigerant vapor as it enters compressor housing, the easier it will be for heat to flow from motor to gas. Thus, it is important that refrigerant vapor temperature in suction line be kept as low as is reasonably possible. As outlined above, heat capacity shows the relationship between ability of gas to absorb heat on a pound basis and temperature rise associated with increase in heat content. A high rate of heat capacity indicates that the gas can absorb relatively large amounts of heat with a minimum increase in temperature. For example, if heat capacity of the gas was 0.5 Btu/ (lb)(°F) and 10 Btu per second must be removed from the motor in order to keep it reasonably cool, the temperature of gas flowing at a rate of 1 lb/sec will be increased by 20°, as a result of absorbed motor heat. If its heat capacity were 0.2 Btu/ (lb)(°F) the temperature increase would be 50° F under equal circumstances.

THE COMPRESSOR

The compressor is the mechanical heart of a refrigeration system. It causes refrigerant to flow and is where energy is applied to perform the work of removing heat in the evaporator. The compressor serves two functions. First, it regulates pressure in the evaporator by withdrawing refrigerant vapors when pressure (or temperature) is higher than desired. By regulating pressure, evaporating temperature is fixed. Second, it compresses the gas and in so doing, adds energy or heat content. Electrical energy in the motor is exchanged for mechanical energy in the system, which, in turn, is changed into heat energy in the gas.

Compressing gas increases its temperature and decreases its specific volume (increases its density). It is essential that gas temperature be raised to a level higher than that of condensing fluid, whether it is air, water or some other liquid. Heat can flow from refrigerant to condensing medium only if there is a reasonable difference in temperature. The compressor functions to provide that higher temperature. At the same time, an increase in gas density reduces volumes that need to be handled in the condenser.

Compression of gas is nearly adiabatic or isentropic. This means that essentially all mechanical energy applied is converted into energy that is retained by the gas. In other words, mechanical energy is changed into heat energy which results partly in an increase in temperature and partly in a change in molecular velocities. Both are reflected by an increase in pressure and a decrease in volume. During isentropic compression, all of this mechanical energy is converted to heat which changes the properties of gas and none of it is lost. At the same time, no heat is added from other sources. In an actual compressor, the gas is not insulated from its surroundings and some heat of compression is lost by conduction through the metal walls of the cylinder, while at the same time heat is added from the friction of piston rings and other sources. However, the gains and losses are usually almost in balance so that the net result is close to isentropic compression.

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In any given refrigeration system, the compressor operates at a constant speed and, of course, the cylinder bore and stroke are constant. The amount of gas a compressor can handle and, therefore, the amount of cooling capacity a system, as a whole, can produce, depends on the properties of the gas as it enters and leaves the compressor. Using tables of thermodynamic properties, much can be learned about properties of refrigerant gas at these points in the cycle.

As an example, consider R-12 with an evaporating temperature of 0°F and a condensing temperature of 100°F. Assume that the temperature of the refrigerant vapor entering the compressor cylinder is 80°F, as it might well be after passing through the suction line and around the motor. Ignoring any pressure drop in the line or in compressor shell, pressure at the compressor inlet will be the same as the pressure of the evaporating liquid in the evaporator. From the tables of properties of R-12, vapor entering the compressor cylinder will have the following properties.

Pressure	=	9.15 psig (23.85 psia)
Temp.	=	80° F
Volume	=	1.943 cu ft/lb
Heat Content	=	89.000 Btu/lb
Entrophy	=	0.1924 Btu/(lb)(°F)

Isentropic compression means compression at constant entropy. In this example, the entropy of gas leaving compressor will be identical to that of gas entering compressor. Pressure of gas as it leaves the compressor is determined by the vapor pressure of liquid refrigerant in condenser. Assuming that there is an open pipe between condenser and outlet valve on compressor cylinder and ignoring the small pressure drop that will be present, pressure in the discharge line will be constant all the way from condenser to compressor. It is assumed that temperature of liquid refrigerant in condenser is 100°F. Accordingly, pressure throughout the discharge side of compressor will be 117.2 psig. Since the entropy of the discharge gas and its pressure are known, values of other properties of the gas can be determined from appropriate tables for R-12. Properties of R-12 vapor as it leaves the compressor cylinder are as follows:

Pressure	=	117.2 psig (131.9 psia)
Temp.	=	200.4° F
Heat Content	=	104.804 Btu/lb
Volume	=	0.4022 cu ft/lb

Accordingly, in passing through the compressor, there has been an increase in temperature from 80° to 200 °F, an increase in heat content or enthalpy of 15.80 Btu/lb, and the new specific volume is about 20% of the volume of entering gas.

CAPACITY

Previously all references to changes in heat content or enthalpy have been on the basis of one pound of refrigerant. In order to relate to capacity, the element of time must be introduced. The capacity of a system depends on how often a pound of refrigerant evaporates and this depends on compressor size and on properties of the refrigerant at refrigeration cycle temperatures.

In an example with R-12, assume the compressor is of the right size to deliver one ton of refrigeration when refrigerant evaporates at 0°F and is condensed at 100°F. In an earlier ion it was seen that each pound of R-12 could absorb 49.06 Btu. Accordingly this amount of heat is available for cooling work.

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Since one ton of refrigeration is equal to 200 Btu/min, one can find out how many pounds of R-12 must pass through the evaporator per minute in order to produce this amount of refrigeration by using this formula:

$$\text{Refrigerant circulated} = \frac{200\,\text{Btu}/\text{min}}{49.06\,\text{Btu}/\text{lb}} = 4.077\,\text{lb}/\text{min}$$

HEAT OF COMPRESSION

Heat added to refrigerant gas by compressing it has been found to be 15,804 Btu/lb. Knowing the rate at which the refrigerant circulates, calculation of amount of heat added on a time basis is as follows:

15.804 Btu/lb ×4.077 lb/min = 64.433 Btu/min

POWER OF COMPRESSION

Energy can be expressed in different ways but the unit of primary interest in refrigeration is horsepower. By definition, one horsepower = 42.42 Btu/ min., so power required to compress the gas can be calculated.

Horsepower of compression =

$$\frac{64.433\ \text{Btu}/\text{min}}{42.42\ \text{Btu}/\text{min}} = 1.519\,\text{hp}/\text{ton of refrigeration}$$

Theoretically about 1.5 hp is required to produce one ton of refrigeration with R-12 at an evaporating temperature of 0°F and a condensing temperature of 100°F. Actual horsepower required will be greater depending on volumetric and mechanical efficiency of compressor and also on whether or not entropy of the gas remains constant during compression.

COMPRESSOR DISPLACEMENT

An idea of the size of compressor needed for a refrigeration application can be obtained from properties of the refrigerant. In the R-12 example at 0°F evaporating and 100°F condensing temperatures, net refrigerating effect is 49.06 Btu/lb. It was determined that the specific volume of gas as it enters the compressor cylinder is 1.94 cu ft/lb. By proper division, relationship between refrigerating ability and volume of gas to be handled by compressor can be obtained.

$$\frac{49.06\ \text{Btu}/\text{lb}}{1.94\ \text{cu ft}/\text{lb}} = 25.3\ \text{Btu}/\text{cu.ft.}$$

The above relationship does not indicate time required to remove the heat. To produce cooling at the rate of 200 Btu/min (1 ton) the corresponding compressor displacement can be calculated as follows:

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Compressor Displacement =

$$\frac{200\ \text{Btu}/\text{min}}{25.2\ \text{Btu}/\text{cu ft}} = 7.91\ \text{cu ft}/\text{min}$$

COMPRESSION RATIO

Inlet pressure to compressor is established by the temperature of boiling refrigerant in evaporator. Outlet or discharge pressure from compressor is established by the temperature of condensing refrigerant in condenser. The ratio of these two pressures is called compression ratio and indicates levels of pressure between which the compressor must be able to operate. In determining compression ratio absolute pressures must always be used. For example, the vapor pressure of R-12 liquid at 100°F is 131.86 psia and vapor pressure at 0°F is 23.849 psia. Compression ratio, then, is:

$$\frac{131.86\ \text{psia}}{23.849\ \text{psia}} = 5.5$$

A low compression ratio is desirable in the first place, because a low ratio means low power consumption in compressing the gas. This is true regardless of the level of inlet pressure. For example, it would take about the same increase in Btu/lb to compress from 100 psia to 500 psia as it would to compress from 10 psia to 50 psia. This change in heat content per pound of refrigerant, however, is not the whole story since power required is a function of the flow of refrigerant, that is, number of pounds per minute of refrigerant passing through compressor. Flow rate would be different at different levels of inlet pressure. A low compression ratio is also desirable because of its effect on volumetric efficiency of compressor as explained in the next section.

VOLUMETRIC EFFICIENCY

The piston in a compressor cannot go all the way to the top of the cylinder on its compression stroke since a little room must be left for the action of the valve. Any contact between the piston and the top of the cylinder would be very undesirable. Space at top of cylinder when piston is as high as it can go is called clearance volume as illustrated in Figure 2F62. Refrigerant gas in this volume is not expelled from the cylinder and remains behind when the piston goes through its downward stroke. Power required to compress this amount of gas does not do any useful work and represents a loss factor in compressor operation. Wasted power may vary from 10 to 50% of total power applied to compressor depending on its mechanical construction, nature of refrigerant and operating conditions of system. Ratio of usable power to total power is called volumetric efficiency and is usually determined experimentally for each compressor design.

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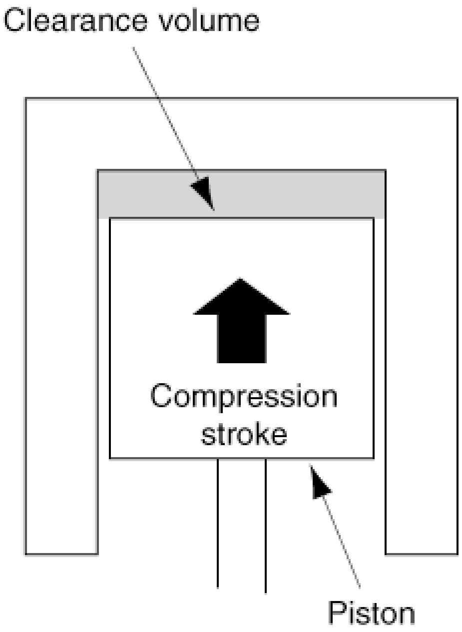

FIGURE 2F62 On the compression stroke the piston does not quite fill the top of the cylinder. The power used to compress the gas remaining at the top of the cylinder is wasted.

Volumetric efficiency is directly affected by compression ratio. At high compression ratios, pressure of refrigerant gas in the clearance volume is high with respect to inlet or suction pressure. As a result, a higher percentage of total power is wasted in compressing this portion of refrigerant gas and volumetric efficiency is lower.

EFFECT OF SUPERHEAT

It was mentioned in the previous section that superheat in return suction gas might have some disadvantages. In order to illustrate this possibility, let us assume that R-12 while still evaporating at 0°F, has absorbed enough heat to raise the temperature to 120°F as it enters compressor cylinder. Refrigerant gas at this point then will have the following properties.

Temperature = 120°F

Spec. Vol. = 2.103 cu ft/lb

Heat Cont. = 95.062 Btu/lb

Entropy = 0.2032 Btu/(lb)(° F)

Assuming that isentropic compression occurs and that entropy stays the same, properties of the gas as it leaves compressor, at a condensing temperature of 100° F, will be:

Temperature = 243° F

Heat Content = 112.181 Btu/lb

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By comparing these properties with those shown above for a superheat temperature of 80° F, for gas entering the compressor cylinder, some differences can be found. Volume of each pound of refrigerant at the higher temperature is 2.10 cu ft instead of the 1.94 cubic feet at the lower temperature. Since compressor speed cannot be changed (at least in a hermetic compressor), its displacement in terms of cubic feet per minute cannot be changed. Accordingly the compressor will have to run longer to handle each pound of refrigerant. This is reflected in a lesser amount of refrigerant circulated in pounds per minute. On the other hand, as long as condensing temperature, evaporating temperature, and amount of superheat added to refrigerant inside of evaporator all remain the same, the net refrigerating effect of each pound of refrigerant also is unchanged. Since fewer pounds of refrigerant are now able to be handled by the compressor, refrigerating capacity of the system decreases. In the example used, capacity changes from 200 Btu/ min with the 80°F superheated temperature to 185 Btu/min if temperature rises to 120°F, or a decrease of 7.5%. Some of these comparisons are shown in the following table.

Effect Of Increasing Superheat Temperature From 80°F To 120°F With R-12

	Case 1	**Case 2**
Evaporating Temperature, °F	0	0
Condensing Temperature, °F	100	100
Gas Temperature as it enters compressor, °F	80	120
Discharge gas temperature, °F	200	243
Heat of Compression, Btu/lb	15.80	17.12
Specific Volume of gas at cylinder inlet, cu ft/lb	1.94	2.10
Net refrigerating effect, Btu/lb	49.06	49.06
Compressor displacement, cu ft/min	7.91	7.91
Refrigerant circulated, lb/min	4.08	3.77
Refrigerating capacity, Btu/min	200	185
Heat of compression, Btu/min.	64.5	64.5

In this example, heat of compression per pound of refrigerant was increased by increasing the superheat temperature of entering gas, but rate of heat added during compression or Btu/min, was about the same since fewer pounds of refrigerant are being circulated. However, power per unit of refrigeration is greater since total capacity has been reduced.

As mentioned above, direct calculations of compressor horsepower and other refrigeration properties are subject to considerable correction because of volumetric and mechanical efficiencies. However, calculations of changes resulting from different operating temperatures and pressures are considerably more realistic since operating efficiencies peculiar to a given compressor and motor remain relatively unchanged by moderate changes in operating conditions.

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EFFECT OF CONDENSING TEMPERATURE

As a further illustration of the effect of changing conditions on refrigeration system capacity, assume in the R-12 example that condensing temperature is 120° F instead of 100° F and evaporating temperature remains at 0°F. Net refrigerating effect will then be:

Heat Content of Gas with 20° F of Superheat = 80.161 Btu/lb

Heat Content of Liquid at 120°F = 36.013

Net Refrigerating Effect = 44.148 Btu/lb

It will be noted that net refrigerating effect is lower when condensing temperature is 120°F than when it is 100°F. Assume use of the same compressor with the same fixed displacement as in the example above and that temperature of the gas entering compressor cylinder is 80°F and has a specific volume of 1.94 cu ft/lb. The weight of refrigerant that the compressor is able to circulate will remain the same.

$$\frac{7.91 \text{ cu ft}/\text{min}}{1.94 \text{ cu ft}/\text{lb}} = 4.08 \text{ lb}/\text{min}$$

Since each pound of refrigerant is able to do less cooling, the total capacity of the system will be less.

$$44.15 \text{ Btu}/\text{lb} \times 4.08 \text{ lb}/\text{min} = 180 \text{ Btu}/\text{min}$$

With the condenser at 100°F, refrigerating capacity was 200 Btu/min. So, if condensing temperature is raised to 120°, there will be about a 10% reduction in capacity, if all other conditions remain the same.

CHANGES IN OPERATING CONDITIONS

By similar calculations of refrigerant and refrigerating properties it will be determined that for a given compressor, refrigeration capacity is increased by the following changes in operating conditions. In this summary, it is assumed that the condition listed is changed without affecting other conditions or properties of refrigerant. In practice, this is not always possible and, in some cases, a change in one condition is accompanied by an opposing change in another condition and both changes must be taken into consideration in determining change in capacity.

a. Lower condensing temperature (or lowering the liquid temperature by any means, such as a liquid vapor heat exchanger)

b. Higher evaporating temperature

c. Higher superheat in the evaporator

d. Lower temperature of gas entering the compressor cylinder

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THE CONDENSER

The last step in the refrigeration cycle is to dispose of heat that the refrigerant gas has picked up in the evaporator and in going through the compressor. The function of the condenser is to remove heat from refrigerant vapor and transfer it to something else, usually either air or water.

When refrigerant vapor leaves compressor, it is in a superheated state, that is, it contains more heat than if it were saturated vapor at the same pressure. Pressure at which the compressor discharges vapor from the cylinder is regulated by the temperature of the liquid in condenser. Whenever liquid is present in a piping system, unrestricted by orifices or small passageways, pressure throughout the system will be vapor pressure of liquid at its temperature except for very small differences due to pressure drop as the vapor passes through piping. Discharge pressure can be found by referring to tables of properties for saturated liquid at the condensing temperature. Using R-12 as an example and assuming that the condensing temperature is 100° F, discharge pressure will be 117.2 psig.

Continuing with the R-12 example, it was previously determined that when evaporating temperature is 0°F and condensing temperature 100°F, with suction gas temperature as it enters compressor cylinder at 80°F, temperature of the gas leaving compressor will be about 200°F and will have a heat content of 104.80 Btu/lb. Referring to tables of properties, saturated vapor at 100°F has a heat content of 87.03 Btu/lb. The condenser, then, must first cool the refrigerant gas from 200°F to 100°F and in so doing remove 17.77 Btu/lb of heat.

As more heat is removed from saturated vapor of refrigerant in condenser, it changes to a liquid without any further change in temperature. Latent heat of vaporizations or, in this case, condensation, since the same amount of heat is involved in going either from a liquid to a vapor or from a vapor to a liquid, at 100° F is 55.93 Btu/lb. When this amount of heat has been removed a pound of refrigerant vapor has been completely changed into liquid.

The temperature of the material used in cooling the condenser, must be at a lower temperature than refrigerant being cooled and condensed. Or, explained in another way, if a cooling medium is available in a condenser, at a given temperature and flow rate, condensing temperature of the refrigerant will automatically be established at some temperature higher than that of the cooling material. When air is used as the cooling fluid, refrigerant condensed temperature may usually be the order of 20 to 30°F higher than air temperature. With water cooled condensers, condensing temperature would more likely be 8 to 10°F higher than water temperature.

Condensed liquid refrigerant leaves the condenser and is carried back toward evaporator ready to begin another cycle.