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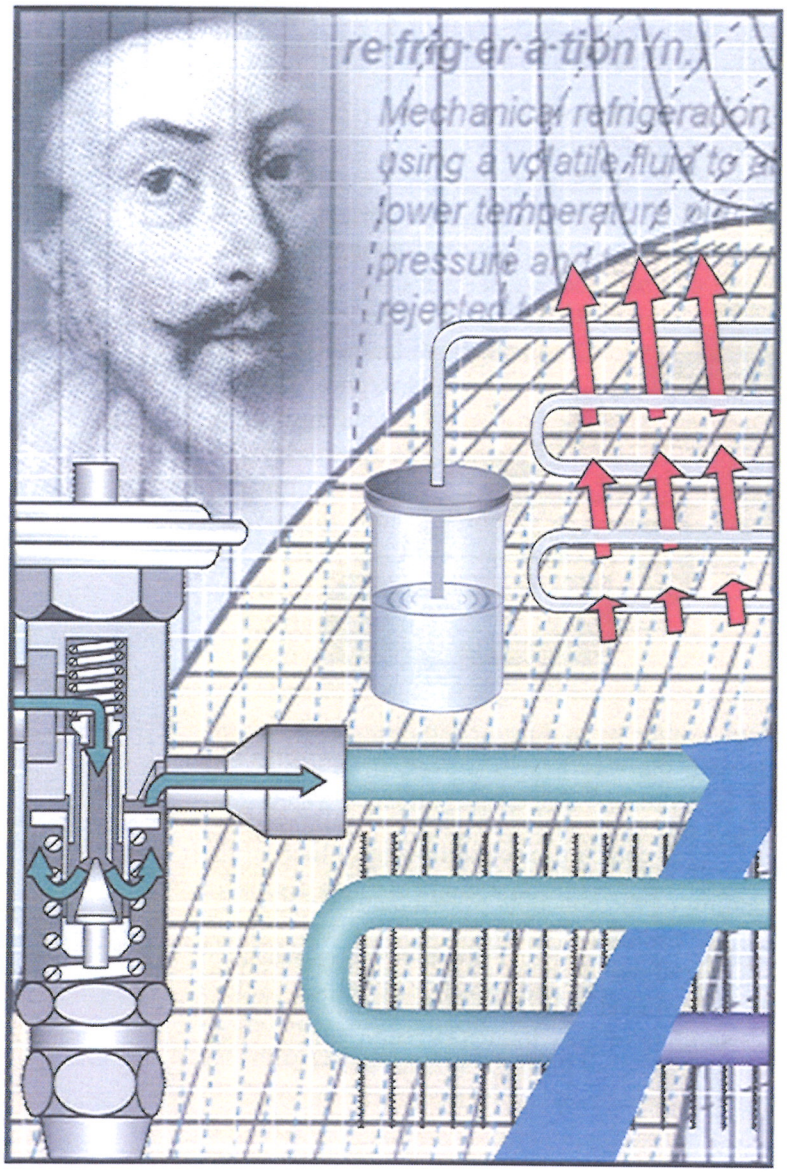


REFRIGERATION CYCLE

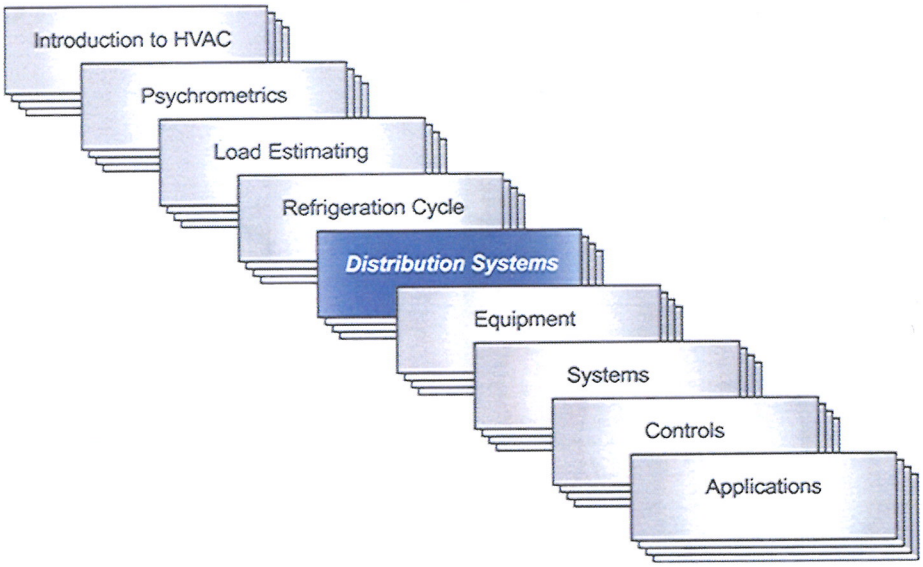
Principles of Mechanical Refrigeration

Level 1: Introduction

Technical Development Program

Technical Development Programs (TDP) are modules of technical training on HVAC theory, system design, equipment selection and application topics. They are targeted at engineers and designers who wish to develop their knowledge in this field to effectively design, specify, sell or apply HVAC equipment in commercial applications.

Although TDP topics have been developed as stand-alone modules, there are logical groupings of topics. The modules within each group begin at an introductory level and progress to advanced levels. The breadth of this offering allows for customization into a complete HVAC curriculum – from a complete HVAC design course at an introductory-level or to an advanced-level design course. Advanced-level modules assume prerequisite knowledge and do not review basic concepts.



Air conditioning is all about moving heat energy, either by adding or removing it from one place and moving it to another. This module deals with the way heat is moved from a place of lower temperature to a place of higher temperature in a process called mechanical refrigeration. This process is used in preserving the food we eat and for comfort air conditioning. Much of the equipment discussed in other TDP modules dealing with equipment uses the principles discussed in this TDP. A designer needs a thorough understanding of the concepts of mechanical refrigeration to create the best performing and cost effective projects. The Principles of Mechanical Refrigeration is divided into two modules, Level 1: Introduction, and Level 2: Analysis. Before proceeding to the equipment TDPs, the information in the Level 1: Introduction, should be understood. Level 2: Analysis, will provide a better understanding of how to evaluate unit performance and select refrigeration components.

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Introduction

The process of mechanical refrigeration has changed our daily lives. Thanks to mechanical refrigeration the variety, quality, and safety of the foods we eat has improved; and the buildings where we live and work are more comfortable and productive. The mechanical refrigeration cycle is the process of how heat is moved. This module will explain the process.

This book is the first of two modules on the topic of mechanical refrigeration. The first step is to understand the terminology used in mechanical refrigeration, and understand how four basic principles are applied to cause the movement of heat. These principles can then be applied to the refrigeration process that uses four basic components to accomplish moving heat – the evaporator, the compressor, the condenser, and the metering device. The process also requires a fluid, called a refrigerant, to move heat through the system. This module describes what constitutes a good refrigerant and how to determine its properties anywhere in the refrigeration cycle.

The second module of Principles of Mechanical Refrigeration deals with analyzing the refrigeration cycle. The pressure-enthalpy diagram (p-h) is a useful tool used by system designers. The construction of this diagram will be explained and the function of each refrigeration system component is explained using the p-h diagram. Finally, this second module will use the p-h diagram to evaluate several system variations and evaluate their performance.

It is important for a designer to understand the operation of a refrigeration system. While the designer may not actually design the refrigeration system, as is typical with packaged units, proper selection and application depends on a working knowledge of mechanical refrigeration. This module will develop an understanding of the mechanical refrigeration system and demonstrate how to analyze system performance.

Definition

Heat is a form of energy, and energy is simply the potential to do work. The first law of thermodynamics states that energy can neither be created nor destroyed, we only transferred heat energy from one place to another. The total heat energy into a system must therefore always equal the heat energy out. The second law of thermodynamics says that energy can only flow from a level of higher potential to a level of lower potential. Therefore, heat transfer is the movement of heat energy from a higher temperature substance to a lower temperature substance.

Mechanical Refrigeration

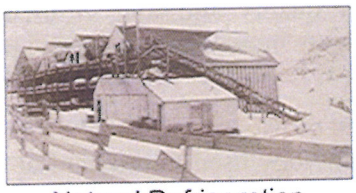
is the process of using a volatile fluid to absorb heat from a lower temperature place, raising the fluid's pressure and temperature so it can be rejected to a higher temperature place.

The refrigeration process becomes the process of providing a substance at a lower temperature to which heat can flow from a higher temperature substance.

History of Refrigeration

The earliest use of a cold substance for taking away heat was using ice or snow. The Chinese were among the first to learn that ice made drinks cooler and tastier. Early Greek and Roman slaves were used to carry snow from mountaintops to be stored in pits for later use in creating frozen delicacies. In France during the 16th century, ice and snow were used to cool beverages, and frozen dishes became popular.

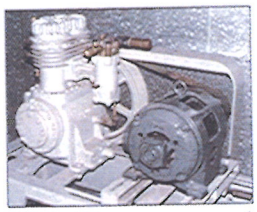
In 1626, Francis Bacon was the first to experiment with refrigeration for preserving foods. He experimented with a chicken stuffed with snow to see if it would preserve it; but it was not until the discovery of the microscope in 1683 that tangible results were obtained. With the microscope, scientist learned about bacteria, enzymes, and molds. They discovered that these microscopic organisms multiply with heat, but below 50° F they seem to hibernate.



Natural Refrigeration



Francis Bacon



Mechanical Refrigeration

Figure 1

The History of Mechanical Refrigeration

Lower temperature does not kill these organisms, but it does control their growth. Food could now be maintained in its fresh state by the use of cold instead of preserving it through drying, smoking, or salting. The use of cold, or refrigeration for food preservation grew to the worldwide business it is today.

For nearly a hundred years, all refrigeration for foods was provided by nature through the use of ice or snow. It was not until 1775 that experiments were made to create lower temperatures artificially, but these first experiments never got beyond the laboratory. In 1834 the first patent was granted on a mechanical refrigeration machine. This was a British patent, and a quotation from it is of interest because in principle it describes the mechanical refrigeration cycle as it is used today:

> *What I claim is an arrangement whereby I am enabled to use volatile fluids for the purpose of producing the cooling or freezing of fluids, and yet at the same time constantly condensing such volatile fluids and bringing them again and again into operation without waste.*

In 1855, the first mechanical refrigeration machine was put to use in the United States, in Cleveland, Ohio, where it was used for the artificial making of ice. About 1900, electricity began to enter homes, and with the development of the small electric motor, the "ice plant" was brought into the home.

It was recognized that the same cooling used to preserve foods could be used to cool the air and improve comfort. Over the next 100 years the use of mechanical refrigeration for comfort and food preservation grew dramatically to the point it became universally accepted. Now refrigeration machines are made in sizes up to hundreds of horsepower, and multiple machines are used for systems totaling several thousands of horsepower in a single installation – all with the same principle as described in that original patent.

The mechanical refrigeration cycle can be classified into two broad categories, comfort cooling and process cooling. Both involve the process of removing heat energy from a place where it is not wanted and rejecting it to a place where it is not objectionable.

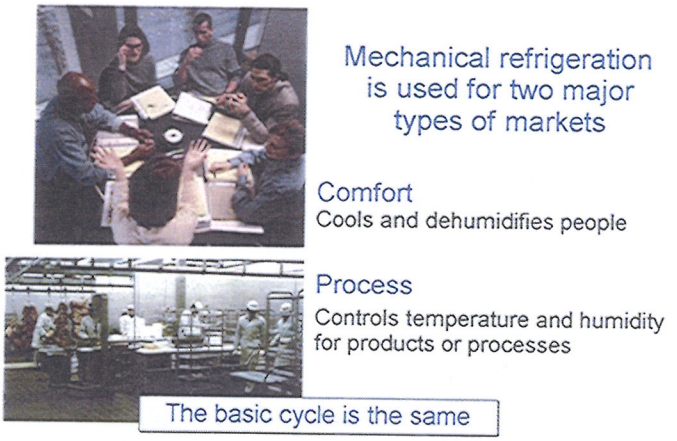


Figure 2

There are two major categories of mechanical refrigeration.

In general, the concepts presented here apply equally well to either comfort or process applications. There are some differences however.

Systems used for comfort, often referred to as air conditioning, operate at higher refrigeration system temperatures than most process or refrigeration applications like food storage. In this module reference to refrigeration means the mechanical process of refrigeration not necessarily lower temperature mechanical refrigeration in food or process application. The TDP text will clearly distinguish between comfort applications and low-temperature or process applications.

Basic Principles

To understand the way mechanical refrigeration works, we must first understand how heat moves. The process can then be explained by four fundamental principles. Heat transfer must first be understood so the four principles of refrigeration can be explained.

Heat Transfer

Heat energy can move by one of three methods of heat transfer.

Conduction is heat transfer from one molecule to another either in the same material or two materials in contact with each other. We have most likely experienced this when we grabbed a spoon that has been in a hot pan of food on the stove. First, the spoon got hot from the contact with the hot food (conduction), then the spoon handle got hot as heat energy moved up the spoon (conduction), and finally, our hand got hot when we touched the spoon (also conduction). This principle is used extensively in refrigeration, for example the refrigerant in the tubes is in contact with the tubes and heat transfer takes place from the refrigerant to the tube to the fluid that surrounds the tube.

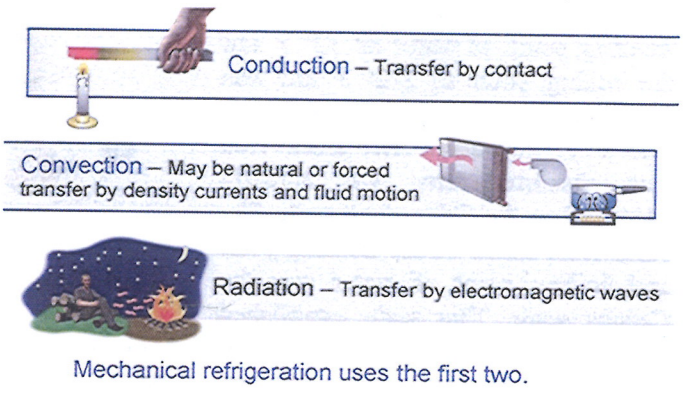


Figure 3

There are three methods of transferring heat.

Convection is the second method of heat transfer that takes place by flow movement. Convection can further be classified into one of two categories, natural or forced. Natural convection is the movement that occurs from the density differences in a fluid. If you observe a pot of water heating on a stove, as the water heats you will notice a turbulence begin to occur in the pot. This is the result of the difference in density between the warm water and the cooler water. This same phenomena can be observed when we stand on a chair in a room on a hot day, the air near the ceiling is warmer than near the floor because the lower density of the hot air caused it to rise toward the ceiling. If a force, fan or pump, is used to cause movement, it is called forced convection. This process is also used extensively in mechanical refrigeration when a fan is used to force air over a coil.

Types of Heat Transfer

- **Conduction, heat transfer by molecular movement**
- **Convection, heat transfer by density currents**
- **Radiant, heat transfer by electromagnetic waves**

The mechanical refrigeration cycle depends primarily on conduction and convection.

The final heat transfer method is radiant heat transfer, which is the transfer of heat from a warmer surface to a colder surface by electromagnetic waves. This transfer does not warm the fluids in between the surfaces but only the surfaces themselves. We have all experienced this with the heat energy we get from the sun or the way we can be warmed by a fire without the air around us actually being warmed. Radiant heat transfer is not used in the basic refrigeration cycle.

Measuring Heat

The primary device used to measure heat energy is a thermometer. The thermometer works by a fluid in a sealed tube responding to the degree of molecular movement in the fluid that surrounds the thermometer. As substances are heated, they contain more heat energy; therefore, they have a greater amount of movement. If all heat energy were removed, molecular motion would stop, a point referred to as absolute zero.

The readings on a thermometer are a relative scale. Two common types are in general use. The Fahrenheit scale was developed with the freezing point of water as 32° F and the boiling point as 212° F and was based on the theory that absolute zero was 0° F. Scientists later discovered that absolute zero was actually -459.7° F on the Fahrenheit scale. The other scale based on the freezing point and boiling point of water was the Celsius scale. This scale established 0° C as the freezing point of water and 100° C as the boiling point. Absolute zero on the Celsius scale is -273° C.

A thermometer measures molecular motion

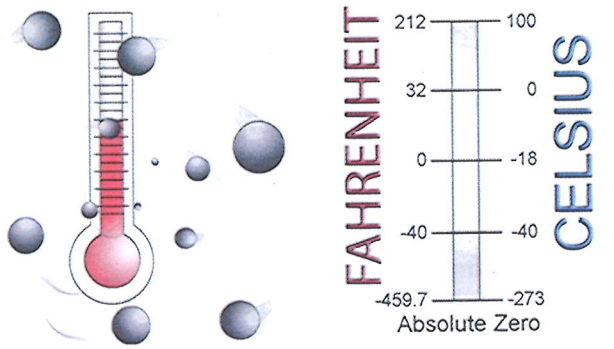


Figure 4

Thermometers measure molecular motion, typically in Fahrenheit or Celsius.

Two variations of these temperature scales also are used which have the same scale increments as the Fahrenheit and Celsius scale but starting at absolute zero; these are the Rankin and Kelvin scales, respectively.

When we measure heat energy with a thermometer we are measuring the heat's intensity. It is also important to understand that heat energy must be considered as a quantity as well. For example, a container with one pound of water at 100° F has twice the heat intensity as one with two pounds of water at 50° F. However, both the one-pound and two-pound containers have the same quantity of heat energy. Both intensity and quantity heat values are important in refrigeration.

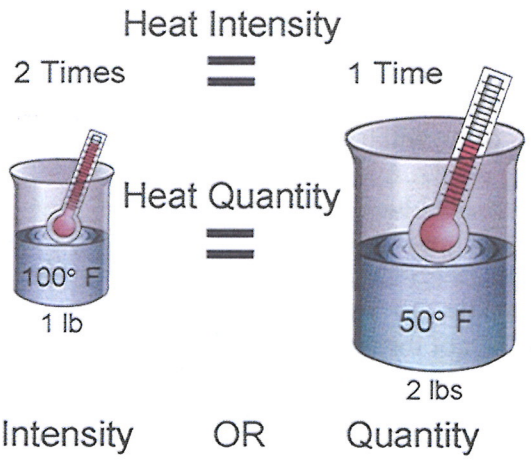


Figure 5

Heat energy has both intensity and quantity.

To explain the four principles used in mechanical refrigeration, we will use water as our refrigerant since it is common and familiar. Water can be a refrigerant, but not a very good one. Characteristics of refrigerants are explained later in this module.

As explained before, heat energy causes internal movement of the molecules within the substance. The amount of movement is an indication of the amount of heat energy. A thermometer responds to this internal movement. This is a measurement of heat intensity.

There is no device that can directly read heat quantity, so an arbitrary unit of measure has been defined to measure heat energy quantity, the Btu or British thermal unit. It is defined as the quantity of heat necessary to raise the temperature of one pound of water one degree Fahrenheit. The term Btu can be used if heat is being added or removed.

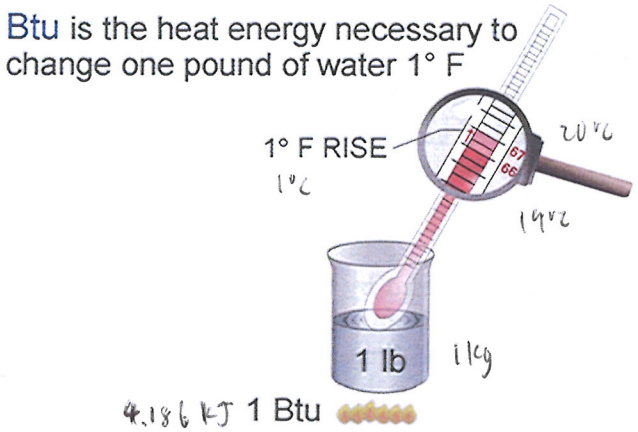


Figure 6

The British thermal unit measures the quantity of heat energy.

Sensible Heat

Heat energy is stored in a substance in two forms. The first of these is sensible heat energy. The heat energy associated with molecular movement is referred to as sensible heat energy. The temperature measured with a thermometer is a measure of this sensible heat energy.

We can plot this on a graph with temperature on one axis and enthalpy Btu/lb (we will define enthalpy shortly), on the other axis. For each Btu of sensible heat added per pound of water the line on our graph will rise one degree on the temperature scale. For example, 10 Btu will raise the temperature of the water from 32° F to 42° F. This same process is true up to 212° F, at which point the water begins to boil.

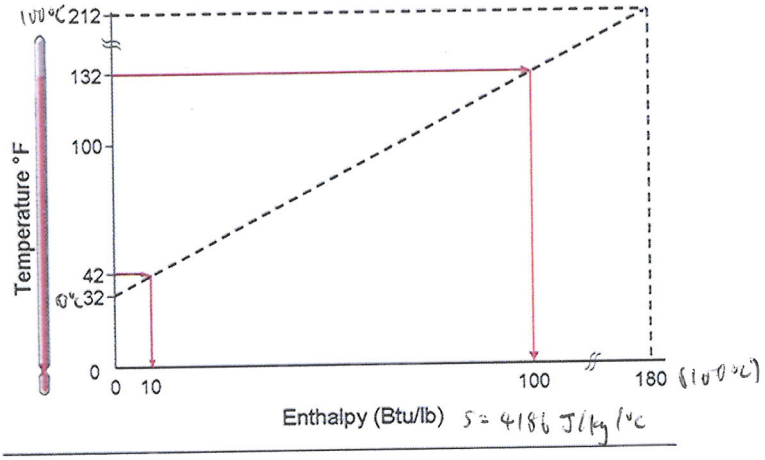


Figure 7

A plot of the sensible heat process

Latent Heat

The second form of stored heat energy is latent heat energy.

The "iceboxes" of the past were periodically stocked with a block of ice. The ice melted and the pan of water below the box had to be emptied on schedule to avoid overflow.

In melting from a solid to a liquid, the ice absorbed heat energy from the foods within the icebox. This energy is its latent heat of fusion, which is 144 Btu per pound.

The water created by the melting ice was discarded even though it was cold, because it had limited refrigeration capacity. This is because 1 Btu raises the temperature of 1 pound of water one degree. Therefore, when 1 pound of water starting at 32° F absorbs 10 Btu, its temperature rises ten degrees to 42° F. The same 1 pound of ice at 32° F melting to water at 32° F would absorb 144 Btu of heat energy. The water has a reduced cooling effect.

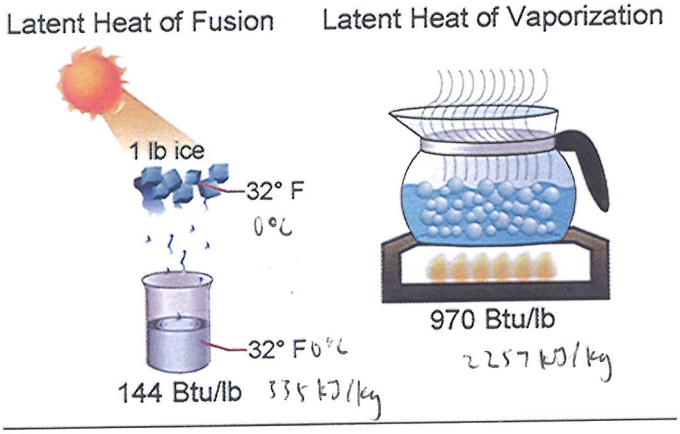


Figure 8

Latent heat energy is the energy required to change the state of a substance from a solid to a liquid or from a liquid to a vapor.

Latent heat energy is the energy required to change the state of a substance from solid to liquid or liquid to vapor. This heat energy transfer takes place at a constant temperature and cannot be measured by a thermometer.

If the temperature of one pound of water at 32° F is raised to the point at which water will boil we will add 180 Btu (212° F - 32° F = 180° F, each degree equals one Btu). Latent heat energy must then be added to change the water from a liquid into a vapor. This energy is the latent heat of vaporization. The latent heat of vaporization for water at sea level requires 970 Btu/lb to change from a liquid to a vapor.

A thermometer does not measure latent heat energy, but we can still use the heat quantity measurement of a Btu to measure latent heat energy. Again we can use our graph to demonstrate these principles. Notice we have negative values below 32° F since 32° F is the reference point we established for our graph. When the ice melted and the water boiled, the quantity of energy changed but the temperature did not. The combined sensible and latent heat energy quantity is called enthalpy and is a measure of total heat energy.

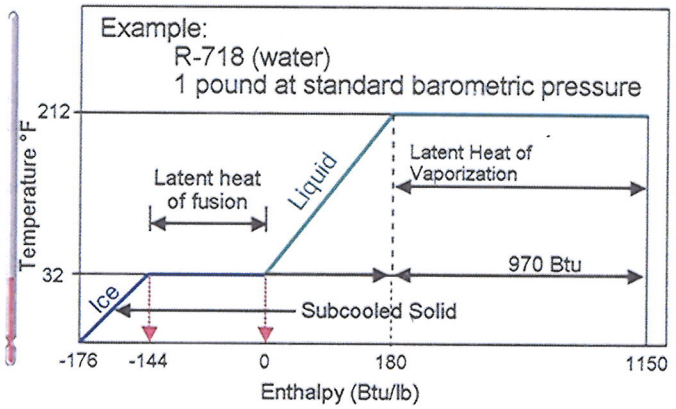


Figure 9

A plot of the latent heat process.

Heat can still be added to the vapor after it has completely boiled. This heat continues to raise the temperature of the vapor and is called superheat. For example if the vapor is heated by 30° F, from 212° F to 242° F, the vapor is said to have 30° of superheat.

In the superheat region, the vapor expands slightly in volume as its temperature is raised. Moreover, the specific heat of the vapor is different than the same fluid in liquid state. For example, it takes only 0.45 Btu to raise 1 pound of water vapor 1° F. If a pound of steam is superheated by 30° F, then 30 * 0.45, or 13.5 Btu, is required.

Our chart can now be used to explain several important refrigeration terms. As ice melts the latent heat involved is the heat of fusion, the latent heat involved in changing a liquid to a vapor is the latent heat of vaporization and is sometimes also referred to as the latent heat of condensation when the

Superheat / Subcooling

Superheat – temperatures above the saturated vapor temperature

Subcooling – temperatures below the saturated liquid temperature

Saturated vapor and saturated liquid temperature are a function of the refrigerant and the pressure.

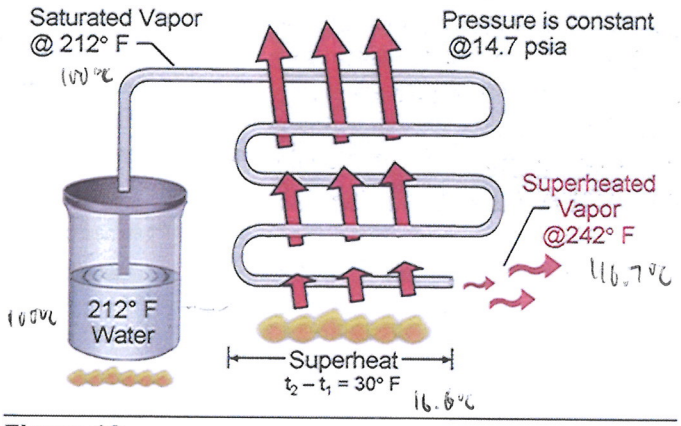


Figure 10

Superheat is heat energy above the saturated vapor.

process is condensing the vapor to a liquid. Enthalpy is a measure of the total heat content and includes both the latent and sensible heat energy. When the vapor is heated above the boiling point it is referred to as superheated. Also when the liquid is at a temperature below the boiling point it is referred to as subcooled. Like superheat is the number of degrees above the boiling point, subcooling is the number of degrees below the boiling point. For example a liquid at 180° F could be said to have 32° of subcooling.

Two other important points are on our chart. The point at which the liquid just begins to turn to a vapor is called saturated liquid. When heat is added to a fluid so it has all evaporated, it reaches a point identified as saturated vapor. It is saturated with all the heat it can contain at that pressure and still remain at the saturation temperature. The change of state has been completed, and any additional heat results in a rise in temperature of the vapor. This additional heat is called superheat. Between saturated liquid and saturated vapor is a mixture of liquid and vapor.

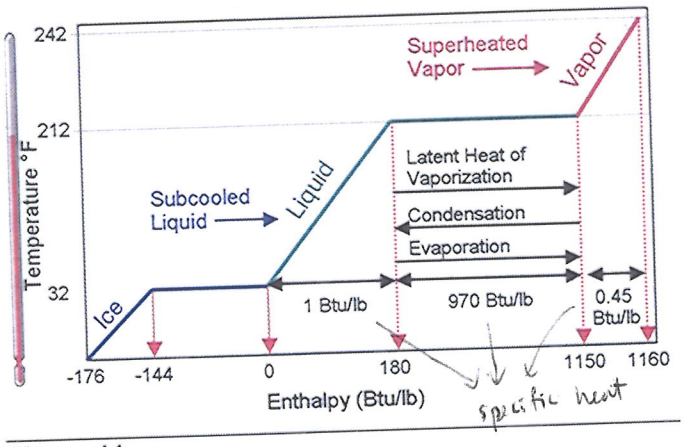


Figure 11

The greatest heat energy occurs during phase change.

Notice the heat energy involved in each step of the process: 970 Btu/lb are required to change liquid to a vapor, 144 Btu/lb are required to change solid ice to liquid, 1 Btu is required to change the liquid temperature 1 degree, and 0.45 Btu/lb are required to change the vapor temperature 1 degree. The greatest heat energy is in changing from a liquid to a vapor or vapor to a liquid.

One final term related to the transfer of heat needs to be defined. In all the heat flow we have discussed to this point, the time it took to transfer a Btu was not a consideration. The heat flow was the same if it was a day or a minute. When the rate of time for heat flow is important, another term is used. The common measurement is a refrigeration ton. The refrigeration ton is the amount of heat energy required to melt one ton (2000 lb) of ice in 24 hours. We saw that the latent heat of fusion was 144 Btu per pound this would then be 2000 lb * 144 Btu/lb and would equal 288,000 Btu per day. For most of our analyses, it is more convenient to use smaller time increments. We normally rate per hour, (one ton or 288,000/24 hours equals 12,000 Btu per hour), or rate 200 per minute.

A ton of refrigeration

is the heat energy required to melt one ton (2000 lb) of ice in 24 hours. In common terms this equates to 288,000 Btu per day, 12,000 Btu per hour and 200 Btu per minute. The Btu is not time dependent; when time rate of change is considered, we use Btuh (Btu per hour) or tons.

When heat flows are time dependent, we use the term tons or the terms ton or Btu per hour, Btuh.

Principle 1 – Heat Flows from Warm to Cold

The first basic principle of mechanical refrigeration is that heat flow can only take place if a temperature difference exists. Heat energy only moves from a warmer substance to a cooler substance. In the context of air conditioning, this means to remove heat from a space. The temperature of the fluid used to absorb the heat must be colder than the space temperature. Conversely, for the fluid to give up its heat, it must be warmer than the air or water to which it is rejecting heat.

Also notice that the greater the difference in intensity between the two substances, the greater the heat flow will be.

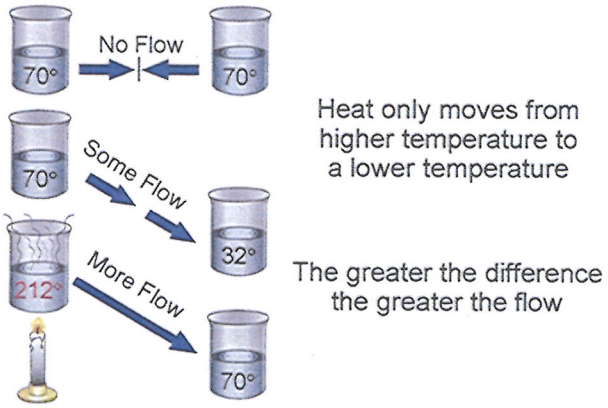


Figure 12

Heat moves from a warmer substance to a cooler substance.

Principle 2 – Phase Changes Require Large Amounts of Energy

The change of state is important to the mechanical refrigeration cycle for two reasons. First, the change absorbs a relatively large amount of heat per pound of substance; and second, this change of state takes place at a constant temperature.

This is the second basic principle of mechanical refrigeration systems. From a practical standpoint, this principle means the greatest amount of heat energy is transferred when the refrigerant changes state. The greatest amount of heat energy is in the change from liquid to vapor, and it is also much easier to transport a liquid than to transport a solid.

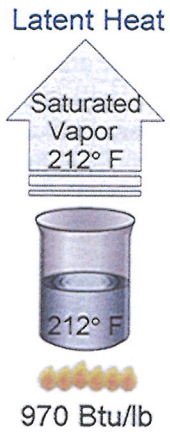


Figure 13

A large amount of energy is required to change the state of matter.

Principle 3 – Boiling Temperature is a Function of Pressure

Since we are familiar with the properties of water, and its behavior is similar to commonly used refrigerants, water is used here to demonstrate the boiling process.

If one pound of water at 32° F is heated, its temperature increases one degree for each Btu added. This process continues until the water reaches its boiling point, or boiling temperature. The pressure over the water determines this boiling temperature. In an open container, the pressure over the water is atmospheric pressure. If the process occurs at a higher elevation the pressure is less and the boiling temperature is lower. In a closed container, the pressure in the container controls the boiling temperature. Notice that the temperature required to boil the water changes with pressure, as does the amount of heat energy required. The lower the pressure the greater the heat energy between saturated liquid and saturated vapor; but the lower the boiling temperature.

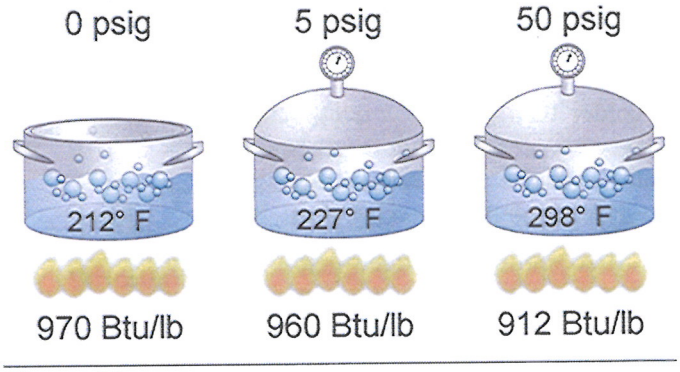


Figure 14

Pressure affects the boiling point.

Measuring Pressure

To begin the discussion of pressure, it is necessary to understand pressure measurements. Pressure readings are a comparison of pressures to a datum point.

The column of air in the atmosphere has weight that exerts a pressure on surfaces below. The weight of the air column will change depending on the elevation. Higher elevations will have lower atmospheric pressure. It is customary practice to use the weight of the column at sea level as a datum point to describe other pressures. The pressure of the column of air is called the barometric pressure.

When a pressure reading is taken, it is the difference above or below the sea level datum point and is called gage pressure or psig, often, just psi. If the pressure associated with the column of air is included in the reading, it is called pounds per square inch absolute, or psia.

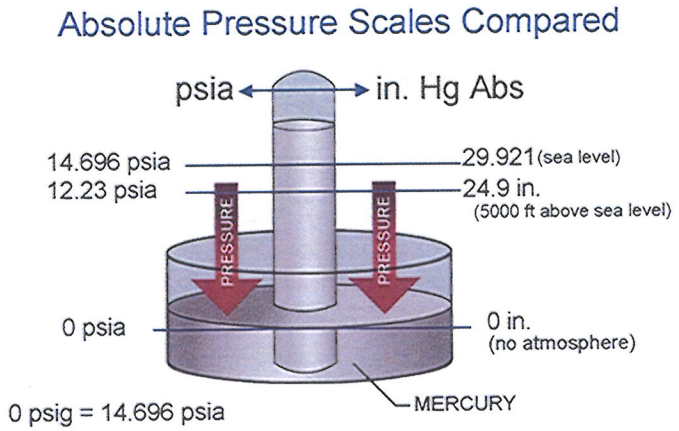


Figure 15

Measuring Pressure

Change of State

The temperature at which a fluid changes state is dependent on the pressure.

At sea level the pressure is 29.921 in. of mercury (Hg) or 14.696 psia. This point is often referred to as standard barometer. At a 5000-foot elevation, the pressure is 12.23 psia.

Most calculations in refrigeration use psia.

At the boiling point, either the pressure or the temperature establishes the other. Water at the boiling temperature for a given pressure is identified as saturated liquid. It is saturated with all the heat it can contain at that pressure and still remain a liquid. As more heat is added, it evaporates into a vapor until all the liquid is a vapor; it is then at saturated vapor. When the process is reversed and heat is removed from a vapor, the vapor begins to condense at the saturated vapor point until it is all a liquid at the saturated liquid point. This reverse process is the condensing process.

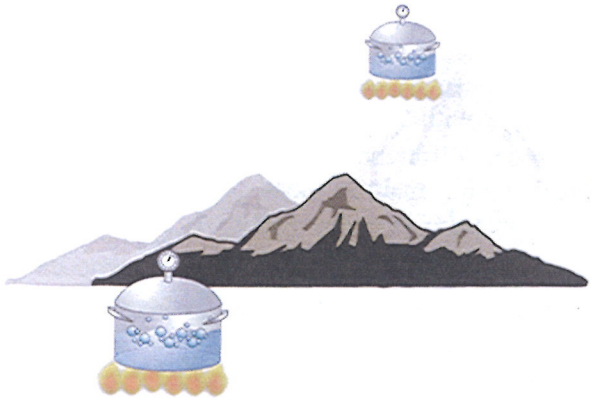


Figure 16

Changing pressure changes the point at which matter changes state.

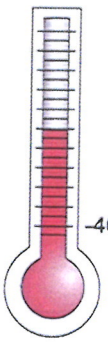
The third principle of mechanical refrigeration is that the temperature at which a fluid changes state is dependent on the pressure. In mechanical refrigeration this means that by changing the pressure, the temperature at which the change occurs can be controlled.

Refrigerant Enthalpy

To this point 32° F was our datum point. Actually, all matter contains heat or energy down to absolute zero (-460° F), but, for convenience purposes, other datum lines are selected arbitrarily.

Because water freezes at 32° F, the datum line for water could be taken at 32° F. Any values of heat content below 32° F are thus negative. With most common refrigerants the datum would be much lower.

To avoid the use of heat contents with negative values down to lower temperatures, the heat content of most refrigerants is taken at a datum line of -40° F. The figure shows the boiling points of some of the most common refrigerants at atmospheric pressure.



Water	212° F
HFC-134a	-15° F
HCFC-22	-41° F
HFC-410A	-62° F

Figure 17

Different refrigerants boil at different temperatures.

Total energy in a fluid involves not only the internal energy represented by heat, but also the external energy or work required to reach that state. The sum of these energies is called enthalpy. Since it is the more accurate term, enthalpy is used in refrigerant tables and in this text to indicate total heat content.

Principle 4 – Flow Occurs because of a Pressure Difference

The fourth principle of mechanical refrigeration is that flow of a liquid or vapor will only occur if a pressure difference exists. As with heat flow, if no differential exists, flow will not occur. Also, flow will not occur from a point of lower pressure to one of higher pressure unless mechanical work is added. Flow can be caused by static difference, as with a column of liquid, by pressure difference, or by mechanical work creating positive or negative pressure.

In mechanical refrigeration this means a pump is required to move the vapor from the low-pressure side of the system to the high-pressure side of the system.

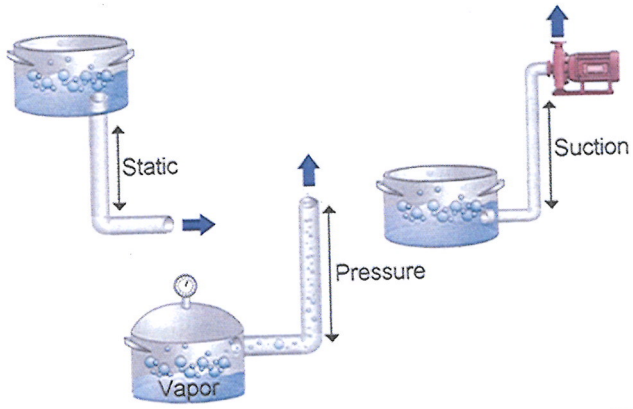


Figure 18

Flow only occurs when there is a difference in pressure.

Summary of the Four Basic Principles

The four basic principles can be summarized as:

- Heat energy will only flow from a warmer temperature to a cooler temperature and the greater the difference, the higher the rate of flow.
- Two types of heat energy exist in a substance, sensible and latent. A larger amount of energy is required to change states in the latent heat energy.
- The temperature at which a change of state occurs is dependent on the pressure. By controlling the pressure, we can control the boiling point.
- Flow of a liquid or vapor will occur only if a pressure difference exists, unless mechanical work is added.

With these four principles the steps of the mechanical refrigeration cycle can easily be explained.

Specific Heat
Heat 2012

The Mechanical Refrigeration Cycle

As was mentioned in the introduction, all mechanical refrigeration systems require four basic components to form a complete cycle. In this section the basic components will be described with the function they serve in the process. Several other components are typically found in refrigeration systems and are identified with their function and location in the system.

Four Components

The mechanical refrigeration cycle requires four components for its operation to be a continuous cycle. First is the evaporator, a section where the refrigerant absorbs the heat from the fluid that is being cooled. Second is a device that raises the vapor's pressure to a temperature where it can be condensed, the compressor. Third is the condenser, a section where the absorbed heat is rejected from the refrigerant. Fourth is a device that controls the flow and drops the refrigerant pressure back to the temperature required in the evaporator, the metering device.

A mechanical refrigeration system requires 4 components:

1. **Heat absorber – evaporator**
2. **Vapor pump – compressor**
3. **Heat rejecter – condenser**
4. **Pressure/flow control valve – metering device**

Refrigerant

The first thing required for a system to remove heat is a refrigerant. A refrigerant is the fluid that absorbs and transports the heat energy. For the refrigerant to deliver the most heat transfer capability, it must change from a vapor to a liquid at a reasonable pressure and temperature to take advantage of the latent heat capacity.

Many fluids can be refrigerants. The chart below shows properties of several refrigerants with the pressures associated with a few of the common temperatures found in comfort and process refrigeration. These pressures and temperatures define the work the mechanical refrigeration system must do to perform the function of moving heat. This text will use R-22 and R-410A to explain the refrigeration cycle. Notice the difference in pressures associated with these two refrigerants. Properties of a good refrigerant are discussed later in this module. A comparison chart of refrigerants is included in TDP-401, Principles of Mechanical Refrigeration, Level 2, Analysis.

A refrigerant is a fluid that absorbs heat and changes from vapor to liquid phase at reasonable pressures and temperatures as encountered in mechanical refrigeration.

	PRESSURE psia					
°F	Water	HCFC-22	HFC-410A	HFC-134a	CO_2	Propane
-40	0.00186	15.26	26	7.43	145.77	16.1
0	0.0185	38.73	64	21.62	305.80	38.4
40	0.122	82.28	132	49.70	567.50	78.6
100	0.950	210.70	340	138.80	X	188.6
130	2.225	311.60	500	213.40	X	273.3
212	14.696	*CP	*CP	587.20	X	X

*Critical Point, pressure psia

Figure 19

Refrigerants and their pressures at common comfort and process refrigeration temperatures.

Evaporator

If a volatile refrigerant is available in liquid form, it will absorb heat in evaporating or changing to a vapor. It is this change of state that accomplishes the cooling effect in a refrigeration cycle.

Since heat will only flow from a warmer substance to a cooler substance, the temperature of the evaporator must be less than the temperature of the substance to be cooled. For instance, if heat and moisture are to be removed from air, the temperature of the coil must be below the dew point temperature of the air. If the dew point temperature is 55° F the refrigerant temperature in the evaporator must be at least a few degrees colder than 55° F for latent heat removal from the air to occur. If the air is in a frozen food case which needs to be kept at 0° F, then the temperature must be at least a few degrees below zero.

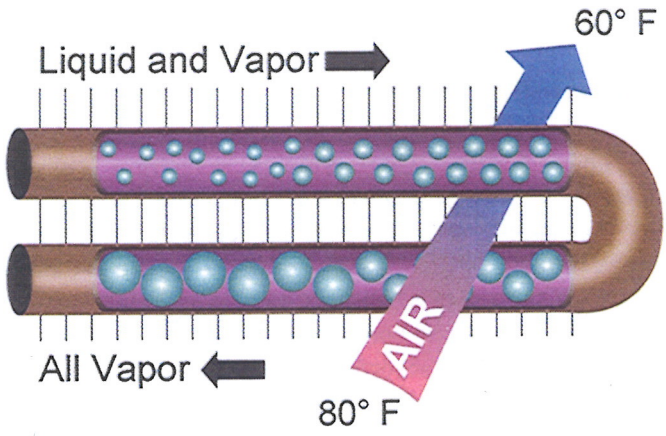


Figure 20

An evaporator absorbs heat.

If liquid refrigerant is allowed to expand through a cooling coil, which is open to the atmosphere, the refrigerant absorbs heat from the surrounding air and evaporates at a temperature corresponding to atmospheric pressure. With R-22, this would be at -41.4° F at standard atmospheric pressure, and for R-410A this would be -60.8° F.

Since it is evaporation that accomplishes the greatest cooling, that part of the equipment in which the cooling is done and the evaporation takes place is called the "evaporator."

The evaporator and metering valve alone would provide refrigeration or cooling. However, such an arrangement would be very expensive to operate because the refrigerant would be wasted. Therefore, the balance of the cycle or equipment is needed and used to recover the refrigerant, so that "*the volatile fluids are brought again and again into operation without waste*," to quote again from the original patent.

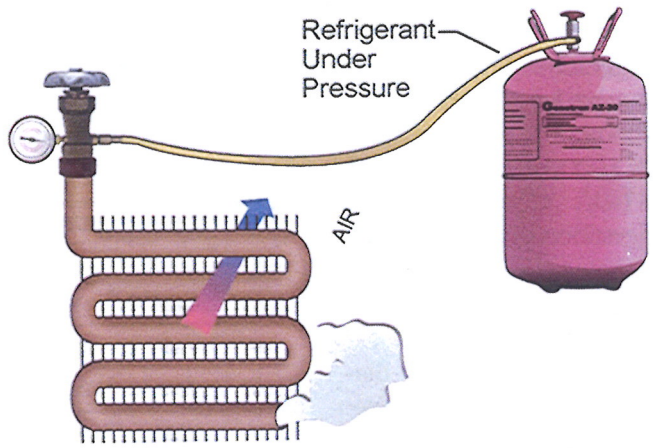


Figure 21

An open cycle requires only two components.

In order for the refrigerant to be used over and over, a closed cycle is required. Two other components are required if the refrigerant is to be returned to a state where it is ready once again to be used in the evaporation process. These are a vapor pump, compressor, to increase the pressure and therefore the temperature high enough that a temperature difference exits between the fluid to be used to absorb the rejected heat and the refrigerant. The other is a heat exchanger where the heat to be rejected can be adsorbed by the heat rejection fluid and the refrigerant vapor can be condensed back to a liquid. Since the vapor is being condensed this heat exchanger is called the condenser.

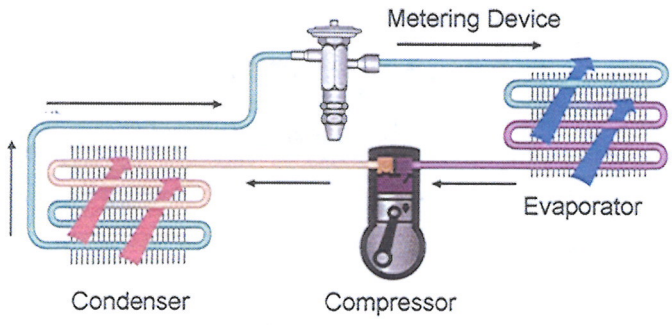


Figure 22

A closed cycle requires four components.

The system can be divided into two sections based on the pressure in that part of the system. The evaporator is at a low pressure so that a low temperature exists to absorb heat. It is often referred to as the low-pressure side of the system or low side. The condenser on the other hand is at a high pressure, so its temperature is high enough to reject heat to the condensing fluid. The condenser side of the system is referred to as the high-pressure side or high side. The compressor and metering device divide the high-pressure and low-pressure sides of the system since a pressure change takes place within each of these components.

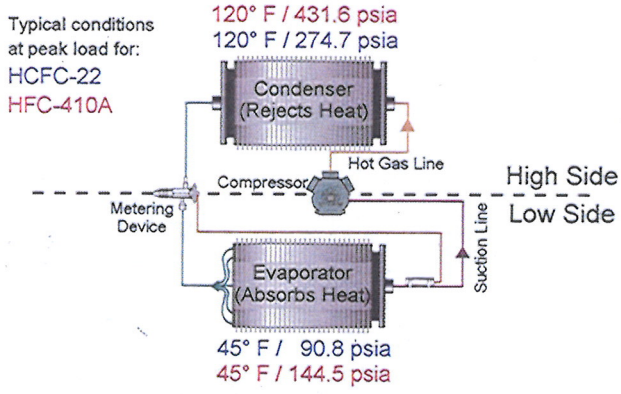


Figure 23

Refrigeration systems have two pressure zones, the low-pressure side (low side) and the high-pressure side (high side).

Then the function of the evaporator is to absorb heat energy at a rate that will cool or maintain the temperature of the fluid to be cooled, normally air or water, to match the load requirements of the space or process. Since the most heat transfer is accomplished with a change from liquid to vapor, the evaporation process is primarily used to absorb the heat load. For reasons to be discussed shortly, the refrigerant enters the evaporator as a cold mixture of vapor and mostly liquid. As it progresses through the evaporator, the refrigerant boils, absorbing heat until all the liquid has turned to a cold vapor. The point at which this occurs is called the saturated evaporator temperature, SET.

SET and SST:

SET is Saturated Evaporator Temperature and is the temperature that corresponds to the pressure leaving the evaporator

SST is Saturated Suction Temperature and is the temperature that corresponds to the pressure at the inlet of the compressor.

SST is less than the SET by the temperature corresponding the pressure loss in the interconnecting suction line.

It is common practice on most systems to allow the refrigerant to absorb some additional heat above the saturated evaporator temperature. Refrigerant vapor leaves the evaporator as a cold, superheated vapor. Superheat is often required to assure that liquid will not be returned to the compressor. As was demonstrated earlier, the superheated vapor has much lower heat absorbing capacity than the evaporation process, therefore, the superheat region in the coil should be kept to a reasonable minimum.

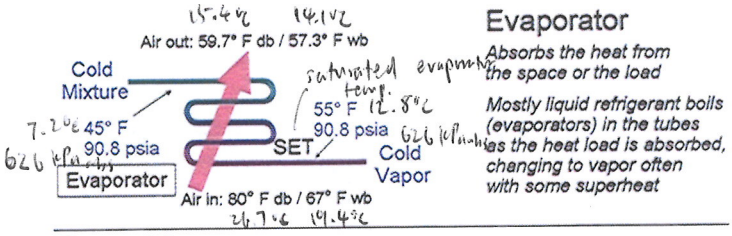


Figure 24

Evaporator Function

Compressor

If the refrigerant vapor from the evaporator were merely passed into a chamber or tank, the pressure in that chamber would rise until the pressure in the chamber and that of the refrigerant supply reached equilibrium. The pressure would correspond to ambient temperature and the cooling effect would stop. Therefore, it is necessary to continually pull off the refrigerant vapor as rapidly as it is formed to maintain proper pressure and hence, saturation or boiling temperature in the evaporator. This is one function of the compressor.

If the load increases and boils off refrigerant faster than the compressor withdraws it, the pressure and temperature rise. Thus, a refrigeration cycle "rides with the load," until compressor capacity and evaporator load reaches a balance.

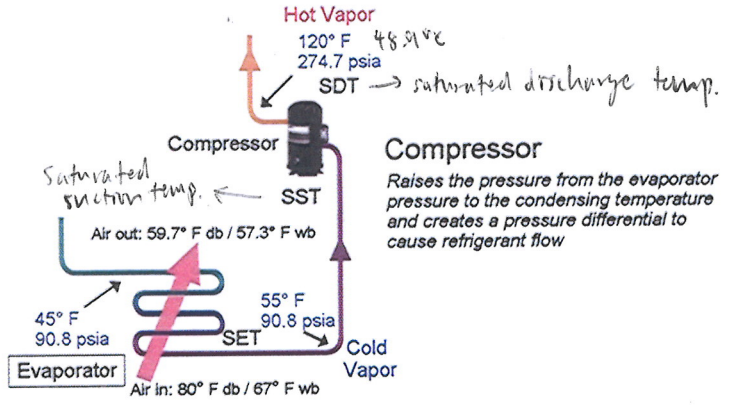


Figure 25

Compressor Function

To convert the refrigerant to a liquid so that it may be used again, heat must be removed so it will condense. To do this, some fluid, normally water or air, to which the rejected heat can flow, must be used. For heat flow to occur, the temperature of the refrigerant must be higher than the temperature of the fluid. A second function of the compressor, therefore, is to raise the temperature of the refrigerant above the temperature of the condensing fluid (air or water). By compressing the refrigerant, the pressure and temperature are increased. The temperature is raised above the saturated liquid temperature, and this permits the fluid to cool the refrigerant vapor and condense it to a liquid state.

Work of Compression

Refrigerant leaves the evaporator and enters the compressor as either a saturated or superheated vapor. Work needs to be added to the vapor to raise its pressure. The work done in compressing the vapor raises the vapor temperature. The refrigerant absorbs this heat during compression, and leaves the compressor in a superheated state with more energy, and hence more heat than it had when it entered the compressor. This increase in heat is referred to as the "heat of compression," and is equivalent to the work done on the vapor as it is being compressed.

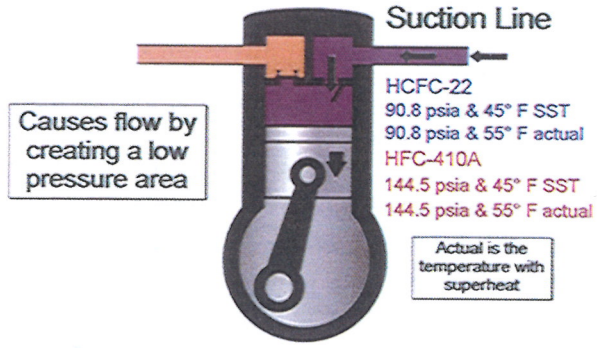


Figure 26

Compressor suction creates flow.

SCT and SDT

SCT is Saturated Condensing Temperature and is the boiling temperature that corresponds to the pressure leaving the condenser

SDT is Saturated Discharge Temperature and is the boiling temperature that corresponds to the pressure at the outlet of the compressor.

SDT is greater than the SCT by the temperature corresponding the pressure loss in the interconnecting hot gas line.

The first function of the compressor, therefore, is to draw the cold vapor from the evaporator. The second function is to provide adequate work energy to raise the pressure such that the temperature will be high enough to reject heat to the heat rejection fluid and condense the refrigerant. The vapor will leave the compressor as a highly superheated hot vapor.

The heat of compression varies only slightly with different refrigerants, but varies greatly with different levels of temperature and pressure between which the cycle is operating. For example, at temperature levels of comfort air conditioning, namely 45° F saturated in the evaporator and the 105° F saturated commonly associated with water-cooled condensers, this work of compression amounts to approximately 1.0 horsepower per ton of refrigeration. For a frozen food cabinet, on the other hand, with -10° F in the evaporator and 120° F in an air-cooled condenser, the compressor would require almost 3.0 horsepower per ton.

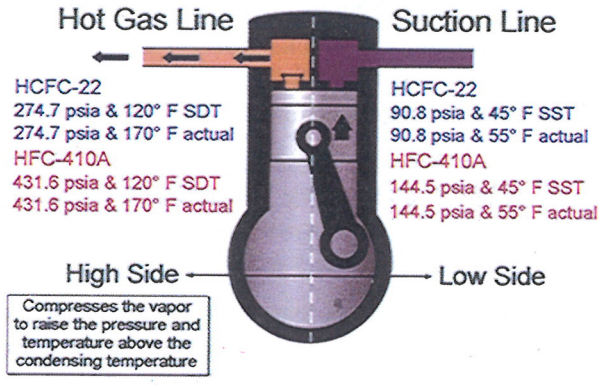


Figure 27

Compressor Discharge – Temperature and pressure are raised.

Condenser

In the condenser, heat is removed from the refrigerant by providing a condensing fluid at lower temperature to which the heat can flow and be dissipated. The condenser removes heat taken on by the refrigerant in the evaporator, and it also removes the heat put into the refrigerant during the compression process.

The first step in the heat removal process lowers the temperature of the superheated refrigerant until it reaches the saturation point at the pressure existing in the condenser. Further removal of heat then affects a change of state and condenses the refrigerant to a liquid so that it can be used over again in the cycle.

The temperature of the fluid (air or water) to which heat flows in the condenser establishes the temperature at which condensation takes place. As it takes on heat from the refrigerant, the temperature of the condensing fluid will rise. To maintain the flow of heat, the temperature of the refrigerant in the condenser must always be greater than the temperature of the condensing fluid.

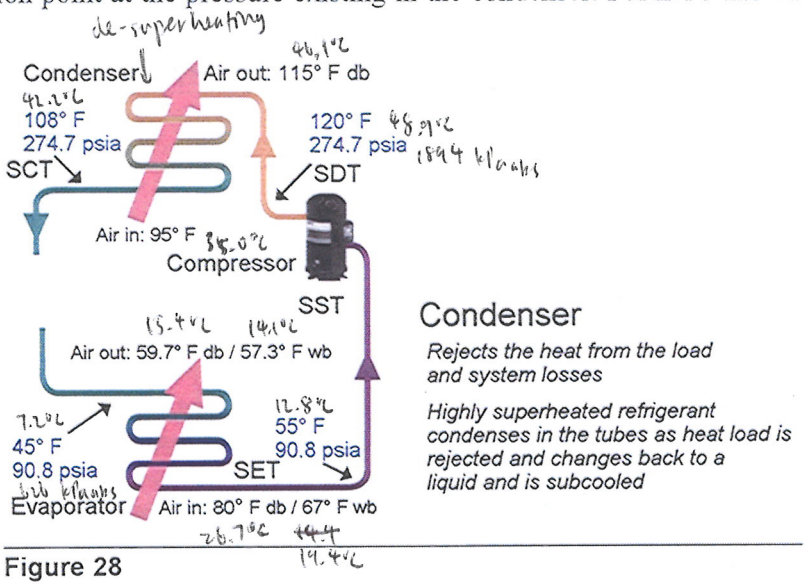


Figure 28

The condenser rejects heat in three forms – desuperheating, condensing and subcooling.

A final portion of the condenser is used to lower the temperature of the liquid refrigerant below the saturated condensing temperature providing subcooling. When the liquid is cooled below the saturated liquid temperature at a given pressure, the liquid is referred to as being subcooled. Most condensers are arranged so as to provide some subcooling of the liquid refrigerant as it leaves the condenser. If this subcooling is retained until the liquid reaches the metering device, then it reduces the percent flash gas and increases the refrigeration effect of each pound of refrigerant circulated. Flash gas will be explained in the next section.

Subcooling can increase system capacity by 1% for each degree of subcooling provided. The amount of available subcooling is limited by the condensing surface and the temperature of the condensing fluid. Like the superheating in the evaporator, the greatest heat transfer occurs in the condensing process not in the subcooling process.

Subcooling also assures that only liquid refrigerant will enter the metering device. The impacts of subcooling will be expanded in the next TDP module, TDP-401, Principles of Mechanical Refrigeration, Level 2: Analysis.

In an air-cooled condenser, the refrigerant passes back-and-forth through the coil several times; and to accomplish flow, there must be a pressure difference, or pressure drop. In most condensers, this will be approximately 10 psi or less.

A portion of the tubes must provide desuperheating for the evaporator superheat and the heat of compression work. Desuperheating represents between 10 percent and 20 percent of the total heat removal in the condenser, and since the density of the vapor is light, the pressure drop in this section will be small.

A section of the coil must also provide for the subcooling.

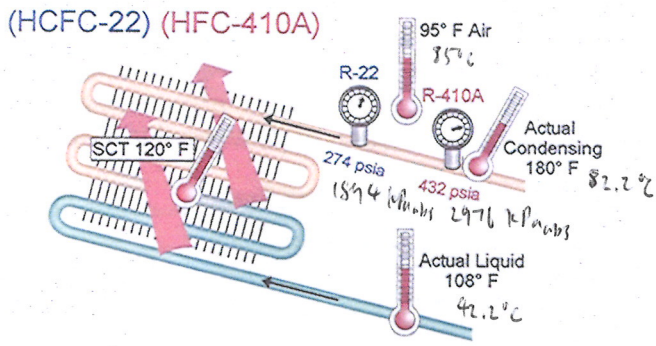


Figure 29

Air-Cooled Condenser – provides desuperheating, condensing and subcooling.

With water-cooled condensers, the refrigerant is often in the shell, and there is little variation in pressure and saturated condensing temperature throughout the shell. The difference between the saturated condensing temperature and the temperature of the condensing fluid as it leaves the condenser is referred to as the leaving difference.

Water-cooled condensers generally have a lower saturated condensing temperature than air-cooled since the condensing fluid can be provided at a lower entering temperature. In the next module of this series, the impact of lower condensing temperature on cycle performance will be evaluated.

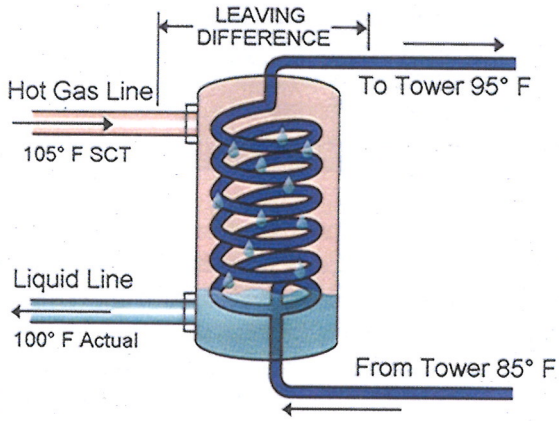


Figure 30

Water-Cooled Condenser – Less subcooling can be provided.

Metering Device

When liquid refrigerant flows from the higher pressure of the condenser to the lower pressure of the evaporator, some type of metering device must control its rate of flow. The pressure drop across the metering device reduces from the condenser pressure to the evaporator pressure. This metering device might be a thermal expansion valve, a hand valve, a float valve, capillary tube or a fixed orifice. In any of these, the refrigerant expands as it enters the area of lower pressure. This pressure reduction process is often referred to as throttling.

Metering device function

can be explained with the perfect gas equation:

$$pv = nRt$$

p pressure
v volume
n weight
R a constant
t temperature

The weight and constant will remain the same and the volume is nearly constant. If no heat comes from external sources, then temperature must change.

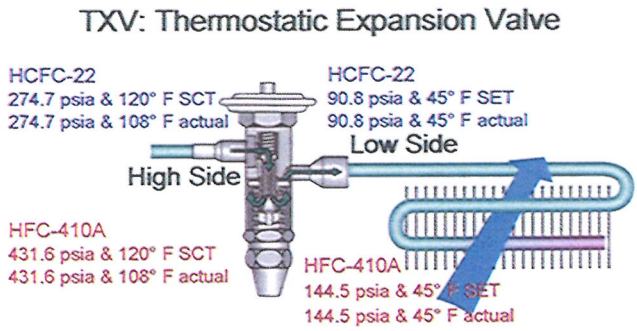


Figure 31

Metering Device

Economizer - to further cool the refrigerant

The pressure drop and expansion takes place quickly and in a relatively short distance through an orifice. Hence it is practical to assume that there is neither a heat gain nor a heat loss from the refrigerant in this process. Since the refrigerant will now boil at a lower temperature, a small portion of the refrigerant will evaporate into a vapor and absorb the required heat of vaporization from the surrounding refrigerant, in turn cooling that refrigerant to the evaporator saturated temperature. The portion of gas, which becomes a vapor is called flash gas.

The metering device serves to regulate the flow of subcooled warm liquid, dropping the pressure and thereby cooling the refrigerant to the evaporator saturation temperature. The refrigerant leaving the metering device is a cold mixture of liquid with a small amount of vapor.

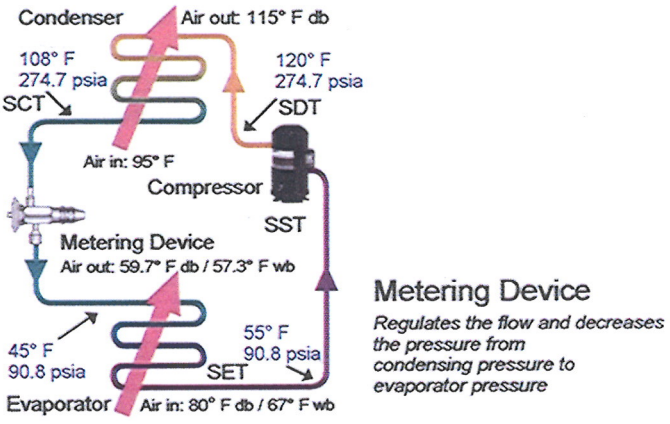


Figure 32

The metering device regulates the flow of subcooled warm liquid.

Refrigerant Lines

Refrigerant lines interconnect each of the four basic components of the mechanical refrigeration system. The line that connects the evaporator to the compressor is the suction line. The suction line carries a low-temperature and low-pressure vapor that occupies a relatively large specific volume. Therefore, the suction line is the largest of the interconnecting lines. It is also at a low temperature that may well have a temperature below the dew point of areas the line passes through. This could cause the line to sweat and the heat gain in the line would also reduce compressor capacity. For these reasons the suction line is usually insulated with a rubber-based insulating material.

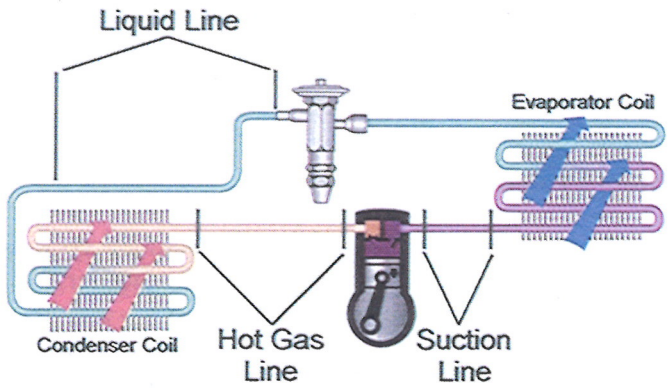


Figure 33

Refrigerant Lines

Refrigerant lines:

Suction lines are the largest and coldest and are normally insulated.

Hot gas lines are the hottest and smaller than the suction line but are not normally insulated.

Liquid lines are the smallest and are warm, so they are not normally insulated. However some types of units (some duct-free splits) use the pressure drop of the liquid line as part of the metering device. In this case, these lines must be insulated.

The line that connects the compressor to the condenser is the hot gas line. Sometimes this line is also called the discharge line. The hot gas line is carrying a high-pressure high-temperature vapor. The specific volume is smaller and the line size is smaller than the suction line. Heat loss from the line is not detrimental to the systems performance, and unless the very hot line would represent a safety hazard, the line is not insulated.

The liquid line connects the condenser and the metering device. The volume occupied by the liquid is the least of the lines and the line size is the smallest. Since the temperature of the liquid line is normally above the ambient temperature of the space the line goes through, it is not normally insulated.

The metering device is mounted as close to the evaporator inlet as is feasible and does not have a special line.

Refrigerant Cycle Accessories

Refrigerant systems may have a number of other components in the system to protect the four basic components, enhance the cycle performance, increase the operating range, and provide for special applications. This section will briefly identify the components and their use. For additional information on the selection, use, and application of these devices, see TDP-403, Expansion Devices and Refrigeration Specialties.

System Protectors

Three components are used in refrigeration systems that are classified as system protectors: filter-driers, moisture-liquid indicators, and mufflers.

The first component is a filter-drier. Filter-driers are normally located in the liquid line, however, in some applications they are located in the suction line. The purpose of the filter-drier is to filter out of the refrigerant both solid contaminants such as metal filings, flux, and dirt, and soluble contaminants such as acid, water, resins, and wax. These contaminants may be introduced into the system during manufacture of the unit, during installation or servicing, or through operation. The filter-drier consists of shell that contains screens and a desiccant material that will absorb the contaminants from the refrigerant. Filter-driers may be a sealed shell style or may be a shell with a replaceable core. Suction line filter-driers are used after a compressor motor failure to remove acids and debris that may have entered the system. Suction line filter-driers are also common on low-temperature refrigeration systems.

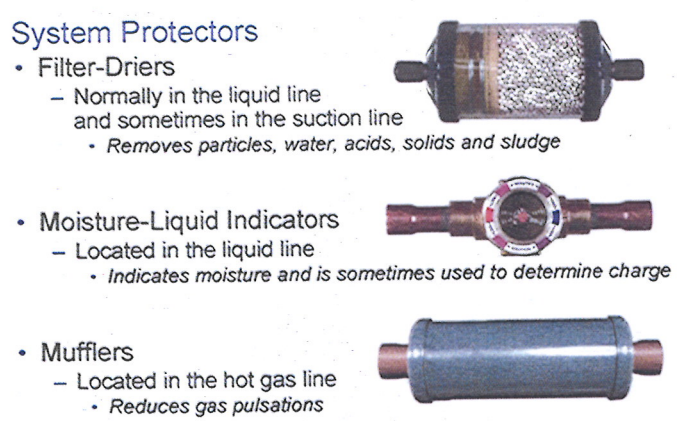


Figure 34

Refrigeration System Protectors

The second device is a moisture-liquid indicator, sometimes called a sight glass. It is located in the liquid line near the metering device. A moisture-liquid indicator is a view port with a chemically sensitive center eye. The color of the eye will change to indicate if the system is contaminated by moisture. Moisture in a refrigeration system can cause freezing in expansion devices, corrosion, and chemical damage. The area around the eye is clear and when the system is operating if flash gas bubbles are seen in the refrigerant flow it is an indication of a liquid line restriction or a low system charge. While the moisture-liquid indicator could be used for evaluating the charging of the system, it is recommended that charging be accurately accomplished by weighing in the system charge or using the appropriate superheat or subcooling method. Using the moisture-liquid indicator to add charge is not recommended since it is impossible to determine how close the system is to the correct charge.

The third device that may be classified as a system protector is a muffler. A muffler is an expansion chamber located in the hot gas line on the discharge side of the compressor. The purpose is to reduce gas pulsations from the compressor. Gas pulsations can cause noise and vibration and

in severe cases the vibration may cause premature failure of refrigerant lines. The muffler often has a series of baffles that help to break up the acoustic waves and gas pulsations, thus reducing the sound. Most reciprocating style compressors use mufflers because of the natural pulsation caused by the alternate opening and closing of the discharge valves. Scroll and many other styles of compressors normally only apply mufflers in situations where the characteristics are such that line vibration or sound generation is a problem.

The muffler is an additional pressure drop in the hot gas line. If the muffler is not provided as part of the manufacturer's package, the pressure drop needs to be included when sizing the hot gas line.

Storage Devices

There are two types of storage device encountered in refrigeration systems, accumulators, and receivers.

An accumulator is a refrigerant storage device located in the suction line before the compressor. The function of the accumulator is to prevent liquid refrigerant from entering the compressor. Since many compressors are positive displacement vapor pumps with small clearance volume, liquid, which does not compress, will do severe damage to the compressor valves and other internal components if it gets into the compressor. As ambient conditions change, so does the amount of charge required in the system. The accumulator provides a place for the excess liquid charge to accumulate. For the accumulator to function properly, it must provide two important features. It must allow adequate vapor flow to the compressor at all load conditions, and it must allow adequate oil return to the compressor. The inlet is high in the accumulator chamber. The outlet is a U-tube that comes from the top of the chamber down to the bottom and back up and out the top. Oil in the accumulator will settle to the bottom of the chamber. Oil return holes in the suction return U-tube pick up the oil from the bottom of the chamber and return it in the vapor to the compressor. Because of the wide changes in charge requirements for heat pump systems, heat pumps have accumulators.

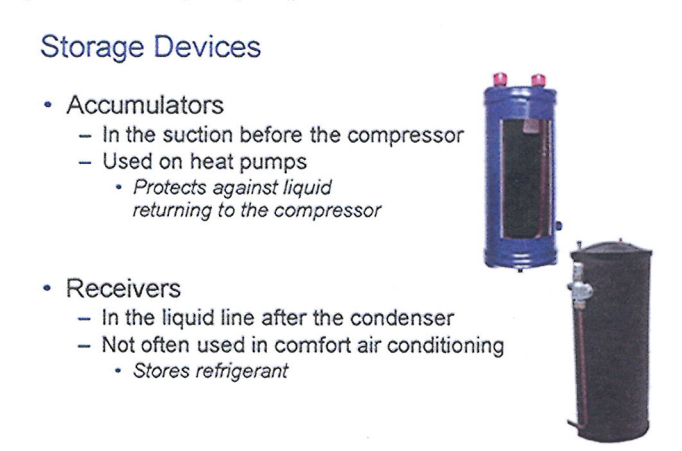


Figure 35

Refrigerant Storage Devices

The second type of storage device is a receiver. Receivers are located in the liquid line after the condenser. The function of the receiver is to hold liquid refrigerant during operation. Receivers are used on most low-temperature refrigeration systems but are not recommended for use in air conditioning-duty equipment. In comfort cooling applications, the range of operating temperature is limited compared to low-temperature refrigeration, and it is desirable to limit the system liquid charge. Because of this, the use of receivers is discouraged.

Performance Devices

Three devices are sometimes used to improve system performance in a mechanical refrigeration system. These are desuperheaters, subcoolers, and economizers.

A desuperheater is a heat exchanger located in the hot gas line. Water for domestic or process hot water requirements is circulated through the desuperheater, picking up some of the heat from the compressor discharge and doing a portion of the work normally done by the condenser. This essentially uses wasted heat to handle a supplemental load and improves condenser system efficiency. These are common on some water source heat pump units. These may be a brazed plate style heat exchanger or a tube-in-tube style.

A subcooler is a heat exchanger located in the liquid line after the condenser to provide additional subcooling. Cold water is circulated through the heat exchanger picking up heat from the liquid refrigerant. The additional subcooling improves system efficiency since it reduces flash gas. These heat exchangers may also be brazed plate, shell, or tube-in-tube.

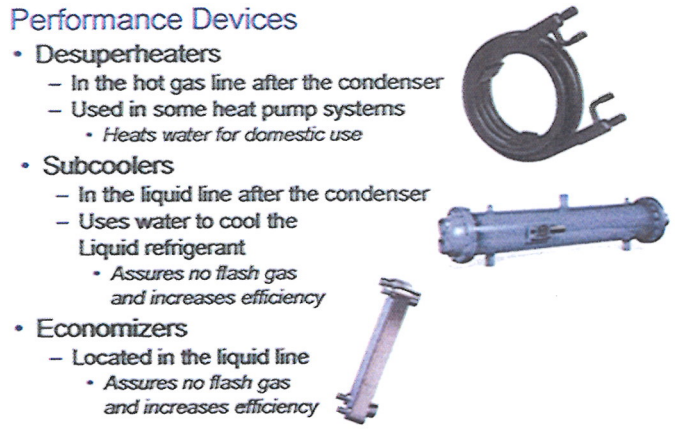


Figure 36

Devices that enhance refrigeration system performance.

The third device is an economizer. The economizer is a heat exchanger located in the liquid line that expands a small amount of refrigerant at an intermediate point between the saturated suction and condensing temperature and uses this to cool the remaining refrigerant. This reduces the amount of flash gas and improves overall unit performance. This system is used primarily with low-temperature refrigeration systems. Economizers are also used on some multi-stage centrifugal compressors.

The performance of these three devices is explained with the p-h diagram in TDP-401, Principles of Mechanical Refrigeration, Level 2: Analysis.

System Pressure Regulators

Refrigeration systems may employ pressure regulators to control system operation by maintaining or limiting pressure at points in the refrigeration cycle. Four types of pressure regulators are used: upstream, downstream, hot gas bypass, and head pressure control.

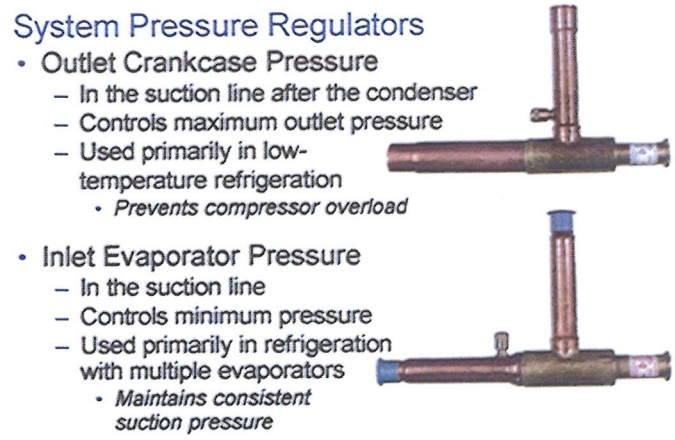


Figure 37

Refrigerant Pressure Regulators

Upstream pressure regulators are used to keep the evaporator temperature above some minimum level by limiting the pressure to a predetermined minimum. These regulators are typically located in the suction line after the evaporator. Typical uses are for multiple evaporators on the same compressor, a situation encountered in low-temperature refrigeration. For example, a system where refrigeration cases are to be kept at 45° F, 20° F, and 0° F all on the same compressor system. An inlet pressure regulator will hold the pressure in each evaporator so that the temperature in each of the cases is held constant at the required pressure. These devices are also used in some chiller applications to limit the evaporator temperature in the cooler to prevent water temperatures from dropping below freezing. Other applications include frost protection on fan coils and defrost applications.

Downstream pressure regulators are primarily used to prevent compressor motor overload. The valve throttles the suction gas flow during high load conditions limiting the current draw of the compressor. These are located in the suction line before the compressor suction.

Air-cooled condensers require a minimum condensing temperature for year round operation. As the ambient temperature drops, the condenser becomes more effective and the saturated condensing temperature drops.

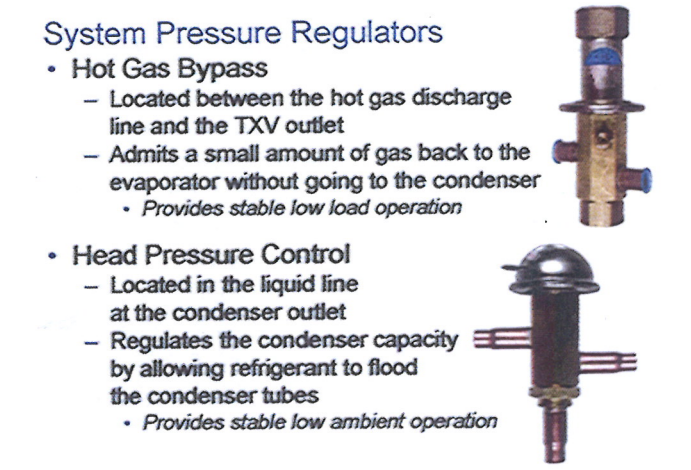


Figure 38

Hot Gas Bypass and Head Pressure Control Regulators

A minimum condensing pressure needs to be maintained to:

- Maintain liquid subcooling and prevent liquid line flashing.
- Provide adequate pressure to the TXV such that adequate pressure drop is present across the valve.
- Provide proper pressure for systems operating with hot gas bypass or hot gas defrost.
- Provide adequate temperatures for heat reclaim systems.

Head pressure control valves function to maintain the required condensing pressure by by-passing discharge gas to the receiver and reducing liquid flow from the condenser. These pressure valve systems may use a combination of inlet and outlet pressure regulators and 3-way bypass regulators. Head pressure control valves are also used with heat reclaim coils where the hot gas is diverted to a coil, which provides some heating or humidity control with condenser heat that would normally be rejected.

The other common application of pressure regulators is hot gas bypass. The hot gas bypass valve allows a small amount of vapor from the hot gas line from the compressor to be injected into the evaporator coil directly after the TXV. This is done to allow the unit to operate at reduced loads. In units without sufficient steps of unloading or no unloading, it allows operation to lower steps of capacity.

These devices are covered in greater detail in TDP-403, Expansion Devices and Refrigeration Specialties.

Valves

Refrigeration systems also use a number of valves to control flow, protect the system, or help in unit servicing. These can be described as hand valves which are used for service, solenoid valves used for flow control during operation, check valves to control flow in one direction only, and relief valves used to protect the system from excessive pressures.

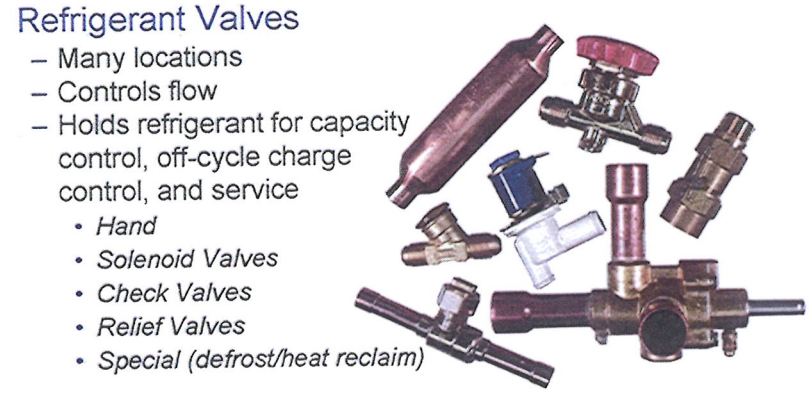


Figure 39

Refrigerant Valves Types

Temperature and Pressure Controls

Refrigeration systems may also require a number of pressure and temperature activated switches that are used to control the system or to protect it from undesirable operating conditions. Pressure switches are commonly used for high-pressure protection on the compressor discharge, and for low pressure or loss of charge protection on the suction. Temperature switches are used for protection on the hot gas or compressor discharge to protect from excessive superheat, and on the evaporator to protect from frost build up on the evaporator. Other pressure and temperature controls may be used to control operation by maintaining a refrigerant temperature or pressure. Some examples are: control of condenser pressure for head pressure control, and control of evaporator case temperature at a constant saturated suction. Oil pressure control may also be used on some units to protect against loss of compressor oil.

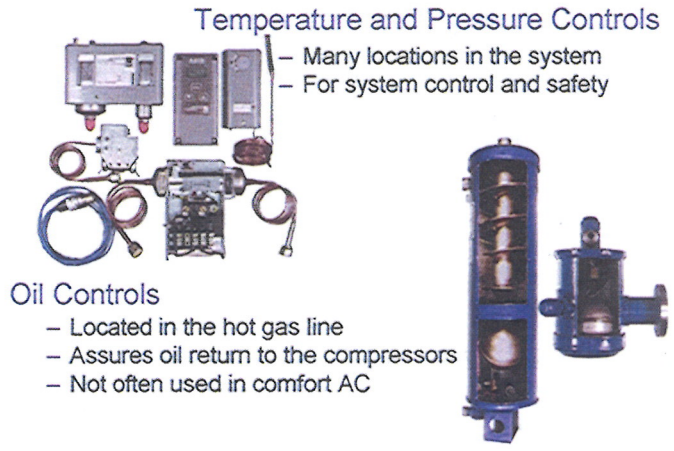


Figure 40

Refrigerant Control, System and Oil

The final component that may be encountered in a refrigeration system is an oil control system. On low-temperature refrigeration systems, too much oil may be in circulation and be pulled from the compressor crankcase. To be sure the oil is returned, an oil separator removes oil from circulation so it can be returned to the compressor.

All the components described in the refrigerant cycle accessories section are covered in greater detail in TDP-403, Expansion Devices and Refrigeration Specialties.

Reverse Cycle Heat Pump

A refrigeration cycle serves to move heat from a low temperature to a higher temperature. When the purpose is that of cooling to a lower temperature, it is referred to as the refrigeration cycle. However, the same cycle can be used to take heat from a source at a low temperature and deliver it at a higher temperature where it can be used for heating. When its purpose is that of heating, it is referred to as a heat pump or reverse cycle system.

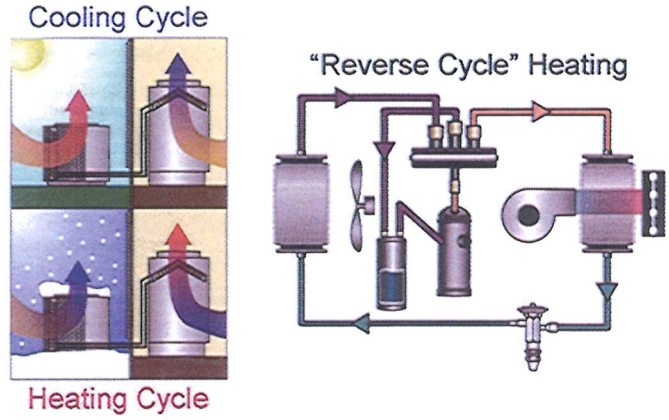


Figure 41

Reverse Cycle Heat Pump

The fluid used for the condenser and the evaporator may be water or air. Units that use air for the condensing and evaporator fluid are called air-to-air heat pumps and units which use air for the evaporator and water for the condensing fluid are water-to-air or water source heat pumps. Other types of systems are also used, for example, water-to-water. The most common type in use today, the air-to-air heat pump, has become popular for residential applications in some parts of the country since the same unit provides heating and cooling.

The feature that most distinguishes a heat pump from the typical refrigeration system we have discussed so far is that it is reversible. This allows the same unit to provide cooling in summer and heating in winter; also at a relatively efficient level. A reversing valve is provided which switches the compressor discharge from the outdoor coil in cooling to the indoor coil in heating.

As was pointed out before, air contains heat down to absolute zero so we can always "cool" it a little more, raising its temperature in the refrigeration process and gaining some heating benefit. In reality this process works best at outside temperatures from the room temperature down to about 32° F. Below 32° F, the moisture in the outdoor air begins to freeze on the outdoor coil and the unit requires a means of eliminating the frost build-up on the coil which, otherwise will become blocked, greatly impeding heat transfer. A means of defrost is provided to overcome this situation. This is usually accomplished by switching the unit back into cooling to use the outdoor coil as a condenser again to remove the frost by melting it. This of course means that the indoor coil is in cooling removing a portion of the condenser heat just added. At some point, the heat added to the space from the heat pump and removed by defrost does not provide adequate heat for the space. In that case, electric heaters may supplement the heat pump capacity.

The components required for a heat pump are much the same as for a traditional air conditioning unit. The same four basic components are used, however, the function of the coils is reversible and the same coils must function as both evaporator and condenser. To allow the operation to be reversed, a reversing valve is added to the basic components. Also to help control the wide range of required refrigerant charge encountered with heat pumps, a storage device called an accumulator (as discussed previously) is used.

A heat pump system has the same four basic components but adds a Reversing Valve and Accumulator

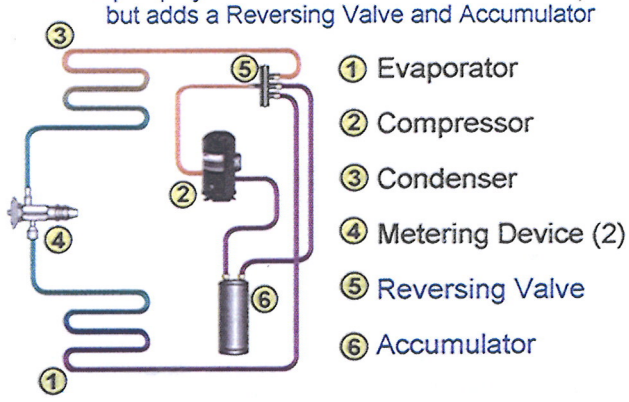


Figure 42

Heat Pump Components

During the cooling cycle, hot gas from the compressor discharge is directed to the outdoor coil by the reversing valve. Here, the hot gas is condensed into liquid as the gas gives up heat to the colder air passing over the coil. Liquid refrigerant then passes through a metering device that causes a drop in its pressure and temperature. The cold liquid-vapor mixture then enters the indoor coil where it evaporates. During evaporation, heat is removed from the warmer indoor air as it passes over the coil. The indoor air is thus cooled to condition the space. The cool refrigerant vapor is then directed to the accumulator where any unevaporated liquid refrigerant is trapped. Cool refrigerant vapor is then drawn into the compressor where its temperature and pressure are increased so the cycle can complete itself.

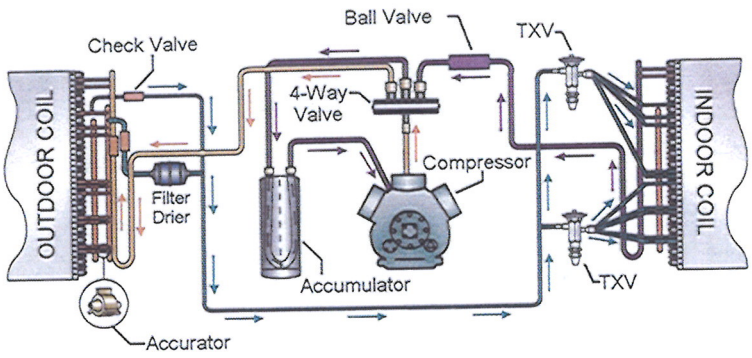


Figure 43

Heat Pump in Cooling Mode

When heat is required, the reversing valve is repositioned. The hot compressor discharge gas is now directed by the reversing valve to the indoor coil, which will act as a condenser. Air is then heated as it passes over the indoor coil and heats the space. Liquid refrigerant now flows in the opposite direction through the metering device to the outdoor coil that now acts as the evaporator. Heat is extracted from the outdoor air as it passes over the coil as the cold liquid refrigerant evaporates. The cold vapor then is drawn through the reversing valve into the accumulator where again liquid refrigerant is trapped. Vapor is drawn from the accumulator into the compressor and the cycle repeats itself.

In reversing the system from heating to cooling, some of the traditional components must have special features to allow for reverse flow. For example, the metering device must be capable of metering flow in both directions. When piston style metering is used, a specially designed orifice is used that allows bi-directional flow. With TXVs, it is common practice to locate an expansion device on both the indoor and outdoor coil. When refrigerant flow is in the opposite direction, either specially designed bi-directional flow valves are used or a bypass around the TXV with a check valve is used.

In addition to the reversing valve and metering devices, there are other design considerations that make the heat pump different from the conventional air conditioning unit. The compressor is specially designed to operate over the wide range of compressor ratios encountered in the heating mode. Both the indoor and outdoor coils are specially designed because they must both evaporate and condense refrigerant. For example, the indoor coil, when acting as a condenser in the heating cycle, must have more than normal surface area to keep the condensing temperature at reasonable levels. Further, most heat pumps are equipped with a suction line accumulator to prevent liquid from reaching the compressor, particularly in the defrost mode of operation. Finally, heat pumps are equipped with crankcase heaters on the compressor.

In the second module of this TDP series, the performance of heat pumps is described on the p-h diagram and the performance factors are calculated. Additional information on reverse cycle units can be found in the TDP-405, Reverse Cycle Refrigeration.

Refrigerants

Water as a Refrigerant

The four general principles of refrigeration were introduced at the beginning of this module using water as the volatile fluid or refrigerant. Actually, water has several desirable properties as a refrigerant. It is low in cost, readily available, and it is entirely safe, being non-toxic and non-flammable; it also has a large heat of vaporization. Although water is used as the refrigerant in steam-jet and in absorption refrigeration machines, it is not a practical refrigerant for a mechanical vapor compression refrigeration cycle.

Water has been used to explain many of the concepts already introduced.

Is water a good refrigerant?

Positive	Negative
• Non-toxic	• Low coefficient of performance
• Non-flammable	• High boiling and freezing point
• No Ozone Depletion Potential (ODP) or Global Warming Potential (GWP)	• Poor oil compatibility
• Abundant	• Potential for corrosive action
• Low cost	• Low pressure and leak potential
• Stable	
• High heat of vaporization	

Water is the refrigerant used in absorption chillers.

Figure 44

The pros and cons of using water as a refrigerant.

At standard atmospheric pressures water is limited to a minimum temperature of 32° F, for below this, the water freezes. To obtain water cool enough for most air conditioning purposes would require operating at extremely low pressures or high vacuums, which are difficult to obtain with positive displacement compression equipment. The specific volume of water vapor is large at the low pressures required, and such volumes are impractical with positive displacement machines, and centrifugal compressors are unable to maintain the required vacuum.

Therefore, it is desirable to use other volatile fluids whose overall characteristics and properties make them more practical for a particular purpose.

Desirable Characteristics

Commercially used refrigerants should have certain desirable characteristics. The following are among the more important ones, and their order of importance varies, depending on use and on the specific requirements of the application.

One of the most important considerations is that the refrigerant needs to be chemically stable over the operating range of pressures and temperatures where it will be applied.

Safe • Efficient • Stable • Cost Effective • Compatible

1. Non-toxic and non-flammable
2. Reasonable operating pressures
3. Leakage resistance
4. Large heat of vaporization
5. Relatively low specific volume
6. Low liquid specific heat (reduced flash gas)
7. Easy to detect leaks
8. Compatible with oils (vapor side)
9. High coefficient of heat transfer
10. Easy to handle and cost effective
11. Non-corrosive and chemically stable
12. Environmentally sound

Figure 45

Characteristics that are desirable in a refrigerant.

The refrigerant needs to be safe, particularly since the refrigerant may be able to leak into an occupied space. ASHRAE Standard 15 defines limits on the use and safety precautions to be taken with different refrigerants. To be safe, the refrigerant should be non-flammable and non-toxic.

A good refrigerant is:

- **Safe (toxicity and flammability)**
- **Efficient**
- **Stable**
- **Cost effective**
- **Compatible**

The pressures corresponding to the saturation temperatures available with normal condensing fluids should not be excessive, so as to eliminate the need for extremely heavy construction.

The pressures corresponding to the saturated suction temperatures required for most air conditioning and refrigeration processes should be above atmospheric pressure to avoid inward leakage of air and water vapor. Air and water vapor brought into the system degrade performance and are a potential corrosion problem.

A relatively large heat of vaporization is desirable so that the required capacities can be obtained with the smallest mass flow of refrigerant.

The vapor should have a relatively low specific volume, as this volume establishes the required size or displacement of the compressor. This property is more important to the positive displacement compressor than it is to the centrifugal machine, which is inherently a large volume, low-pressure pump.

The refrigerant should have a low specific heat in the liquid state so that less heat will be required to cool the liquid from the condensing temperature down to the evaporation temperature. The heat required for this cooling results in "flash gas," and subtracts from the refrigeration effect or cooling capacity of the refrigerant circulated.

The refrigerant should be easily detected by leak detection equipment to locate leaks in the system.

The refrigerant should be compatible with compressor lubricants and oils, and should not detract from their effectiveness as lubricants. The refrigerant and oil also need to miscible, particularly in the refrigerant vapor phase, so that oil in circulation in the system is returned to the compressor.

The coefficients of heat transfer should be conducive to good heat transfer rates. The refrigerant should also have low viscosity to minimize pumping losses.

The refrigerant should be readily available, low in cost, and easily handled.

The refrigerant should be non-corrosive to the metals usually employed in a hermetic refrigeration system and compatible with the materials used for gaskets and in hermetic motor construction.

The refrigerant should be environmentally sound. It has been determined that when refrigerants containing the chlorine atom are released into the atmosphere they tend to breakdown the earth's natural ozone layer. This ozone forms a protective layer to shield us from the sun's UV rays. Different refrigerants also impact the amount of greenhouse gas produced from their use and need to be evaluated on their global warming potential.

The best choice of a refrigerant should be one that is safe, efficient, stable, cost effective, and compatible.

Refrigerant Choices

There is not a perfect refrigerant that meets all of the criteria described; selecting a refrigerant is a compromise. There are a limited number of substances that can be used as a refrigerant. These could be divided into two broad classes, organic compounds and inorganic compounds.

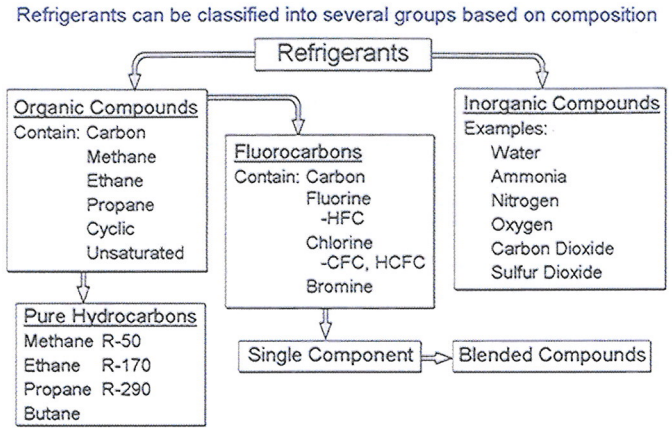


Figure 46

Classes of Refrigerants

Inorganic compounds are compounds like water, which we have used for a large portion of our text. Some of the others are the refrigerants used for many of the early refrigeration systems like carbon dioxide, and ammonia. Ammonia is still used extensively in low-temperature refrigeration work. These refrigerants do not present a safety risk as far as flammability is concerned; but, like ammonia, they do have toxicity issues and corrosion potential issues. As we explained earlier, water is used as a refrigerant but is a poor choice for the vapor compression cycle. Some inorganic compounds, like carbon dioxide, require extremely high pressures. While still used in some applications, these factors have limited the use of inorganic refrigerants in favor of organic substances.

Organic refrigerants contain carbon. The organic group can be divided into two, pure hydrocarbons and fluorocarbons. The pure hydrocarbons are refrigerants like methane, also called natural gas, ethane, propane, and butane. These may be recognized as the ones used for a number of combustion applications, like propane and methane for heating and butane for lighters. This group of refrigerants is all flammable. Though readily available, the flammability issue has limited their use. However, because of the trend away from fluorocarbon refrigerants for environmental reasons, this group of refrigerants is seeing renewed interest. Current technology is to use these in sealed systems limiting the amount of refrigerant, and to use them to cool a secondary fluid to be circulated to the actual load, in much the same way a chilled water chiller operates.

That leaves the choice of refrigerants to the fluorocarbons. This group of refrigerants consists of the ones that contain fluorine, chlorine, or bromine along with the carbon atom. Depending on the amount of chlorine and fluorine, these refrigerants are commonly called CFC, HCFC, and HFC.

Fluorocarbon Refrigerants

The group of fluorocarbon refrigerants has two categories of refrigerants, single element compounds and blends of single element compounds.

The single element refrigerants consist of a carbon atom bonded to one or more of the fluorine, chlorine, or bromine atoms. Refrigerants such as R-11 and R-12 contain both chlorine and fluorine and are referred to as CFC. These refrigerants have a high concentration of the chlorine atom. Refrigerants like R-22 and R-123a also contain the chlorine atom but in a smaller concentration than CFCs. These refrigerants are HCFCs. Refrigerants like R-134a contain fluorine and no chlorine atoms and are called HFCs.

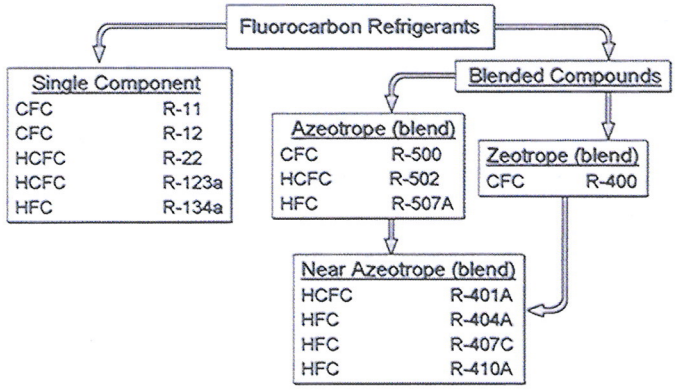


Figure 47

Fluorocarbon Refrigerants

Fluorocarbons

CFC – chlorofluorocarbon, contains both chlorine and fluorine along with carbon, have the most chlorine, and were the first phased out. Examples are: R-11, R-12, and R-500

HCFC – hydrochlorofluorocarbons, contain both chlorine and fluorine along with the carbon atom, have less chlorine and are being phased out on a longer schedule. Examples are: R-22, R-502, and R-123a

HFC – hydrofluorocarbons contain fluorine but no chlorine. These are the choices for the future. Examples are: R-134a, R-410A, R-404A

To develop refrigerants that have more desirable properties, the single component refrigerants are mixed or "blended" in varying proportions. This mixing is done to achieve a mixture of refrigerants that has the required heat transfer properties for an application. In blended refrigerants, the refrigerants do not chemically bond; each of the refrigerants retains it own properties. Like a mix of oil and water, these refrigerants can be separated back to their original refrigerant.

The blended refrigerants are classified into two groups depending on how closely the blend behaves like a single element refrigerant. Refrigerants that act like a single compound refrigerant are called azeotropic blends. Refrigerants that vary from the performance of a single element compound are called zeotropic blends. Zeotropic blends that act much like a single compound are called near azeotrope. In zeotropic blends, the refrigerants have different saturated liquid and saturated vapor boiling points due to the influences of the different refrigerants. This phenomena, referred to as glide, results in different pressure/temperature saturated conditions in the liquid and vapor phases. The liquid-saturated condition is called bubble point and the vapor-saturated condition is called dew point.

Blended refrigerants can be CFCs like R-500 or HCFCs like R-502 or HFCs like R-404A, R-407C and R-410A. Refrigerants R-404A and R-410A are near azeotropic refrigerants.

Research has indicated that refrigerants containing chlorine are major contributors to the breakdown of the earth's natural ozone layer. As a result, world's communities have established a phase out of chlorine based refrigerants. The CFC refrigerants are currently banned from new unit production and replacement refrigerant for existing machines is being ramped down to force their eventual replacement. The HCFC have less chlorine and are also being phased-out but on a longer schedule.

Additional information on refrigerants can be found in TDP-402, Refrigerants.

Common Refrigerants

With phase out and performance issues, what are the refrigerants of choice?

Refrigerant R-22 is one of the most commonly used refrigerants in vapor compression equipment today, but its use is being phased out because of environmental concerns. For long-term choices, R-134a is becoming the choice for chiller and mobile applications. R-410A and R-407C are becoming the choices for packaged units and residential and commercial split system units. Refrigerant R-404A is the choice for low-temperature refrigeration.

Summary

In this module the four principles that explain how mechanical refrigeration works have been described. The principles were applied through four basic system components to have a cycle that could use a volatile fluid and *"and bringing them again and again into operation without waste."* The components of the refrigeration systems have been described, including how the system can be used for cooling and for heating. The location and basic function of the refrigeration specialty components sometimes applied with a refrigeration system were identified. In addition, the terms associated with vapor compression refrigeration have been described.

In the next module (TDP-401, Principles of Mechanical Refrigeration, Level 2: Analysis) the components will be described with the use of the pressure-enthalpy diagram. This will allow the calculation of the performance, selection, and evaluation of operation of each component of the system. The p-h diagram will also be used to show the impacts of various system options and of design operation. A good understanding of these issues will allow a designer to understand the impact design decisions have on system performance.

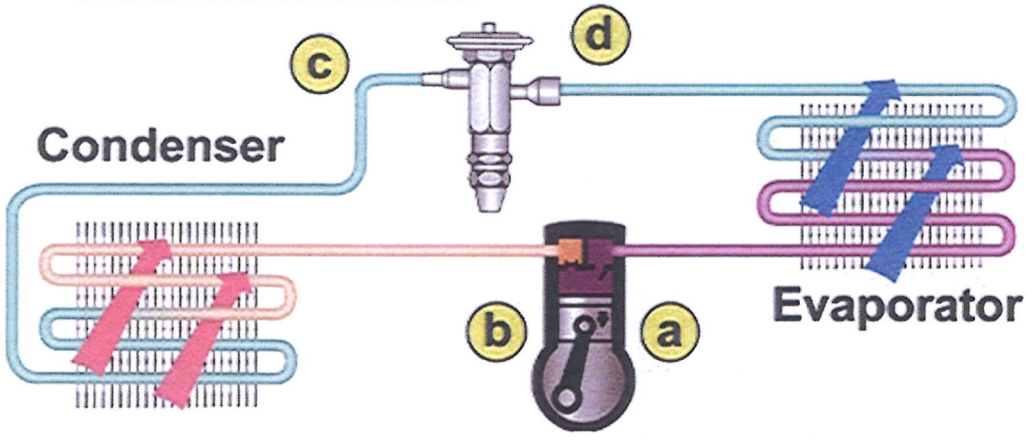
Before proceeding to the next module, Mechanical Refrigeration, Level 2: Analysis, it is a good time to review the material presented in this module. A work session is provided to check your understanding of the material.

Work Session

1. How many Btu are required for each of the following (assume sea level):
   a. Heat 1 pound of water from 60° F to 80° F? _____
   b. Cool 2 pounds of water from 95° F to 85° F? _____
   c. Heat 5 pounds of water from 40° F to 280° F? _____
   d. Cool 2 pounds of water from 40° F to 32° F ice? _____
   e. Heat 1 pound of ice at 32° F to steam at 212° F? _____

2. What is the warmest temperature the refrigerant can be to maintain a deli case cooler at 22° F? _____

3. Identify on the chart below the relative temperature and liquid or vapor condition of the refrigerant at each of the following points.
   a. _____
   b. _____
   c. _____
   d. _____



4. Explain the terms superheat and subcooling?
   a. _____
   b. _____

5. Identify each of the refrigerants as CFC, HCFC, HFC, pure hydrocarbon, inorganic or not a refrigerant

   a. Carbon Dioxide _____
   b. R-410A _____
   c. R-11 _____
   d. R-718 _____
   e. Ammonia _____
   f. R-22 _____
   g. R-123a _____
   h. R-134a _____
   i. Water _____

6. The four principles which can explain how the mechanical refrigeration cycle operate are:

   a. _____
   b. _____
   c. _____
   d. _____

7. List the four components every mechanical refrigeration cycle must contain to be a continuous process:

   a. _____
   b. _____
   c. _____
   d. _____

8. Explain azeotropic, zeotropic, and near azeotropic refrigerants

   _____
   _____
   _____

9. What are the key differences required for a system to operate as a heat pump?

_____

_____

10. Identify the refrigerant line each of the following components is located in:
    a. Accumulator _____
    b. Receiver _____
    c. Moisture-liquid indicator _____
    d. Filter-drier _____
    e. Muffler _____
    f. Head pressure control valve _____

11. What are the two key methods of heat transfer used in mechanical refrigeration?
    a. _____
    b. _____

12. Describe why the temperature of the vapor entering the compressor does not match the saturation temperature at the compressor? _____

_____

13. The _____ molecule in refrigerants is responsible for the breakdown of the earth's protective ozone layer.

14. Describe the terms
    a. Flash gas _____
    b. Heat of compression _____
    c. Enthalpy _____
    d. Desuperheating _____

15. True or False? A thermometer can measure the total heat quantity in a vapor? _____

Notes

Notes

Appendix

Work Session Answers

1.

a. 20 Btu $(80 - 60) * 1$
b. 20 Btu $(95 - 85) * 2$
c. 5740.6 Btu $((212 - 40) * 5) + (970 * 5) + ((240 - 212) * .45 * 5)$
d. 304 Btu $((40 - 32) * 2) + (144 * 2)$
e. 1294 Btu $((144 * 1) * 2) + ((212 - 32) * 1) + (970 * 1)$
ice water vapor

2. Temperature must be less than 22° F

3.

a. cold superheated vapor
b. hot highly superheated vapor
c. warm subcooled liquid
d. cold liquid / vapor mix

4.

a. Superheat is heat added above the saturated vapor temperature
b. Subcooling is temperature below the saturated liquid temperature

5.

a. inorganic
b. HFC
c. CFC
d. Inorganic (water)
e. Inorganic
f. HCFC
g. HCFC
h. HFC
i. Inorganic

6.

a. Heat will only flow from a higher temperature to a lower temperature
b. The greatest heat energy is in a change of state
c. Temperature is a function of pressure
d. Flow only occurs if a pressure difference exists

7.

a. Evaporator – (heat absorber)
b. Compressor – (vapor pump)
c. Condenser – (heat rejecter)
d. Metering device – (pressure reducing valve)

8.
   a. Azeotropic – mix or blend of refrigerants where the mixture does not act as a single refrigerant.
   b. Zeotropic – mixture of refrigerants where the mixture acts like a single refrigerant
   c. Near azeotropic – zeotropic blend of refrigerants which approaches being like a azeotropic blend

9. A heat pump needs an accumulator, reversing valve, bi-flow expansion valves, special coil circuiting, special compressor, and crankcase heater on the compressor.

10.
   a. Suction line before the compressor
   b. Liquid line after the condenser
   c. Liquid line before the metering device
   d. Liquid line before the metering device
   e. Hot gas line after the compressor
   f. Liquid line after the condenser

11.
   a. Conduction, i.e. transfer of heat from refrigerant to tube
   b. Convection, both natural and forced, i.e. transfer of heat from the evaporator coil to the air

12. The vapor is superheated to prevent liquid refrigerant from entering the compressor

13. Chlorine

14.
   a. Flash gas is the small part of the refrigerant which changes to a vapor at the expansion valve and cools the rest of the refrigerant
   b. Heat of compression is the work (heat energy) put in by the compressor in raising the pressure of the vapor above the saturated condensing temperature
   c. Enthalpy is total heat content and is the sum of sensible and latent heat
   d. Desuperheating is the process of removing the superheat from the vapor to the saturated vapor temperature. This heat in the condenser is the superheat added in the evaporator and the heat of compression.

15. False. A thermometer can only measure sensible heat, not total heat.

Prerequisites:

None, however, a basic understanding of the concepts of comfort air conditioning is recommended and is provided in TDP-102, ABCs of Comfort, Cat. No. 796-026.

Learning Objectives:

At the conclusion of this module, participants will be able to:

- Identify the terms commonly used to describe the mechanical refrigeration process.
- List the four basic principles that are applied in a mechanical refrigeration cycle.
- Describe the methods of heat transfer used in the refrigeration cycle.
- Describe the functions of the four parts of refrigeration systems.
- Explain the characteristics required of a refrigerant.
- Describe the location and use of refrigerant specialty components.
- Explain the operational principle of a heat pump.

Supplemental Material:

Form No.	Book Cat. No.	Instructor CD Cat. No.	Title
TDP-401	796-084	797-084	Principles of Mechanical Refrigeration, Level 2: Analysis
TDP-402	796-038	797-038	Refrigerants
TDP-403	796-039	797-039	Expansion Devices and Refrigeration Specialties
TDP-405	796-041	797-041	Reverse Cycle Refrigeration
TDP-501	796-042	797-042	Refrigerant Piping

Instructor Information:

Each TDP topic is supported with a number of different items to meet the specific needs of the user. Instructor materials consist of a CD-ROM disk that includes a PowerPoint™ presentation with convenient links to all required support materials required for the topic. This always includes: slides, presenter notes, text file including work sessions and work session solutions, quiz and quiz answers. Depending upon the topic, the instructor CD may also include sound, video, spreadsheets, forms, or other material required to present a complete class. Self-study or student material consists of a text including work sessions and work session answers, and may also include forms, worksheets, calculators, etc.



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Supersedes Cat. No. 791-108