Consortium for Educational Communication

Module on

Refrigeration

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INTRODUCTION:

Refrigeration or cold storage of food is a gentle method of food preservation. It involves removal of heat from food products so that their temperature is first lowered, and then maintained at low temperature compared to that of the surroundings. The preservation of food by refrigeration is based on a very general principle in physical chemistry: molecular mobility is depressed and consequently chemical reactions and biological processes are slowed down at low temperature. Temperature plays an important role in maintaining the quality of stored food products. Lowering the temperature retards the rates of reactions that cause quality deterioration. It is generally agreed that the reaction rate is reduced by half by lowering the temperature by 10°C. In contrast to heat treatment, low temperature practically does not destroy microorganisms or enzymes but merely depresses their activity. Therefore, refrigeration retards spoilage but it cannot improve the initial quality of the product, hence the importance of assuring particularly high microbial quality in the starting material. Refrigerated and even frozen foods have a definite shelf life, the length of which depends on the storage temperature.

Maintaining temperatures lower than ambient inside a system requires both the removal of heat and prevention of incursion of heat through the system's boundaries. The rate of heat removal from a system necessary to maintain the temperature is the refrigeration load. Refrigeration systems allow transfer of heat from the cooling chamber to a location where the heat can easily be discarded. The transfer of heat is accomplished by using a refrigerant, which like water changes state from liquid to vapor.

1. UNIT OF REFRIGERATION:

Since refrigeration is based on the rate of removal of heat, the unit of refrigeration effect is watt (W) or kilowatt (kW). The standard unit of refrigeration is ton of refrigeration denoted as TR. One TR is equivalent to the production of cold at the rate at which heat is to be removed from one ton of water at 0°C in 24 hours. One ton = 2000lb, and latent heat of fusion of ice = 144 Btu[1]/lb.

Thus, $1TR = \frac{1x\ 2000\ lb\ x\ 144\ Btu/lb}{24\ h}$

= 12,000 Btu/h = 200 Btu/min

But, 1 Btu = 1,055 kJ

1 TR = 211 kJ/min = 3.516 kW

2. REFRIGERATION SYSTEMS:

Refrigeration systems could be grouped into the following three systems:

i. Non-cyclic refrigeration systems: These systems include ice refrigeration, refrigeration by evaporation, and refrigeration by dry ice. These systems were used before the invention of cyclic refrigeration systems.

ii. Cyclic refrigeration systems: These include the air refrigeration cycle, vapor compression refrigeration cycle, and vapor absorption cycle.

iii. Other refrigeration systems: These are thermoelectric refrigeration cycle, steam-jet refrigeration cycle, vortex tube refrigeration system etc.

3. MECHANICAL REFRIGERATION:

3.1 Principle of Operation:

Mechanical refrigeration systems are based on the operation of a simple heat pump working on the compression of vapor. The second law of thermodynamics mandates that heat will flow only in the direction of decreasing temperature. In a system that must be maintained at a temperature below ambient, heat must be made to flow in the opposite direction. A refrigeration system may be considered as a pump that conveys heat from a region of low temperature to another region that is at a high temperature. The low temperature side of a refrigeration system is maintained at a lower temperature than the system it is cooling to allow spontaneous heat flow into the refrigeration system. The high temperature side must have a temperature higher than ambient to allow dissipation of the absorbed heat to the surroundings. In some instances, this absorbed heat is utilized as a heat source for use in heating processes. Maintaining a high and a low temperature in a refrigeration system is made possible by the use of a refrigerant fluid that is continuously recirculated through the system. A liquid's boiling or condensation temperature is a function of the absolute pressure. By reducing the pressure, a low boiling temperature is made possible, allowing for absorption of heat in the form of the heat of the refrigerant's vaporization as it is vaporized at the low pressure and temperature. The vapors, when compressed to a high pressure, will condense at the high temperature and the absorbed heat will be released from the refrigerant as it condenses back into liquid at the high temperature and pressure.

4.2 Components of a Refrigeration System:

Major components of a simple mechanical vapor compression refrigeration system are shown in Figure1. As the refrigerant flows through these components its phase changes from liquid to gas and then back to liquid. The flow of refrigerant can be examined by tracing the path of the refrigerant. At location D on Figure 1, just prior to the entrance to the expansion valve, the refrigerant is in a saturated liquid state. It is at or below its condensation temperature. The expansion valve separates the high pressure region from the low-pressure region. After passing through the expansion valve, the refrigerant experiences a drop in pressure accompanied by a drop in temperature. Due to the drop in pressure some of the liquid refrigerant changes to gas. The liquid/gas mixture leaving the expansion valve is termed "flash gas". The liquid/gas mixture enters the evaporator coils at location E. In the evaporator, the refrigerant completely vaporizes to gas by accepting heat from the media surrounding the evaporator coils. The saturated vapors may reach a superheated stage due to gain of additional heat from the surroundings. The saturated or superheated vapors enter the compressor at location A, where the refrigerant is compressed to a high pressure. This high pressure must be below the critical pressure of the refrigerant and high enough to allow condensation of the refrigerant at a temperature slightly higher than that of commonly available heat sinks, such as ambient air or well water. Inside the compressor, the compression process of the vapors occurs at constant entropy (called an isentropic process). As the pressure of the refrigerant increases, the temperature increases, and the refrigerant becomes superheated as shown by location B. The superheated vapors are then conveyed to a condenser. Using either an air-cooled or a water-cooled condenser, the refrigerant discharges heat to the surrounding media. The refrigerant condenses back to the liquid state in the condenser as shown by location D. After the entire amount of refrigerant has been converted to saturated liquid, the temperature of the refrigerant may decrease below that of its condensation temperature due to additional heat discharged to the surrounding media; in other words, it may be subcooled. The subcooled or saturated liquid then enters the expansion valve and the cycle continues.

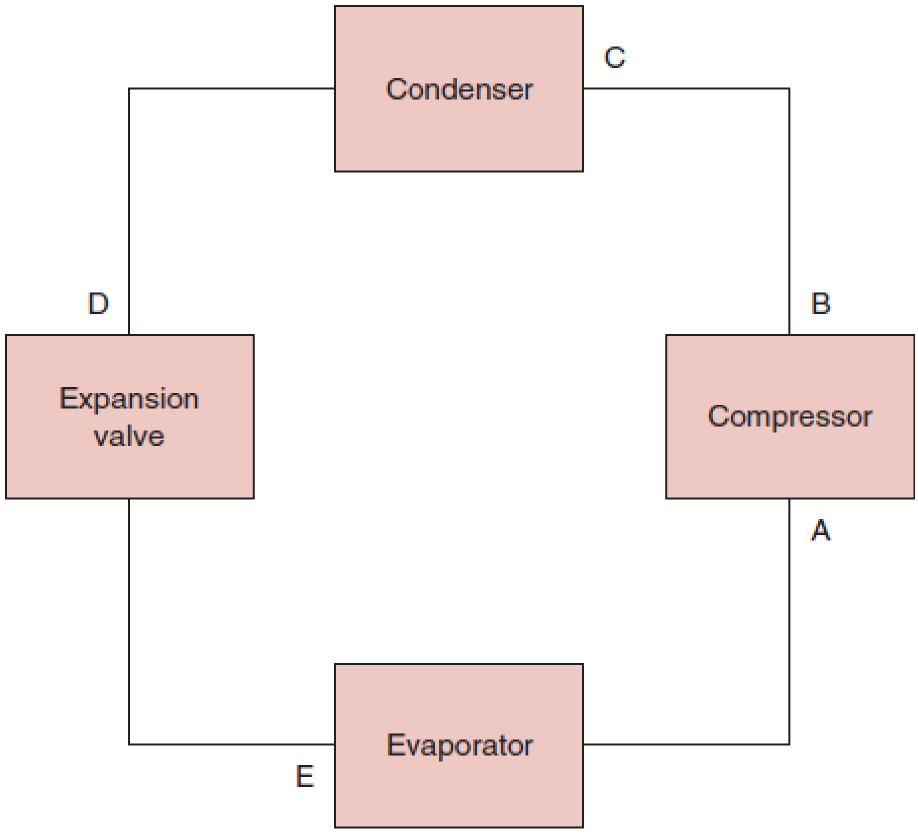


Fig 1: Schematic representation of a vapor compression system

4.2.1 Evaporator:

The evaporator forms the freezing cabinet in a plate or blast freezer and the ice box or freezing compartment of a domestic refrigerator. Refrigerant circulates through the pipework on the surface of the compartment walls or within the hollow walls and evaporates, thereby absorbing heat at a rate Q_2 (Fig 2a) from within the freezer cabinet. Evaporation will continue at a constant temperature as long as the evaporator is never allowed to run dry; in practice the system is arranged so that there is always a continuous supply of liquid refrigerant being pumped into it at a controlled rate. Inside the evaporator, the liquid refrigerant vaporizes to a gaseous state. The change of state requires latent heat, which is extracted from the surroundings. Based on their use, evaporators can be classified into two categories. *Direct-expansion* evaporators allow the refrigerant to vaporize inside the evaporator coils; the coils are in direct contact with the object or fluid being refrigerated. *Indirect-expansion* evaporators involve the use of a carrier medium, such as water or brine, which is cooled by the refrigerant vaporizing in the evaporator coils. The cooled carrier medium is then pumped to the object that is being refrigerated.

4.2.2 Compressor:

The compressor has two functions. It pumps refrigerant around the circuit by drawing the vapor out of the evaporator, compressing it and discharging it at a higher pressure into the next component of the system. Second, by running at constant speed and capacity, the compressor helps to maintain a constant pressure, and therefore a constant temperature, in the evaporator. The refrigerant enters the compressor in a vapor state at low pressure and temperature. The compressor raises the pressure and temperature of the refrigerant. It is due to this action of the compressor that heat can be discharged by the refrigerant in the condenser. The compression processes raise the temperature of the refrigerant sufficiently above the ambient temperature surrounding the condenser, so that the temperature gradient between the refrigerant and the ambient promotes the heat flow from the refrigerant to the ambient. The three common types of compressors are reciprocating, centrifugal, and rotary. As is evident from the name, the reciprocating compressor contains a piston that travels back and forth in a cylinder. The centrifugal compressor contains an impeller with several blades that turn at high speed. The rotary compressor involves a vane that rotates inside a cylinder.

4.2.3 Condenser:

To allow the refrigerant to be used over and over again it must be condensed back into a liquid. Furthermore, if the system is sealed against the ingress of air and contaminants, it will never need replacing. Therefore the condenser enables the warm refrigerant vapour to reject a quantity of heat Q_1 (Fig 2a) to a heat sink at a temperature lower than itself. For the domestic refrigerator the ambient air in a kitchen is cool enough to achieve this condensation and the condenser consists simply of an exposed length of tubing. In an industrial freezer, however, a water-cooled condenser is used. The function of the condenser in a refrigeration system is to transfer heat from the refrigerant to another medium, such as air and/or water. By rejecting heat, the gaseous refrigerant condenses to liquid inside the condenser. The major types of condensers used are (1) water-cooled, (2) aircooled, and (3) evaporative.

4.2.4 Expansion Valve:

The purpose of this valve is to control or constrict the flow of liquid refrigerant between the condenser and the evaporator and, by maintaining a pressure difference between the two components, control the evaporating pressure and temperature. The precise design of this device depends on the particular application, but in the domestic refrigerator, the constriction is often a fixed length of capillary tubing between the condenser and the evaporator. It thus forms a non-adjustable valve with a high resistance to flow because of its length and small bore. Since the capillary tube and compressor are connected in series, the flow capacity of the tube and system must equal the pumping capacity of the compressor. Once the compressor, capillary and other system equipments have been selected, the system will settle down to run at *one* particular condition. That is, the system will operate at a given mass flow rate, depending not only upon the choice of refrigerant, the compressor and the capillary tube, but also on the working temperatures (and design) of the evaporator and condenser. An expansion valve is essentially a metering device that controls the flow of liquid refrigerant to an evaporator. The valve can be operated either manually or by sensing pressure or temperature at another desired location in the refrigeration system.

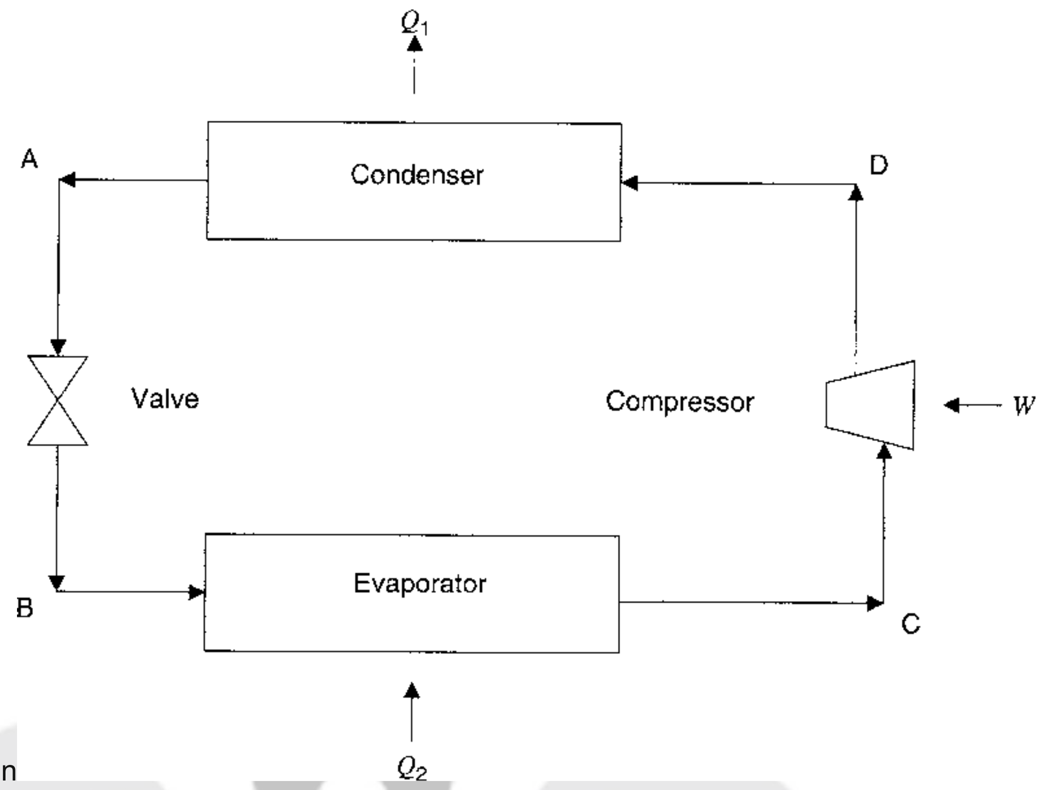
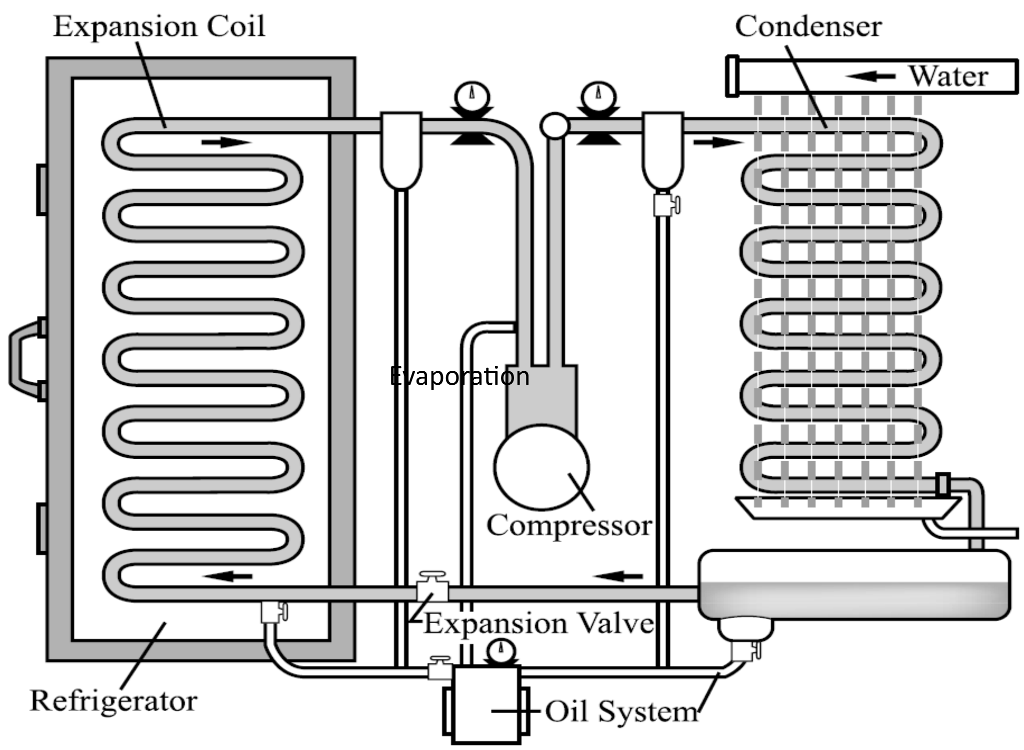


Fig 2a: Heat loss and gain in a refrigeration cycle



GURE 9.1 Compression refrigeration system.

Fig 2b: Vapor Compression Refrigeration Components

4. **THE REFRIGERANT:**

There are particular chemical, physical and thermodynamic properties that make a fluid suitable for use as a refrigerant. First, the fluid must have suitable freezing and boiling points, relative to the temperature of its surroundings, at convenient working pressures. Second, the other thermodynamic properties of the refrigerant should be chosen to give the minimum power input to the cycle. The following is a list of important characteristics that are usually considered:

1. Latent heat of vaporization: A high latent heat of vaporization is preferred. For a given capacity, a high value of latent heat of vaporization indicates that a smaller amount of refrigerant will be circulated per unit of time.

2. Condensing pressure: Excessively high condensing pressure requires considerable expenditure on heavy construction of condenser and piping.

3. Freezing temperature: The freezing temperature of the refrigerant should be below the evaporator temperature.

4. Critical temperature: The refrigerant should have sufficiently high critical temperature. At temperatures above the critical temperature, the refrigerant vapor cannot be liquefied. Particularly in case of air-cooled condensers, the critical temperature should be above the highest ambient temperature expected.

5. Toxicity: In many applications, including air conditioning systems, the refrigerant must be nontoxic.

6. Flammability: The refrigerant should be nonflammable.

7. Corrosiveness: The refrigerant should not be corrosive to the materials used in the construction of the refrigeration system.

8. Chemical stability: The refrigerant must be chemically stable.

9. Detection of leaks: If a leak develops in the refrigeration system, the detection of such a leak should be easy.

10. Cost: Low-cost refrigerant is preferred in industrial applications.

11. Environmental impact: The refrigerant released from the refrigeration systems due

to leaks should not cause environmental damage.

Ammonia, sulphur dioxide, carbon dioxide, methyl chloride and methylene chloride all have suitable characteristics and have been used as industrial refrigerants in the past; ammonia is still widely used. Ammonia offers an exceptionally high latent heat of vaporization among all other refrigerants. It is noncorrosive to iron and steel but corrodes copper, brass, and bronze. It is irritating to mucous membranes and eyes. It can be toxic at concentrations of 0.5% by volume in air. A leak in the refrigeration system that uses ammonia as a refrigerant can easily be detected either by smell or by burning sulfur candles and noting white smoke created by the ammonia vapors. However, the most extensively used refrigerants in recent years have been the chlorofluorocarbons or CFCs. The ideal refrigerant, widely used in domestic refrigerators until very recently, is dichlorodifluoromethane or R12. R12 is completely safe in that it is non-toxic, non-flammable and non-explosive. It is highly stable and is difficult to decompose even under extreme operating conditions. However, CFCs are now known to cause depletion of the ozone layer and since the Montreal Protocol of 1987 have been phased out of use. Alternatives to the CFCs are hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs). Hydrogen-containing fluorocarbons have weak carbon–hydrogen bonds, which are more susceptible to cleavage; thus, they are postulated to have shorter lifetimes.

5. PRESSURE–ENTHALPY CHARTS:

Both pressure and enthalpy of the refrigerant change as the refrigerant is conveyed through various components of a refrigeration system. In both the evaporator and the condenser, the enthalpy of the refrigerant changes and the pressure remains constant. During the compression step, work is done by the compressor, resulting in an increase in the enthalpy of the refrigerant along with an increase in pressure. The expansion valve is a constant-enthalpy process that allows the liquid refrigerant under high pressure to pass at a controlled rate into the low-pressure section of the refrigeration system.

Charts or diagrams have been used extensively in the literature to present thermodynamic properties of refrigerants. These charts are particularly useful during the early, conceptual stages of a refrigeration system design. Looking at a chart, we can easily comprehend a standard process, as well as any deviations from the standard. Most commonly used charts depict enthalpy and pressure values on the *x* and *y* axes, respectively. Another type of chart involves entropy and temperature values plotted along *x* and *y* axes, respectively. The entire refrigeration cycle comprising evaporator, compressor, condenser, and expansion valve can be conveniently depicted on the pressure–enthalpy charts.

A skeleton description of the pressure–enthalpy chart is given in Fig 3. Pressure (kPa) is plotted on a logarithmic scale on the vertical axis. The horizontal axis gives enthalpy (kJ/kg). The pressure–enthalpy chart may be divided into different regions, based on saturated liquid and saturated vapor curves. The area enclosed by the bell-shaped curve represents a two-phase region containing a mixture of both liquid and vapor refrigerant.

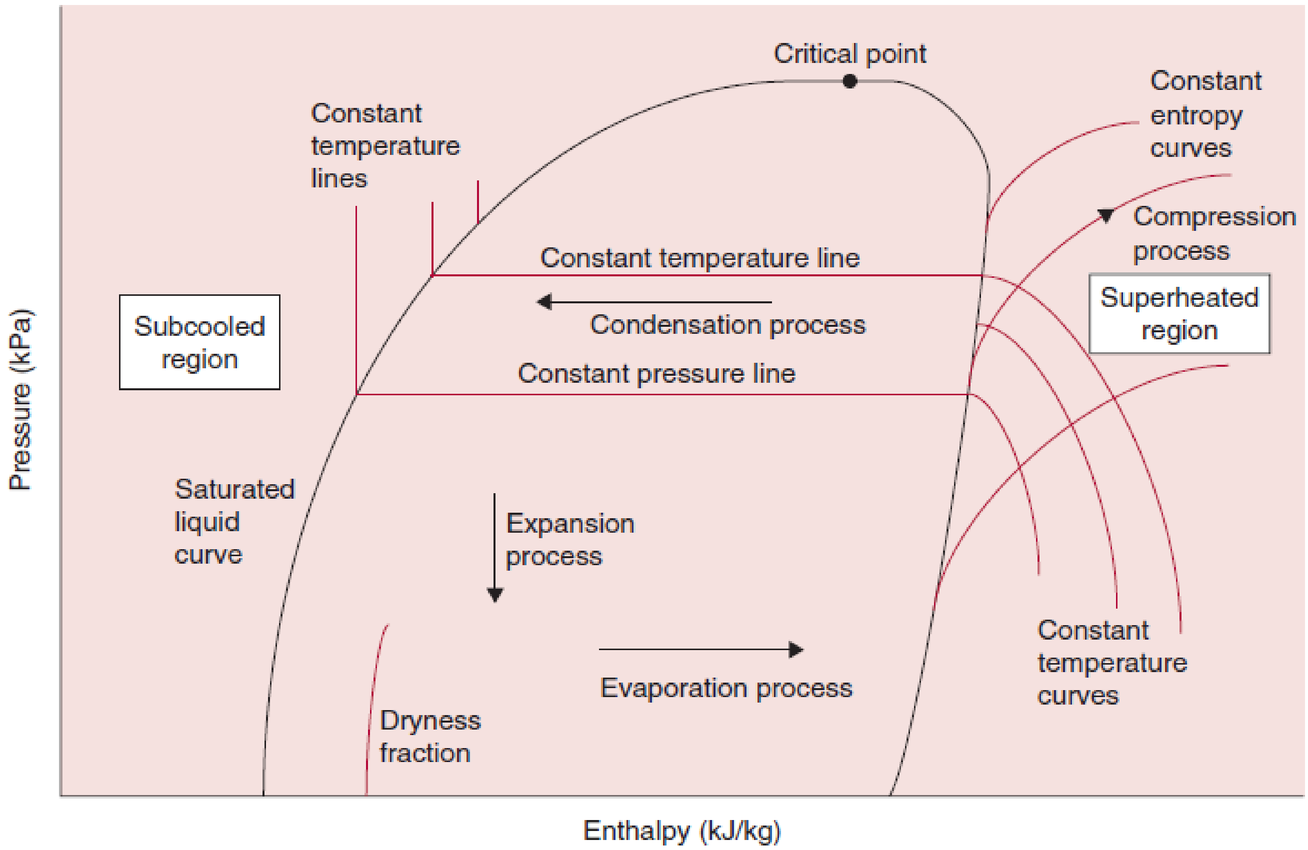


Fig 3: Pressure-enthalpy chart

The horizontal lines extending across the chart are constant-pressure lines. The temperature lines are horizontal within the bell-shaped area, vertical in the subcooled liquid region, and skewed downward in the superheated region. The area on the left-hand side of the saturated liquid curve denotes subcooled liquid refrigerant with temperatures below the saturation temperature for a corresponding pressure. The area to the right-hand side of the dry saturated vapor curve depicts the region where the refrigerant vapors are at superheated temperatures above the saturation temperature of vapor at the corresponding pressure. Within the bell-shaped curve, the dryness fraction curves are useful in determining the liquid and vapor content of the refrigerant. Let us consider a simple vapor-compression refrigeration system, where the refrigerant enters the expansion valve as saturated liquid and leaves the evaporator as saturated vapor. Such a system is shown on a pressure–enthalpy diagram in Fig 4. As dry saturated vapors enter the compressor, the condition of refrigerant is represented by location A. The refrigerant vapors are at pressure P_1 and enthalpy H_2. During the compression stroke, the vapors are compressed isoentropically (or at constant entropy) to pressure P_2 .

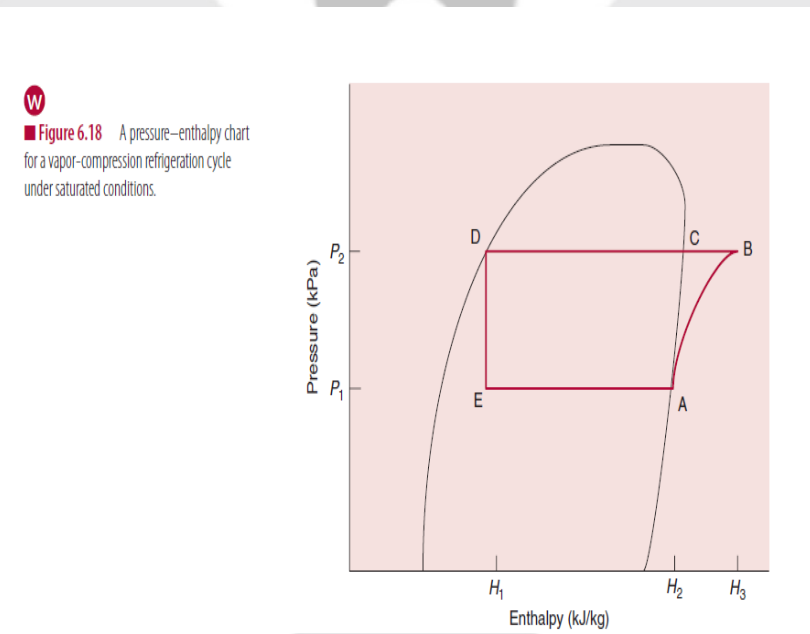


Fig 4: A pressure-enthalpy chart for a vapor-compression refrigeration cycle under saturated conditions

Location B is in the superheated vapor region. The enthalpy of the refrigerant increases from H_2 to H_3 during the compression process. In the condenser, first, the superheat is removed in the desuperheater section of the condenser, and then the latent heat of condensation is removed from C to D. The saturated liquid enters the expansion valve at location D. As refrigerant moves through the expansion valve, the pressure drops to P_1 while the enthalpy remains constant at H_1. Some flashing of the refrigerant occurs within the expansion valve; as a result, location E indicates refrigerant containing liquid as well as vapor. The liquid–vapor mix of refrigerant accepts heat in the evaporator and converts completely to the vapor phase. The evaporator section is represented by the horizontal line from location E to A; the pressure remains constant at P1 and the enthalpy of the refrigerant increases from H_1 to H_2.

7. ANALYSIS OF VAPOR-COMPRESSION REFRIGERATION

7.1 Cooling Load

The cooling load is the rate of heat energy removal from a given space (or object) in order to lower the temperature of that space (or object) to a desired level. The total amount of sensible and latent heat to be removed in cooling a product is given by:

$H = M (ca \times \Delta Ta) + h_l + (cb \times \Delta Tb)$

Where, H = total quantity of heat

M = mass of product

ca = specific heat capacity above freezing

ΔTa = temperature decrease above freezing

h_l = latent heat of freezing

cb = specific heat capacity below freezing

ΔTb = temperature decrease below freezing

7.2 Work done in the refrigeration cycle:

7.2.1 Compressor:

The work done on the refrigerant during the isentropic compression step can be calculated from the enthalpy rise of the refrigerant and the refrigerant flow rate.

$$q_w = m^* (H_3 - H_2)$$

where m* is refrigerant mass flow rate (kg/s), H_3 is enthalpy of refrigerant at the end of compression stroke (kJ/kg refrigerant), H_2 is enthalpy of refrigerant at the beginning of compression stroke (kJ/kg refrigerant), and q_w is rate of work done on the refrigerant (kW).

7.2.3 Condenser:

Within the condenser, the refrigerant is cooled at constant pressure. The heat rejected to the environment can be expressed as

$$\mathbf{q_c = m^* (H_3 - H_1)}$$

where, q_c is rate of heat exchanged in the condenser (kW) and H_1 is enthalpy of refrigerant at exit from the condenser (kJ/kg refrigerant).

7.2.4 Evaporator:

Within the evaporator the refrigerant changes phase from liquid to vapor and accepts heat from the surroundings at a constant pressure. The enthalpy difference of the refrigerant between the inlet and the outlet locations of an evaporator is called the *refrigeration effect*. The rate of heat accepted by the refrigerant as it undergoes evaporation process in the evaporator is given by

$$\mathbf{q_e = m^* (H_2 - H_1)}$$

where q_e is the rate of heat exchanged in the evaporator (kW), and the refrigeration effect is $H_2 - H_1$.

7.2.5 Coefficient of Performance:

The purpose of a mechanical refrigeration system is to transfer heat from a low-temperature environment to one that is at a higher temperature. The refrigeration effect or the amount of heat absorbed from the low temperature environment is much greater than the heat equivalence of the work required to produce this effect. Therefore, the performance of a refrigeration system is measured, like that of an engine, by the ratio of the useful refrigeration effect obtained from the system to the work expended on it to produce that effect. This ratio is called the coefficient of performance. It is used to indicate the efficiency of the system. The coefficient of performance (C.O.P.) is defined as a ratio between the heat absorbed by the refrigerant as it flows through the evaporator to the heat equivalence of the energy supplied to the compressor C.O.P.

$$C.O.P = \frac{H_2 - H_1}{H_3 - H_2}$$

7.2.6 Refrigerant Flow Rate

The refrigerant flow rate depends on the total cooling load imposed on the system and the refrigeration effect. The following expression is used to determine the refrigerant flow rate:

$$m^* = \frac{q}{(H_2 - H_1)}$$

where, m* is the refrigerant flow rate (kg/s), and q is the total cooling load rate (kW).

8. CHANGES IN FOOD DURING REFRIGERATED STORAGE

The deterioration of foods during cold storage are influenced by the growing conditions and varieties of plants, feeding practices of animals, conditions of harvest and slaughter, sanitation and damage to tissues, temperature of cool storage, mixture of foods in storage, and other variables. Too low refrigeration temperature can cause damage called “chill injury” to fruits and vegetables even when these are not physically damaged by freezing. This is not surprising since living plants would be expected to have optimum temperature requirements just as animals do. In the case of bananas and tomatoes on the other hand, storage temperatures below about l3°C slow down the activities of natural ripening enzymes and result in poor colors. Nevertheless, for the majority of perishable foods, no cooling at all generally would be far worse than refrigeration temperatures that are somewhat too low.

Refrigerated storage permits exchange of flavors between many foods. Butter and milk will absorb odors from fish and fruit, and eggs will absorb odors from onions. It is best to store different foods, especially odorous ones, separately, but this is not always economically feasible. In many instances, effective packaging can prevent odor exchange. However, some changes that occur in foods during refrigerated storage represent true nutrient losses. An important example is loss of vitamin C and other vitamins which is common in many foods held for relatively short periods under refrigeration. Still other common changes during refrigerated storage involve loss of firmness and crispness in fruits and vegetables, changes in the colors of red meats, oxidation of fats, softening of the tissues and drippage from fish, staling of bread and cake, lumping and caking of granular foods, losses of flavor, and a host of microbial deteriorations often unique to a specific food and caused by the dominance of a particular spoilage organism. Some foods should not be refrigerated. Bread is an example. The rate of staling of bread is greater at refrigeration temperatures than it is at room temperature.

9. APPLICATIONS OF REFRIGERATION:

9.1 Storage of Raw Fruits and Vegetables:

In case of fruits and vegetables, the use of refrigeration starts right after harvesting to remove the post-harvest heat, transport in refrigerated carriages to the cold storage or the processing plant. A part of it may be stored in cold storage to maintain its sensory qualities and a part may be distributed to retail shops, where again refrigeration is used for short time storage. Refrigeration helps in retaining the sensory, nutritional, and eating qualities of the food. The excess crop of fruits and vegetables can be stored for use during peak demands and off-season; and transported to remote locations by refrigerated transport. The shelf life of most of the fruits and vegetables increases by storage at temperatures between 0 to 10°C. Nuts, dried fruits, and pulses that are prone to bacterial deterioration can also be stored for long periods by this method. The above mentioned fruits, vegetables etc, can be stored in raw state. Some highly perishable items require initial processing before storage. The fast and busy modern day life demands ready-to-eat frozen or refrigerated food packages to eliminate the preparation and cooking time. These items are becoming very popular and these require refrigeration plants.

9.2 Meat and poultry:

These items also require refrigeration right after slaughter during processing, packaging. Short-term storage is done at 0°C. Long-term storage requires freezing and storage at -25°C.

9.3 Dairy Products:

The important dairy products are milk, butter, buttermilk, and ice cream. To maintain good quality, the milk is cooled in bulk milk coolers immediately after being taken from cows. Bulk milk cooler is a large refrigerated tank that cools it between 10 to 15°C. Then it is transported to dairy farms, where it is pasteurized. Pasteurization involves heating it to 73°C and holding it at this temperature for 20 seconds. Buttermilk, curd and cottage cheese are stored at 4 to 10°C for increase of shelf life. Use of refrigeration during manufacture of these items also increases their shelf life.

9.4 Beverages:

Production of beer, wine and concentrated fruit juices require refrigeration. The taste of many drinks can be improved by serving them cold or by adding ice to them. Fruit juice concentrates have been very popular because of low cost, good taste and nutritional qualities. Juices can be preserved for a longer period of time than the fruits. Also, fruit juice concentrates when frozen can be more easily shipped and transported by road. Orange and other citrus juices, apple juice, grape juice and pineapple

juice are very popular. To preserve the taste and flavor of juice, the water is driven out of it by boiling it at low temperature under reduced pressure. The concentrate is frozen and transported at –20°C. Brewing and wine making requires fermentation reaction at controlled temperature, for example, lager-type of beer requires 8 to 12°C while wine requires 27-30°C.