FOOD ENGINEERING
CC 11 UNIT 5 – Refrigeration and Freezing –Pressure Enthalpy and freezing methods(Part 2)

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Introduction

Pressure enthalpy diagrams are must to deal with calculations involved in refrigeration and various thermodynamic cycles. Therefore, these help in designing the refrigerators and related parts. Vapor compression cycle is presented on these charts and, property tables give accurate values of various thermodynamic properties of refrigerants and thereby facilitate the availability of data at various temperatures and pressure.

In the present module following topics are covered

1. Molliers diagram or pressure enthalpy diagram
2. Mathematical Analysis of Vapour Compression Refrigeration
3. Superheating and subcooling
4. Plank's equation
5. Frozen storage
6. Methods of freezing

The following module will throw light on these diagrams and related concepts and numerical.

1. Pressure enthalpy diagram

The pressure-enthalpy diagram or Mollier diagram (Figure 1) describes the various properties of a refrigerant under different conditions or phases. Using thermodynamic tables of refrigerants, the values are taken at both the saturation and superheated conditions for the refrigerant in question.
On the P-H diagram, pressure is indicated on the y-axis and enthalpy is indicated on the x-axis. Typically enthalpy is in units of Btu/lb and pressure is in units of pounds per square inch (psi).

The upside down U figure shown on the diagram designates the points at which the refrigerant changes phase. The left vertical curve indicates the saturated liquid curve and the right vertical curve indicates the saturated vapor curve. The region in between the two curves describes refrigerant states that contain a mixture of both liquid and vapor.

The locations to the left of the saturated liquid curve indicate that the refrigerant is in liquid form and locations to the right of the saturated vapor curve indicate that the refrigerant is in vapor form. The point at which the two curves meet is called the critical point. The importance of this point is that at any point above, no additional pressure will change the vapor into a liquid.

The curves break up the diagram into three regions (1) Liquid, (2) Vapor and (3) Mix.

(1) Liquid Region: The liquid region is also known as the sub-cooled region. In this region there are vertical temperature lines, which increase as enthalpy is increased. Figure 8 is a simplified P-H diagram illustrating the constant temperature lines.

(2) Vapor Region: The vapor region is also known as the super heated region. In this region there are vertical temperature lines, which increase as enthalpy is increased. Refer to Figure 8. There are also lines of constant entropy, which are also important. Entropy is the measure of the amount of disorder in the system.

(3) Liquid-Vapor Mix Region: In this region, the P-H diagram shows horizontal temperature lines, which indicate constant temperature. The mix region is the phase change region, where any addition of enthalpy will cause additional liquid to vaporize instead of raising the temperature. Figure 8 illustrates the horizontal temperature lines in the mix region. There are upward sloping curves in the mix region which indicate quality. Quality is a measure of the ratio of vapor mass to total mass. For example quality of 0.1 or 10%, which is located near the saturated liquid line, describes points that have 10% vapor by mass.

Figure 2 represents a generalized Mollier diagram, and its various lines and regions are explained below:

a) Line A to B represents the change from high to low pressure, or expansion process

b) Line B to B' represents the amount of liquid 'flashed-off' in the expansion valve cooling the remaining liquid.

c) Line B to C represents the evaporation process at constant saturation temperature and pressure in the evaporator. At point C the refrigerant is a dry saturated vapour.

d) Line C to C' represents the superheat absorbed by the dry saturated vapour

e) Line C' to D represents the compression process.

f) Line D to E represents the superheat given up by the vapour in the condenser. At point E the refrigerant is a dry saturated vapour.

g) Line E to F represents the condensation process at constant saturation temperature and pressure. At point F the refrigerant is a saturated liquid.

h) Line F to A represents the sub cooling of the condensed liquid

2. Mathematical Analysis of Vapour Compression Refrigeration

Refrigerating effect: Refrigerating effect is the amount of heat absorbed by therefrigerant in its travel through the evaporator. In Figure 3this effect is represented by theexpression.

$$Q_{evap} = (h_2 - h_1) kJ/kg$$

In addition to the latent heat of vaporization it may include any heat of superheat absorbed in the evaporator.

Refrigeration capacity: The rate at which system will absorb heat from the refrigerated space or substance, is known as refrigerating capacity

$$Q_E = m - q_E \ kj/s$$

Where m= mass flow rate of refrigerator through evaporator
$q_E$is refrigeration effect

Mass of refrigerant: Mass of refrigerant circulated (per second per tonne of refrigeration) may be calculated by dividing the amount of heat by the refrigerating effect.
∴ Mass of refrigerant circulated,

$$m = \frac{14000}{3600\ (h_2 - h_1)} \text{ tonne}$$

because one tonne of refrigeration means cooling effect of 14000 kJ/h.

Theoretical piston displacement: Theoretical piston displacement (per tonne of refrigeration per minute) may be found by multiplying the mass of refrigerant to be circulated (pertonne of refrigeration per sec.) by the specific volume of the refrigerant gas, $(v_g)_2$, at its entranceof compressor. Thus,

$$\text{Piston displacement} = \frac{14000}{3600\ (h_3 - h_2)}$$

Power (Theoretical) required. Theoretical power per tonne of refrigeration is the power, theoretically required to compress the refrigerant. Here volumetric and mechanical efficiencies are not taken into consideration. Power required may be calculated as follows :

(a) **When compression is isentropic :**

$$\text{Work of compression} = h_3 - h_2$$

$$\text{Power required} = m(h_3 - h_2) kW$$

where, m = Mass of refrigerant circulated in kg/s.

(b) **When compression follows the general law pV^n= constant :**

$$\text{work of compression} = \frac{n}{n-1}(p_3 v_3 - p_2 v_2) Nm/kg$$

$$\text{Power required} = m \times \frac{n}{n-1}(p_3v_3 - p_2v_2) \times \frac{1}{10^3}\ \text{kW (p in N/m}^2)$$

Heat rejected to compressor cooling water: If the compressor cylinders are jacketed, an appreciable amount of heat may be rejected to the cooling water during compression. If the suction and discharge compression conditions are known, this heat can be determined as follows:

Heat rejected to compressor cooling water= $m(h_3 – h_4)$ kJ/s
(m = mass of refrigerant circulated in kg/s)

3. Superheating and sub-cooling:

Superheating: Superheat is a measured value. It is the difference between two temperatures. Superheat is measured as the difference between the actual temperature of the refrigerant vapor and the saturation temperature of the refrigerant at that same point.
As may be seen from the Figure 4(a)the effect of superheating is to increase the refrigerating effect but this increase in refrigerating effect is at the cost of increase in amount of work spent to attain the upper pressure limit. Since the increase in work is more as compared to increase in refrigerating effect, therefore overall effect of superheating is to give a low value of C.O.P.

Sub-cooling:'Sub-cooling' is the process of cooling the liquid refrigerant below the condensing temperature for a given pressure. In Figure 4(b)the process of sub-cooling is shown by 4-4′. As is evident from the figure the effect of sub-cooling is to increase the refrigerating effect. Thus sub-cooling results in increase of C.O.P. provided that no further energy has to be spent to obtain the extra cold coolant required.

4. Plank's equation

The freezing time is the time taken to lower the temperature of the product from its initial temperature to a given temperature at its thermal centre.

Plank's equation is an approximate analytical solution for a simplified phase-change model.

Plank assumed that the freezing process:

(a) commences with all of the food unfrozen but at its freezing temperature.
(b) occurs sufficiently slowly for heat transfer in the frozen layer to take place under steady-state conditions.

Plank's equation considers only phase change period during freezing process. However, Plank's approximate solution is sufficient for many practical purposes.
This method when applied to calculate the time taken to freeze to the centre of a slab (Figure 5) whose length and breadth are large compared with the thickness, results in the following equation:

Also $L_f = m_m L$ (for a food material)

where m_m = moisture content of food (fraction)

L = latent heat of fusion of water, 333.2 kJ/(kg.^{0}C)

The general form of Plank's equation is

$$t_f = \frac{L\rho_f}{(T_F - T_a)}\left[\frac{P'a}{h} + \frac{R'a^2}{k_f}\right]$$

where P' and R' are constants accounting for the product shape with P'=1/2, R'=1/8 for infinite plate; P'=1/4, R'=1/16 for infinite cylinder; and P'=1/6 and R'=1/24 for sphere or cube.

The limitations of Plank's equation are as follows:
1. It neglects the time required to remove sensible heat above the initial freezing point.
2. It does not consider the gradual removal of latent heat over a range of temperatures duringthe freezing process.
3. Constant thermal conductivity assumed for frozen material.

Despite the limitations, Plank's equation is the most popular method for predicting freezing time.

5. Frozen food storage

The storage life of fresh perishable foods such as meats, fish, vegetables, and fruits can be extended by several days by storing them at temperatures just above freezing, usually between 1-4^{o}C. The storage life of foods can be extended by several months by freezing and storing them at subfreezing temperatures, usually between 18 and 35^{o}C, depending on the particular food
Food, on being stored, may get spoilt by three mechanisms:

- Living organisms may feed on the food and contaminate and spoil it
- Biochemical activity within the food itself with time diminish its quality & usefulness
- Physical processes (e.g. bursting & spillage of the contents of the package) may have the same effect

The rate of freezing has a major effect on the size of ice crystals and the quality, texture, and nutritional and sensory properties of many foods. During slow freezing, ice crystals can grow to a large size, whereas during fast freezing a large number of ice crystals start forming at once and are much smaller in size. Large ice crystals are not desirable since they can puncture the walls the cells, causing a degradation of texture and a loss of natural juices during thawing.
The freezing of foods involves three stages:

1. cooling to the freezing point (removing the sensible heat)
2. freezing (removing the latent heat)
3. further cooling to the desired subfreezing temperature (removing the sensible heat of frozen food)

Fresh fruits and vegetables are *live products*, and thus they continue givingoff heat that adds to the refrigeration load of the cold storage room. Thestorage life of fruits and vegetables can be extended greatly by removing thefield heat and cooling as soon after harvesting as possible. The optimumstorage temperature of most fruits and vegetables is about 0.5 to 1^{o}C abovetheir freezing point. But this is not the case for some fruits and vegetables such as bananas and cucumbers that experience undesirable *physiological changes*,when exposed to low (but still above-freezing) temperatures, usually between0 and 10^{o}C. The resulting tissue damage is called the **chilling injury** and ischaracterized by internal discoloration, soft scald, skin blemishes, soggybreakdown, and failure to ripen. The severity of the chilling injury dependson both the temperature and the length of storage at that temperature. Lower the temperature, greater the damage in a given time. Therefore,products susceptible to chilling injury must be stored at higher temperatures.Chilling injurydiffers from **freezing injury**,which is causedbyprolonged exposureof the fruits and vegetables to subfreezing temperatures and thus the actual*freezing* at the affected areas.

Thefreezing injury is characterizedbyrubberytexture, browning, bruising, and drying due to rapid moisture loss. The freezingpoints of fruits and vegetables do not differ bymuch, but their susceptibility tofreezing injury differs greatly. Some vegetables are frozen and thawed severaltimes with no significant damage, but others such as tomatoes suffer severe tissueinjury and are ruined after one freezing. Products near the refrigerator coilsor at the bottom layers of refrigerator cars and trucks are most susceptible tofreezing injury. To avoid freezing injury, the rail cars or trucks should be *heated*during transportation in sub-freezing weather, and adequate air circulation mustbe provided in cold storage rooms. Damage also occurs during *thawing* if it isdone too fast. It is recommended that thawing be done at 4^{o}C.

6. Methods of freezing

The method of freezing is an important consideration in the freezing of foods. Common freezing methods include:

- Air-blast freezing, where high-velocity air at about 30^{o}C is blown over the food products
- Contact freezing, where packaged or unpackaged food is placed on or between cold metal plates and cooled by conduction
- Immersion freezing, where food is immersed in low temperature brine
- Cryogenic freezing, where food is placed in a medium cooled by a cryogenic fluid such as liquid nitrogen or liquid or solid carbon dioxide; and the combination of the methods above

The method of freezing is an important consideration in the freezing of foods.Common freezing methods include *air-blast freezing*, where high-velocity airat about -30^{o}C is blown over the food products; *contact freezing*, where packaged or unpackaged food is placed on or between cold metal plates andcooled by conduction; *immersion freezing*, where food is immersed in lowtemperaturebrine; *cryogenic freezing*, where food is placed in a mediumcooled by a cryogenic fluid such as liquid nitrogen or liquid or solid carbondioxide; and the combination of the methods above.

In **air-blast freezers**, refrigerated air serves as the heat transfer medium andthe heat transfer is primarily by convection. Perhaps the easiest method offreezing that comes to mind is to place the food items into a well-insulated*cold storage room* maintained at subfreezing temperatures. Heat transfer inthis case is by natural convection, which is a rather slow process. The resultinglow rates of freezing cause the growth of large ice crystals in the food andallow plenty of time for the flavors of different foods to mix. This hurts thequality of the product, and thus this simple method of freezing is usuallyavoided.

The next step is to use some large fans in the cold storage rooms to increasethe convection heat transfer coefficient and thus the rate of freezing.Thesebatch-type freezers, called *stationary blast cells*, are still beingused for many food products but are being replaced by conveyor-type air-blast freezers as appropriate since they allow the automation of the prod-cut flowand reduce labor costs.

A simple version of mechanized freezers, called a*straight-belt freezer,* is very suitable for cooling fruits, vegetables, anduniform-sized products such as french fries. For smaller uniform-sized productssuch as peas and diced carrots, *fluidized-bed freezers* suspend the fooditems by a stream of cold air, usually at -40°C, as they travel on a conveyorbelt. The high level of air motion and the large surface area result in high ratesof heat transfer and rapid freezing of the food products. The floor spacerequirements for belt freezers can be minimized by using *multi-pass straightbelt freezers or spiral belt freezers*, shown in, which now dominatethe frozen food industry. In another type of air-blast freezer, called the *impingement-style freezer*, cold air impinges upon the food product verticallyfrom both sides of the conveyor belt at a high velocity, causing high heat transferrates and very fast freezing.

In **contact freezers**, food products are sandwiched between two cold metalplates and are cooled by conduction. The plates are cooled by circulating coldrefrigerant through the channels in the plates. Contact freezers are fast and efficient,but their use is limited to flat foods no thicker than about 8 cm withgood thermal conductivity, such as meat patties, fish fillets, and chopped leafyvegetables.

In **immersion freezing**, food products are immersed in brine oranother fluid with a low-freezing point.At atmospheric pressure, *liquid nitrogen* boils at -195°C and absorbs198 kJ/kg of heat during vaporization. Carbon dioxide is a solid at atmosphericpressure (called *dry ice*) and sublimes at -79°C while absorbing572 kJ/kg of heat. The saturated nitrogen and carbon dioxide vapors canfurther be used to pre-cool the incoming food products before the vapors arepurged into the atmosphere. The low boiling points and safety of these cryogenicsubstances make them very suitable for **cryogenic freezing** of foodproducts.

A common type of nitrogen freezer involves a long tunnel with amoving belt in it. Food products are frozen by nitrogen as they pass throughthe channel. Nitrogen provides extremely fast freezing because of the largetemperature difference. Cryogenic cooling is used in limited applicationsbecause of its high cost. Sometimes cryogenic cooling is used in combinationwith air-blast freezing for improved quality and reduced cost. The foodproduct is first crust-frozen in a bath of nitrogen to seal moisture and flavor in,and then transferred into the air-blast freezing section, where the freezingprocess is completed at a lower cost. This practice also reduces to negligiblelevels the dehydration losses, which can be as high as 4 percent for poorlydesigned and maintained systems.

Conclusion

Refrigeration is the science of producing and maintaining temperatures below that of the surrounding atmosphere. Refrigeration could be achieved by melting a solid, sublimation of a solid, evaporation of a liquid. In a simple vapour compression cycle compression, condensation, Expansion and Vaporization are completed. To represent the steps thermodynamically relating to state of refrigeration, p-h chart is used. *p-h*chart gives directly the changes in enthalpy and pressure during evaporation, compression, condensation and expansion process for thermodynamic analysis which is important to consider while designing refrigeration system.