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Subject: Food Technology

Production of Courseware

e-Content for Post Graduate Courses

Paper No. : 04 Unit Operations in Food Processing

Module : 11 Principles of Refrigeration

ज्ञान-विज्ञान विमुक्तये

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Description of Module	
Subject Name	Food Technology
Paper Name	04 Unit Operations in Food Processing
Module Name/Title	Principles of Refrigeration
Module Id	FT/UOFP/11
Pre-requisites	Thermodynamics, principle of heat transfer
Objectives	To know about refrigeration cycle To solve problems in refrigeration cycle
Keywords	Refrigerant, mechanical vapour compression, refrigeration effect, coefficient of performance

11.1 Introduction

Preservation of foods is a vital processing step in food processing. There are different methods available for preservation of foods like heat treatment, chemical treatment etc. Preservation by cooling is proved to be the best method as retention of sensory and textural characteristics is relatively good. According to the principle of physical chemistry; "*molecular mobility is depressed and consequently chemical reactions and biological processes are slowed down at low temperature*." Refrigeration is essentially maintaining temperatures inside a system lower than the surrounding ambient temperature by removal of excessive heat from the system boundary and prevention of incursion of heat to the system. Refrigeration is not a permanent method of food preservation. Refrigerated foods have definite shelf life and for improving shelf life refrigeration must me combined with other preservation techniques (hurdle technology).

The rate of heat removal from a system is termed as *refrigeration load*. The system must be designed in such a way that it can handle refrigeration load efficiently. For high refrigeration load as in cold storage, mechanical refrigeration system is adopted. Mechanical refrigeration system works as a heat pump which continuously removes heat from the defined system.

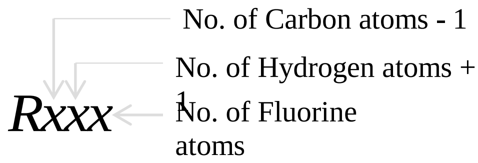
In this module we shall study about the refrigeration system, the refrigerants and the principle of heat removal from the system.

11.2 Refrigerants

The refrigerants are volatile liquids used in mechanical vapour compression system. Refrigerant in a refrigeration system undergoes phase transition from liquid to gas and back to liquid again. In doing so, the heat from a system (evaporator) is drawn to meet the requirement of latent heat of evaporation and the same heat is carried to the condenser where it is dissipated to outside atmosphere. The selection of refrigerant for a system is very vital to provide good performance characteristics. The important characteristics are as follows;

a. *High latent heat of vaporization*: smaller amount of refrigerant needed for a specific capacity.
b. *Condensing pressure*: should be low to minimize expenditure on construction of condense or piping.
c. *Freezing temperature*: it should be below the evaporation temperature.
d. *Critical temperature*: should be high otherwise if the temperature exceeds the critical temperature, refrigerant cannot be liquefied.
e. *Toxicity, flammability, corrosion and chemical stability*: refrigerants should be nontoxic, non flammable, non corrosive and chemically stable.
f. *Cost*: low-cost refrigerant preferred for minimum running cost of industries.
g. *Environment friendly*: any leak of refrigerant to the environment should not cause any harm.

Ammonia is a very common refrigerant used extensively in high capacity refrigeration plant. It satisfies maximum characteristics listed above. However, it is toxic, irritant and flammable. Among other refrigerants, halogenated hydrocarbons are extensively used in domestic refrigerators and air conditioning. Their coding is given as follows.



Let us take a hydrocarbon, dichlorodifluoromethane (CCl_2F_2). Here, number of fluorine atom is 2. So, the first digit from the right would be 2. The number of hydrogen atom is zero. So the second number from the right would be 0+1 = 1. The number of carbon atom is 1. So, the third digit from the right would be 1-1 =0. Hence, the coding would be R-12. The number of chlorine atom is found from the valance of carbon atom not occupied by hydrogen or fluorine. R-12 is commonly known as *Freon*. Refrigerated transportation, retail display cases, cold storage, refrigerated vending machine use R-502 which is an azeotrope and R-22 most of the cases. Chlorofluorocarbons (CFCs) have many characteristics to be required by a refrigerant; however their excessive use cause harmful effects to environment like ozone depletion. So, the alternatives are the zeotropes and azeotropes.

11.3 Refrigeration cycle

The basic principle of mechanical refrigeration cycle is based on cyclic thermodynamic process known as *Rankine-cycle* or *vapour compression cycle*. The cycle consists of four components as shown in figure 11.1. As the refrigerant flows through these components its phase changes from liquid to gas and then back to liquid. The components are;

1. *Component 1- Compression*: The refrigerant enters to compressor in gaseous state at low temperature and pressure. Work is done by compressor to increase the temperature and pressure of refrigerant sufficient enough to maintain a temperature gradient between condenser and surrounding.
2. *Component 2-Condensation*: The compressed hot refrigerant has temperature above the ambient temperature. In condenser, the heat is lost to the environment at constant pressure and temperature. By doing so, the gaseous refrigerant changes its phase to liquid inside condenser, the phenomenon is known as condensation.

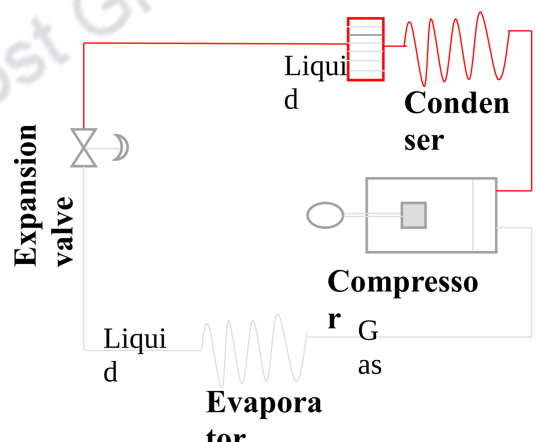


Fig.11.1: Schematic of a Refrigeration cycle

3. *Component 3-Expansion:* High pressure liquid refrigerant need to release the pressure, so that temperature drops below the boiling point of refrigerant. Heat content of refrigerant does not change with pressure drop. The pressure is released using a throttling device called expansion valve.
4. *Component 4- Evaporation*: The cold liquid refrigerant flows through a heat exchanger, called evaporator. The latent heat of vaporization is drawn by the refrigerant from the environment at constant temperature

and pressure. Finally, the cold refrigerant is sucked by the compressor through suction pipe, and thus the cycle completes.

11.4 Pressure-Enthalpy Diagram

The refrigerant when passes through different components of refrigeration system, it changes its pressure and enthalpy. The enthalpy at evaporator and condenser changes at constant pressure. Work is done on refrigerant by compressor and thus the enthalpy increases with pressure. Expansion valve is a device, where high pressure liquid passes through a small opening at controlled rate to low pressure side of refrigeration system. In this process enthalpy remains constant.

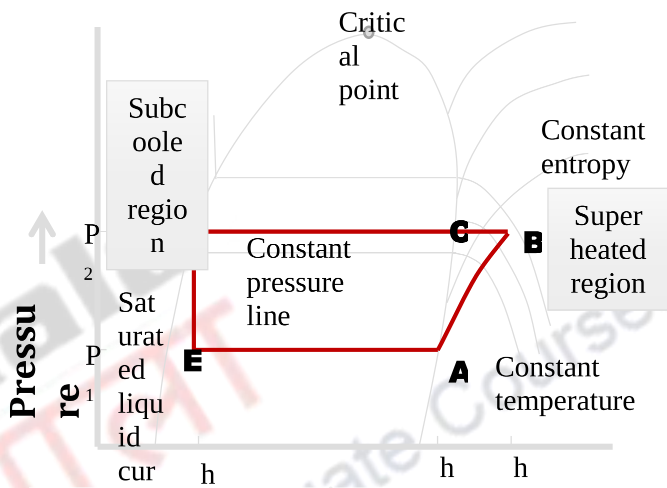


Fig.11.2: Pressure-Enthalpy diagram for Freon

A chart or diagram can be prepared showing all the components of a refrigeration system. This can either be a pressure-enthalpy diagram or a temperature-entropy diagram. The pressure-enthalpy diagram of Freon (R-12) is shown in figure 11.2. The enthalpy and pressure are plotted along x and y axis. As shown in the figure a bell-shaped curve divides the two regions like saturated liquid on the left side and saturated vapour on the right side. The area confined in the bell shape is a mixture of vapour and liquid. The point at which the saturated liquid line meets the saturated vapour line, it is called critical point. Region beyond saturated liquid line at a particular pressure is known as sub cooled region and region of the extreme right is a dry saturated line called super heated region whose temperature is higher than saturated vapour corresponding to a particular pressure. The pressure lines are horizontal to the x axis. Temperature line is vertical in saturated liquid region, horizontal to x axis in bell shaped region and skewed downward in saturated vapour region. Constant entropy line is skewed upward in the saturated vapour region.

As shown in figure 11.2, the red lines depict thermodynamic changes of different components of a mechanical vapour compression system. As shown here, line AB represents compression, BD condensation, DE expansion and EA evaporation. The liquid refrigerant enters to expansion valve at point D in saturated state. During expansion pressure drops from P_2 to P_1. However, the enthalpy remains constant at h_1. The low pressure refrigerant enters at location E to evaporator. Vaporization takes place in evaporator, thus latent heat is increased from h_1 to h_2. Vaporization converts the liquid to dry vapour that enters to compressor at location A. As the work is done on the refrigerant, pressure is increased and enthalpy increases to h_3 at location B which is in a superheated region. The compression takes place at constant entropy or isentropic process. The pressure is increased from P_1 to P_2. In the condenser first super heat is removed and enthalpy reduces to h2 and afterward latent heat of vaporization is removed (CD).

The usual thermodynamic behaviour of refrigerant may deviate due to certain factors. The deviation is as shown in figure 11.3. The superheating of refrigerant before coming to compressor is needed to remove refrigerant liquid from entering the compressor, which otherwise would affect the performance of compressor. Superheating is due to the refrigerant vapours receiving heat from the environment. The superheated refrigerant extends to A' and the pressure remain constant at P_1. Another deviation we can see here is the sub-cooling of liquid refrigerant coming out of condenser. The point D' shown in the figure is beyond saturated liquid line. Sub-cooling is achieved by the remaining liquid refrigerant in the condenser due to temperature gradient between the refrigerant and condensing liquid. The pressure in sub-cooled state remains at P_2.

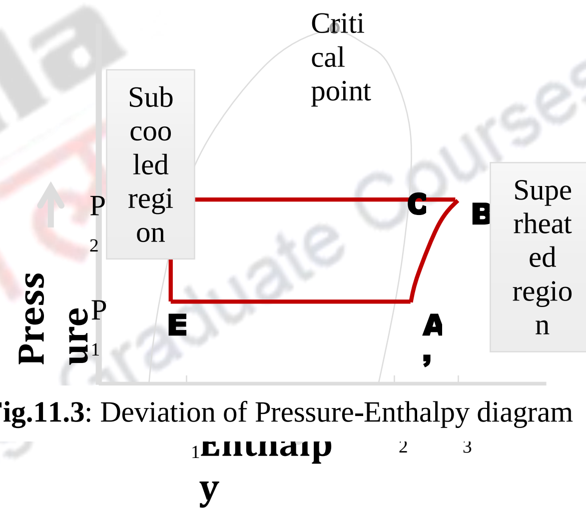


Fig.11.3: Deviation of Pressure-Enthalpy diagram

The temperature-entropy diagram also is used to represent refrigeration cycle.

11.5 Performance of a vapour-compression refrigeration cycle

11.5.1 Cooling load

Cooling load is the rate of removal of heat from a defined space in order to lower the temperature of that space to a desired level. The cooling loads of refrigeration systems are designated with a common unit called *ton of refrigeration (TR)*. One ton of refrigeration is equivalent to latent heat of fusion of one ton of ice in 24 hours. The value of one TR is 3.52 kW. So, a mechanical refrigeration system that has the capacity to absorb heat at the rate of 3.52 kW is rated as one TR of refrigeration. The cooling load helps in selecting the refrigeration system for desired quantity of food product and desired condition to be maintained. The cooling load is calculated taking into the consideration of heat infiltration from the surrounding through the walls and ceiling and the rate of respiration of fresh fruits and vegetables.

11.5.2 Work done in refrigeration cycle

Mechanical work is done by the compressor on the refrigerant. The process is an isentropic one with rise in enthalpy and pressure. If *m* is the mass flow rate of refrigerant, the work done by the compressor is represented as;

$$q_w = m(h_3 - h_2) \qquad \ldots (11.1)$$

Where, h_2 and h_3 are the enthalpies of refrigerant at the start and end of compression.

11.5.3 Heat removal and absorption

In the condenser heat is removed from the compressed liquid refrigerant at a constant pressure. The enthalpy thus decreases from h_3 to h_1 as shown in fig.11.2. The amount of heat removed is expressed as follows;

$$q_c = m(h_3 - h_1) \qquad \ldots (11.2)$$

Where, h_3 and h_1 are the enthalpies of refrigerant at the entry and exit of condenser.

Inside the evaporator, the refrigerant changes its phase from liquid to gas at constant pressure. The latent heat of evaporation is required for the phase change which is gained from the refrigeration space. Thus, the enthalpy increases from h_1 to h_2. This change of enthalpy is called *refrigeration effect*. The rate of heat received by the refrigerant from the space is represented as;

$$q_e = m(h_2 - h_1) \qquad \ldots (11.3)$$

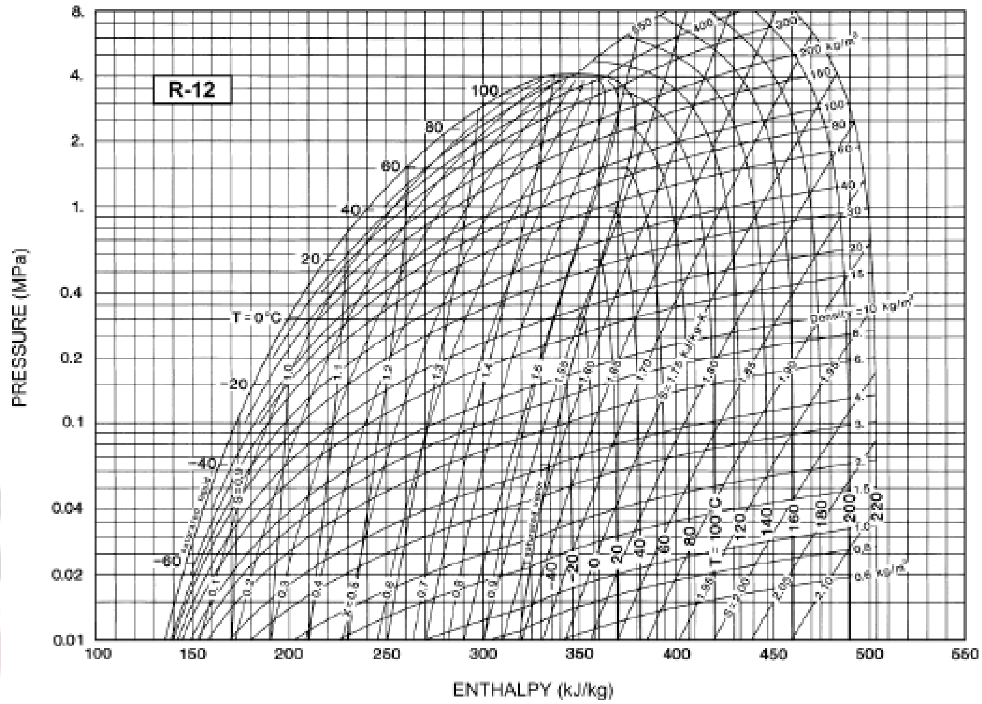
11.5.4 Coefficient of performance

Coefficient of performance (COP) checks the efficacy of a refrigeration cycle. It is the ratio of refrigeration effect and the work done to achieve this effect. The beauty of a refrigeration system is that, a small amount of work is done to achieve greater refrigeration effect. The coefficient of performance is given as follows;

$$COP = \frac{h_2 - h_1}{h_3 - h_2} \qquad \ldots (11.4)$$

Since, the refrigeration effect is more than the work done coefficient of performance is always greater than unity. More the COP, better be the refrigeration system.

Example: An ideal refrigeration cycle operates using R-12 refrigerant operates between 30 and 400 kPa. Determine evaporator and condenser temperatures and coefficient of performance. If the system is used as a heat pump, what will be its coefficient of performance?



Solution:

For solving this problem graphically, we take the help of pressure enthalpy chart of R-12 as shown in fig.11.4. The pressure enthalpy charts for refrigerants have individual charts. The pressure of refrigerant at the entry of compressor is 30 kPa and at exit is 400 kPa. We can trace the respective temperatures of evaporator and condenser from the figure (11.4).

Evaporator temperature (corresponding to 30 kPa pressure) = -43 ^{0}C (by interpolation)

Condenser temperature (corresponding to 500 kPa pressure) = 12 ^{0}C (by interpolation)

The corresponding enthalpy at high pressure (400 kPa) in liquid saturation line i.e. h_1=225 kJ/kg

The enthalpy at high pressure (400 kPa) in saturated vapour line i.e. h_2= 320 kJ/kg

A constant entropy of 1.62 kJ/kg.K (corresponding to low saturated vapour pressure line) meets the high pressure line at a point in the region of super heat and the corresponding enthalpy is 363 kJ/kg. i.e. h_3= 363 kJ/kg. According to equation (11.4), the COP is calculated as;

$$COP = \frac{335-225}{363-320} = 2.55$$

Heat pump is one which removes heat from a space. In this case the COP is the ratio of rate of removal of heat to the work done, i.e.

$$COP = \frac{h_3 - h_1}{h_3 - h_2} = \frac{363 - 225}{363 - 320} = 3.20$$

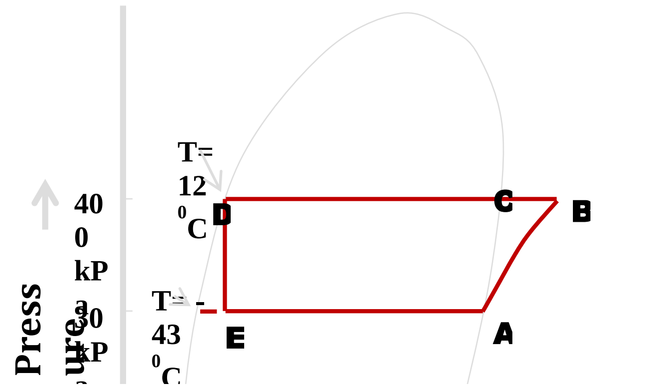


Fig.11.5: Pressure-Enthalpy diagram with given situation

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