Lesson

8

Methods of producing Low Temperatures

The specific objectives of the lesson :

In this lesson the basic concepts applicable to refrigeration is introduced. This chapter presents the various methods of producing low temperatures, viz. Sensible cooling by cold medium, Endothermic mixing of substances, Phase change processes, Expansion of liquids, Expansion of gases, Thermoelectric refrigeration, Adiabatic demagnetization. At the end of this lesson students should be able to:

1. Define refrigeration (*Section 8.1*)
2. Express clearly the working principles of various methods to produce low temperatures (*Section 8.2*)

8.1. Introduction

Refrigeration is defined as “the process of cooling of bodies or fluids to temperatures lower than those available in the surroundings at a particular time and place”. It should be kept in mind that refrigeration is not same as “cooling”, even though both the terms imply a decrease in temperature. In general, cooling is a heat transfer process down a temperature gradient, it can be a natural, spontaneous process or an artificial process. However, refrigeration is not a spontaneous process, as it requires expenditure of exergy (or availability). Thus cooling of a hot cup of coffee is a spontaneous cooling process (not a refrigeration process), while converting a glass of water from room temperature to say, a block of ice, is a refrigeration process (non-spontaneous). “All refrigeration processes involve cooling, but all cooling processes need not involve refrigeration”.

Refrigeration is a much more difficult process than heating, this is in accordance with the second laws of thermodynamics. This also explains the fact that people knew ‘how to heat’, much earlier than they learned ‘how to refrigerate’. All practical refrigeration processes involve reducing the temperature of a system from its initial value to the required temperature that is lower than the surroundings, and then maintaining the system at the required low temperature. The second part is necessary due to the reason that once the temperature of a system is reduced, a potential for heat transfer is created between the system and surroundings, and in the absence of a “perfect insulation” heat transfer from the surroundings to the system takes place resulting in increase in system temperature. In addition, the system itself may generate heat (e.g. due to human beings, appliances etc.), which needs to be extracted continuously. Thus in practice refrigeration systems have to first reduce the system temperature and then extract heat from the system at such a rate that the temperature of the system remains low. Theoretically refrigeration can be achieved by several methods. All these methods involve producing temperatures low enough for heat transfer to take place from the system being refrigerated to the system that is producing refrigeration.

8.2. Methods of producing low temperatures

8.2.1. Sensible cooling by cold medium

If a substance is available at a temperature lower than the required refrigeration temperature, then it can be used for sensible cooling by bringing it in thermal contact with the system to be refrigerated. For example, a building can be cooled to a temperature lower than the surroundings by introducing cold air into the building. Cold water or brine is used for cooling beverages, dairy products and in other industrial processes by absorbing heat from them. The energy absorbed by the substance providing cooling increases its temperature, and the heat transferred during this process is given by:

$$Q = mc_p(\Delta T) \tag{8.1}$$

Where m is the mass of the substance providing cooling, c_p is its specific heat and ΔT is the temperature rise undergone by the substance. Since the temperature of the cold substance increases during the process, to provide continuous refrigeration, a continuous supply of the cold substance should be maintained, which may call for an external refrigeration cycle.

8.2.2. Endothermic mixing of substances

This is one of the oldest methods known to mankind. It is very well-known that low temperatures can be obtained when certain salts are dissolved in water. This is due to the fact that dissolving of these salts in water is an endothermic process, i.e., heat is absorbed from the solution leading to its cooling. For example, when salts such as sodium nitrate, sodium chloride, calcium chloride added to water, its temperature falls. By dissolving sodium chloride in water, it is possible to achieve temperatures as low as -21^0C, while with calcium chloride a temperature of -51^0C could be obtained. However, producing low temperature by endothermic mixing has several practical limitations. These are: the refrigeration effect obtained is very small (the refrigeration effect depends on the heat of solution of the dissolved substance, which is typically small for most of the commonly used salts), and recovery of the dissolved salt is often uneconomical as this calls for evaporation of water from the solution.

8.2.3. Phase change processes

Refrigeration is produced when substances undergo endothermic phase change processes such as sublimation, melting and evaporation. For example, when ice melts it produces a refrigeration effect in the surroundings by absorbing heat. The amount of refrigeration produced and the temperature at which refrigeration is produced depends on the substance undergoing phase change. It is well-known that pure water ice at 1 atmospheric pressure melts at a temperature of about 0^0C and extracts about 335 kJ/kg of heat from the surroundings. At 1 atmospheric pressure, dry ice (solid carbon dioxide) undergoes sublimation at a temperature of -78.5^0C, yielding a refrigeration effect of 573 kJ/kg. Both water ice and dry ice are widely used to provide refrigeration in several applications. However, evaporation or vaporization is the most commonly used phase change process in practical refrigeration systems as it is easier to handle fluids in cyclic devices. In these systems, the working fluid (refrigerant) provides refrigeration effect as it changes its state from liquid to vapor in the evaporator.

For all phase change processes, the amount of refrigeration produced is given by:

$$Q = m(\Delta h_{ph}) \tag{8.2}$$

where Q is the refrigeration produced (heat transferred), m is the mass of the phase change substance and Δh_{ph} is the latent heat of phase change. If the process is one of evaporation, then Δh_{ph} is the latent heat of vaporization (difference between saturated vapour enthalpy and saturated liquid enthalpy at a given pressure). From the above equation it can be seen that substances having large latent heats require less amount of substance (m) and vice versa. Apart from the latent heat, the temperature at which the phase change occurs is also important. For liquid-to-vapour phase change, the Normal Boiling Point (NBP) is a good indication of the usefulness of a particular fluid for refrigeration applications. The Normal Boiling Point is defined as the temperature at which the liquid and vapour are in equilibrium at a pressure of 1 atm. The latent heat of vaporization and normal boiling point are related by the Trouton's rule, which states that the molar entropy of vaporization is constant for all fluids at normal boiling point. This can be expressed mathematically as:

$$\Delta\bar{s}_{fg} = \frac{\Delta\bar{h}_{fg}}{T_b} = 85 \text{ to } 110 \text{ J/mol.K} \qquad (8.3)$$

where Δs_{fg} is the molar entropy of vaporization (J/mol.K), Δh_{fg} is the molar enthalpy of vaporization (J/mol) and T_b is the normal boiling point in K. The above equation shows that higher the NBP, higher will be the molar enthalpy of vaporization. It can also be inferred from the above equation that low molecular weight fluids have higher specific enthalpy of vaporization and vice versa.

The fluids used in a refrigeration system should preferably have a low NBP such that they vaporize at sufficiently low temperatures to produce refrigeration, however, if the NBP is too low then the operating pressures will be very high. The Clausius-Clayperon equation relates the vapour pressures with temperature, and is given by:

$$\left(\frac{d\ln p}{dT}\right)_{sat} = \frac{\Delta h_{fg}}{RT^2} \qquad (8.4)$$

The Clausius-Clapeyron equation is based on the assumptions that the specific volume of liquid is negligible in comparison with the specific volume of the vapour and the vapour obeys ideal gas law. Clausius-Clapeyron equation is useful in estimating the latent heat of vaporization (or sublimation) from the saturated pressure-temperature data.

8.2.4. Expansion of Liquids

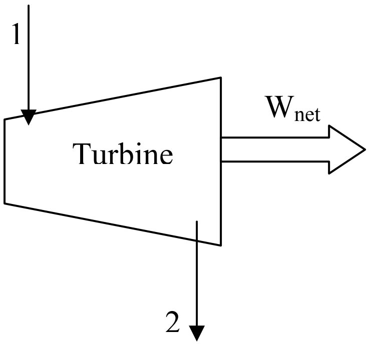

Fig.8.1(a). *Expansion through a turbine*

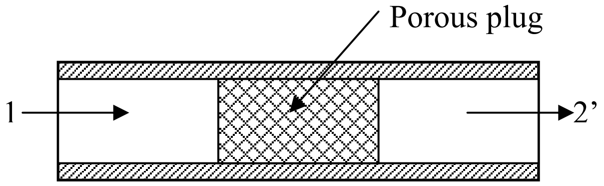

Fig.8.1(b). *Isenthalpic Expansion through a porous plug*

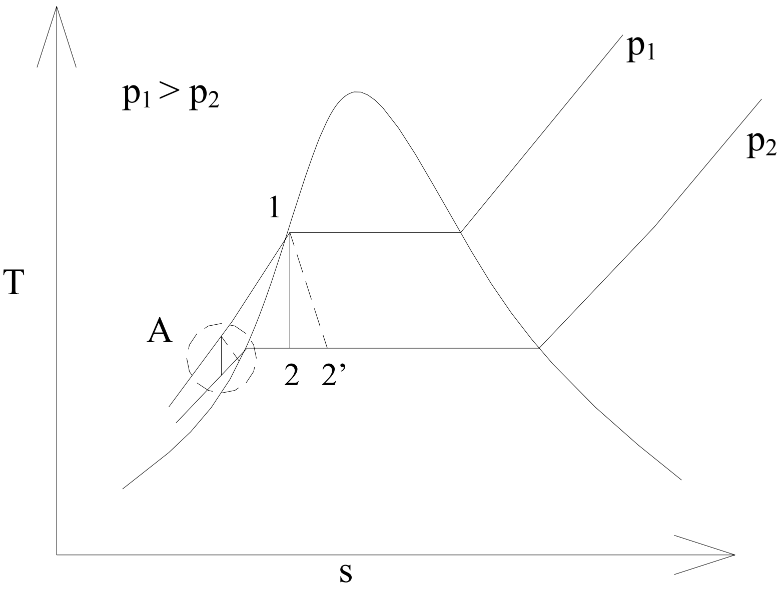

***Fig.8.2(a)**. Expansion of saturated liquid*
1-2: Isentropic; 1-2’: Isenthalpic

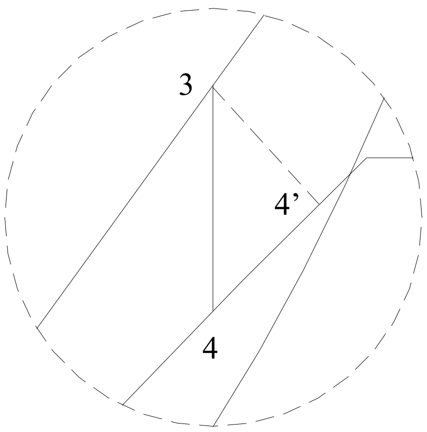

***Fig.8.2(b)**. Expansion of subcooled liquid*
3-4: Isentropic; 3-4’: Isenthalpic

When a high pressure liquid flows through a turbine delivering a net work output (Fig.8.1(a)), its pressure and enthalpy fall. In an ideal case, the expansion process can be isentropic, so that its entropy remains constant and the drop in enthalpy will be equal to the specific work output (neglecting kinetic and potential energy changes). When a high pressure liquid is forced to flow through a restriction such as a porous plug (Fig.8.1 (b)), its pressure decreases due to frictional effects. No net work output is obtained, and if the process is adiabatic and change in potential and kinetic energies are negligible, then from steady flow energy equation, it can be easily shown that the enthalpy of the liquid remains constant. However, since the process is highly irreversible, entropy of liquid increases during the process. This process is called as a *throttling process*. Whether or not the temperature of the liquid drops significantly during the isentropic and isenthalpic expansion processes depends on the inlet condition of the liquid. If the inlet is a saturated liquid (state 1 in Fig. 8.2(a)), then the outlet condition lies in the two-phase region, i.e., at the outlet there will be some amount of vapour in addition to the liquid for both isentropic expansion through the turbine as well as isenthalpic process through the porous plug. These processes 1-2 and 1-2’, respectively are shown on a T-s diagram in Fig. 8.2 (a). Obviously, from energy balance it can be shown that in isentropic expansion through a turbine with a net work output, the enthalpy at state 2 will be less than enthalpy at state 1, and in case of isenthalpic expansion through porous plug (with no work output), the entropy at state 2’ will be greater than the entropy at state 1. For both the cases the exit temperature will be same, which is equal to the saturation temperature corresponding to the outlet pressure p_2. It can be seen that this temperature is much lower than the inlet temperature (saturation temperature corresponding to the inlet pressure p_1). This large temperature drop is a result of vapour generation during expansion requiring enthalpy of vaporization, which in the absence of external heat transfer (adiabatic) has to be supplied by the fluid itself.

On the contrary, if the liquid at inlet is subcooled to such an extent that when it expands from the same inlet pressure p_l to the same outlet pressure p_2, the exit condition is in a liquid state, we observe that the temperature drop obtained is much smaller, i.e., $(T_3\text{-}T_{4,4'}) << (T_1\text{-}T_{2,2'})$ for both isentropic as well as isenthalpic processes. The temperature drop obtained during isenthalpic expansion is less than that of isentropic expansion. Thus in refrigeration systems which use expansion of liquids to produce low temperatures (e.g. vapour compression refrigeration systems), the inlet state of the liquid is always such that the outlet falls into the two phase region.

8.2.5. Expansion of gases

a) By throttling:

Similar to liquids, gases can also be expanded from high pressure to low pressure either by using a turbine (isentropic expansion) or a throttling device (isenthalpic process). Similar to throttling of liquids, the throttling of gases is also an isenthalpic process. Since the enthalpy of an ideal gas is a function of temperature only, during an isenthalpic process, the temperature of the ideal gas remains constant. In case of real gases, whether the temperature decreases or increases during the isenthalpic throttling process depends on a property of the gas called Joule-Thomson coefficient, $\mu_{JT,}$ given by:

$$\mu_{JT} = \left(\frac{\partial T}{dp}\right)_h \tag{8.5}$$

from thermodynamic relations it can be shown that the Joule-Thomson coefficient, $\mu_{JT,}$ is equal to:

$$\mu_{JT} = \frac{\left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right]}{c_p} \tag{8.6}$$

where ‘v’ is the specific volume and c_p is the specific heat at constant pressure. From the above expression, it can be easily shown that μ_{JT} is zero for ideal gases (pv = RT). Thus the magnitude of μ_{JT} is a measure of deviation of real gases from ideal behaviour. From the definition of μ_{JT}, the temperature of a real gas falls during isenthalpic expansion if μ_{JT} is positive, and it increases when μ_{JT} is negative. Figure 8.3 shows the process of isenthalpic expansion on temperature-pressure coordinates.

As shown in Fig. 8.3, along a constant enthalpy line (isenthalpic process), beginning with an initial state ‘i’ the temperature of the gas increases initially with reduction in pressure upto point f3, and $\mu_{JT} = \left(\frac{\partial T}{dp}\right)_h$ is negative from point i to point f3. However, further reduction in pressure from point f3 to f5, results in a reduction of temperature from f3 to f5. Thus point f3 represents a point of inflexion, where $\mu_{JT} = \left(\frac{\partial T}{dp}\right)_h = 0$. The temperature at the point of inflexion is known as *inversion temperature* for the given enthalpy. Therefore, if the initial condition falls on the left of inversion temperature, the gas undergoes a reduction in temperature during expansion and if the initial condition falls on the right side of inversion point, then temperature increases during expansion. Figure 8.4 shows several isenthalpic lines on T-p coordinates. Also shown in the figure is an inversion curve, which is the locus of all the inversion points. The point where the inversion curve intercepts the temperature axis is called as maximum inversion temperature. For any gas, the temperature will reduce during throttling only when the initial temperature is lower than the maximum inversion temperature. For most of the gases (with the exception of neon, helium, hydrogen) the maximum inversion temperature is much above the room temperature, hence isenthalpic expansion of these gases can lead to their cooling.

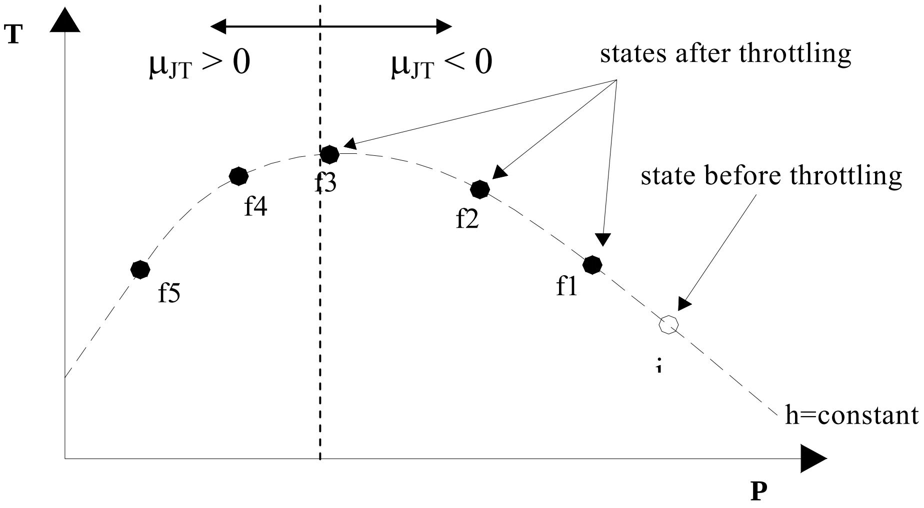

Fig.8.3. *Isenthalpic expansion of a gas on T-P coordinates*

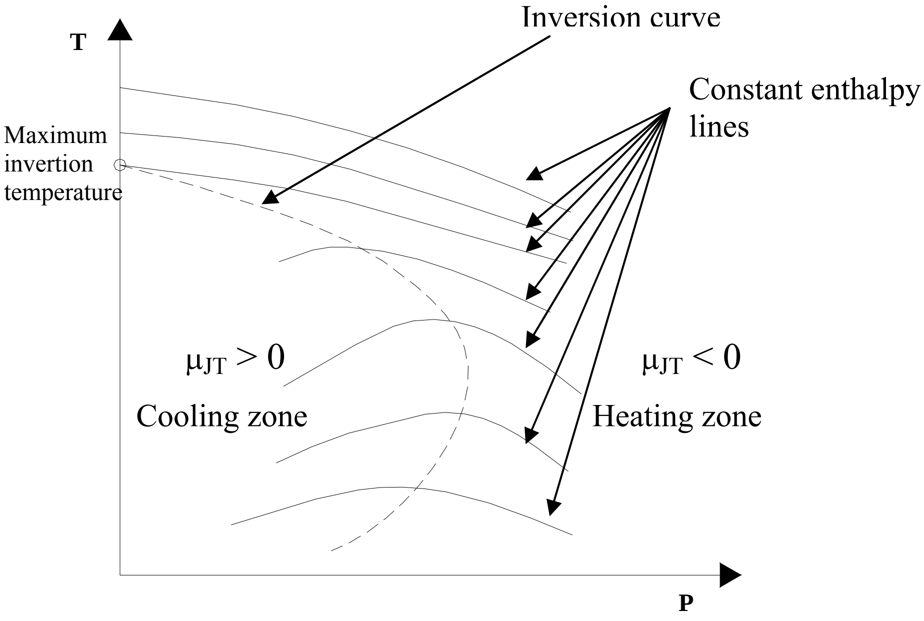

Fig.8.4. *Isenthalpic lines on T-P coordinates*

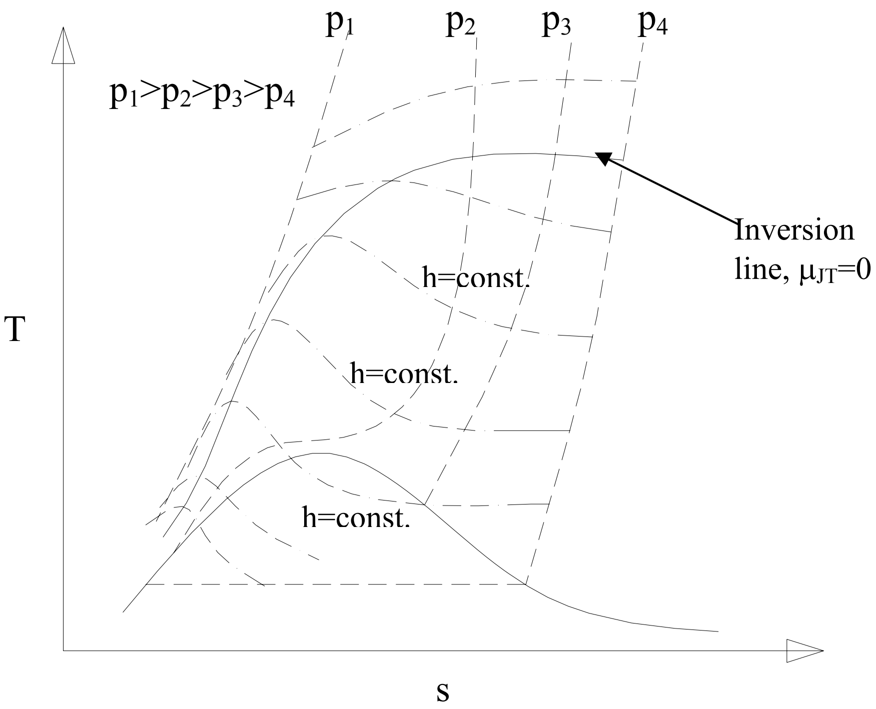

***Fig.8.5**. Inversion temperature line on T-s diagram*

Figure 8.5 shows the inversion temperature line on T-s diagram. Several things can be observed from the diagram. At high temperatures (greater than inversion temperature), throttling increases temperature. Maximum temperature drop during throttling occurs when the initial state lies on the inversion curve. Throttling at low pressures (e.g. p_3 to p_4) produces smaller reduction in temperature compared to throttling at high pressures (e.g. p_2 to p_3). For a given pressure drop during throttling, the drop in temperature is higher at lower temperatures compared to higher temperatures. Gases cannot be liquefied by throttling (i.e., exit condition will not be in two phase region), unless the temperature of the gas is first lowered sufficiently. This fact is very important in the liquefaction of gases. In order to liquefy these gases, they have to be first compressed to high pressures, cooled isobarically to low temperatures and then throttled, so that at the exit a mixture of liquid and vapour can be produced.

b) Expansion of gases through a turbine:

Steady flow expansion of a high pressure gas through a turbine or an expansion engine results in a net work output with a resulting decrease in enthalpy. This decrease in enthalpy leads to a decrease in temperature. In an ideal case, the expansion will be reversible adiabatic, however, in an actual case, the expansion can be adiabatic but irreversibility exists due to fluid friction. Similar to the case of liquids, it can be shown from the steady flow energy equation that expansion with a net work output reduces the exit enthalpy and hence temperature of the gas. If the changes in potential and kinetic energy are negligible and the process is adiabatic, then:

$$w_{net} = (h_1 - h_2) \tag{8.7}$$

Since w_{net} is positive, the outlet enthalpy h_2 is less than inlet enthalpy h_1; hence the outlet temperature T_2 will also be less than inlet temperature T_1. Unlike isenthalpic expansion, an approximately reversible adiabatic expansion with a net work output always produces a decrease in temperature irrespective of the initial temperature. However, one disadvantage with adiabatic expansion through a turbine/expansion engine is that the temperature drop decreases as the temperature decreases. Hence in practice a combination of adiabatic expansion followed by isenthalpic expansion is used to liquefy gases. The adiabatic expansion is used to pre-cool the gas to a temperature lower than the inversion temperature and then throttling is used to produce liquid. This method was first used by Kapitza to liquefy helium (maximum inversion temperature: 43 K). In practical systems efficient heat exchangers are used to cool the incoming gas by the outgoing gas.

8.2.6. Thermoelectric Refrigeration

Thermoelectric refrigeration is a novel method of producing low temperatures and is based on the reverse Seebeck effect. Figure 8.6 shows the illustration of Seebeck and Peltier effects. As shown, in Seebeck effect an EMF, E is produced when the junctions of two dissimilar conductors are maintained at two different temperatures T_1 and T_2. This principle is used for measuring temperatures using thermocouples. Experimental studies show that Seebeck effect is reversible. The electromotive force produced is given by:

$$E = \alpha(T_1 - T_2) \tag{8.8}$$

where α is the *thermoelectroic power* or *Seebeck coefficient*. For a constant cold junction temperature (T_2),

$$\alpha = \frac{dE}{dT} \tag{8.9}$$

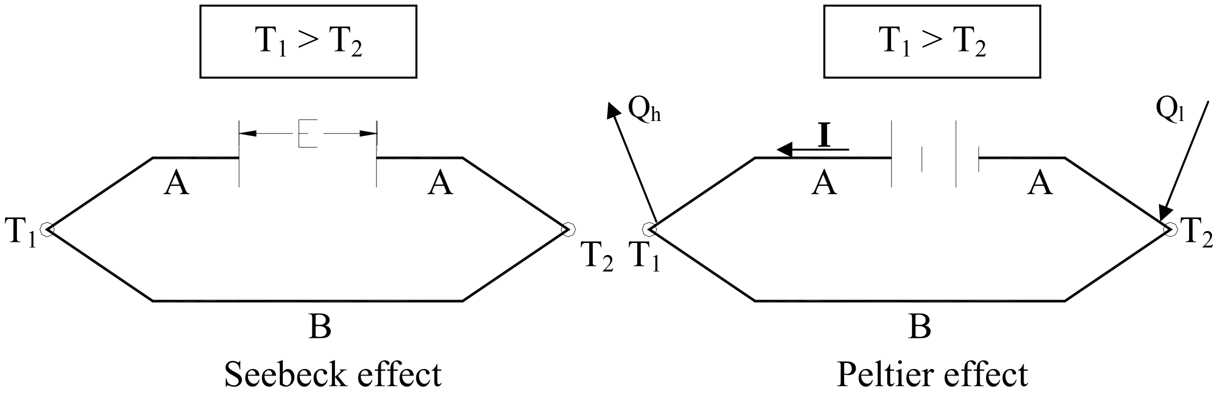

***Fig.8.6**. Illustration of Seebeck and Peltier effects*

If a closed circuit is formed by the conductors, then an electrical current, I flows due to the emf and this would result in irreversible generation of heat ($q_{ir}=I^2R$) due to the finite resistance R of the conductors. This effect is known as *Joulean Effect.*

Due to different temperatures T_1 and T_2 ($T_1 > T_2$), there will be heat transfer by conduction also. This is also irreversible and is called as *conduction effect*. The amount of heat transfer depends on the overall thermal conductance of the circuit.

When a battery is added in between the two conductors A and B whose junctions are initially at same temperature, and a current is made to flow through the circuit, the junction temperatures will change, one junction becoming hot (T_1) and the other becoming cold (T_2). This effect is known as Peltier effect. Refrigeration effect is obtained at the cold junction and heat is rejected to the surroundings at the hot junction. This is the basis for *thermoelectric refrigeration systems*. The position of hot and cold junctions can be reversed by reversing the direction of current flow. The heat transfer rate at each junction is given by:

$$\dot{Q} = \phi I \tag{8.10}$$

where ϕ is the Peltier coefficient in volts and I is the current in amperes.

When current is passed through a conductor in which there is an initial uniform temperature gradient, then it is observed that the temperature distribution gets distorted as heat transfer takes place. This effect is known as *Thomson effect*. The heat transfer rate per unit length (W/cm) due to Thomson effect is given by:

$$Q_\tau = \tau I \frac{dT}{dx} \tag{8.11}$$

where τ is the Thomson coefficient (volts per K), I is the current (amperes) and (dT/dx) is the temperature gradient in the conductor (K/cm).

It has been shown from thermodynamic analysis that the Seebeck, Peltier and Thomson coefficients are related by the equations:

$$\phi_{AB} = (\phi_A - \phi_B) = \alpha_{AB} T = (\alpha_A - \alpha_B) T \tag{8.12a}$$

$$\frac{\tau_A - \tau_B}{T} = \frac{d(\alpha_A - \alpha_B)}{dT} \tag{8.12b}$$

where ϕ_A, α_A and τ_A are the Peltier, Seebeck and Thomson coefficients for material A and ϕ_B, α_B and τ_B are the Peltier, Seebeck and Thomson coefficients for material B, respectively. The Thomson coefficient becomes zero if the thermoelectric power α_{AB} remains constant. From the above equations it is seen that the heat transfer rate due to Peltier effect is;

$$\dot{Q} = \phi_{AB} I = \alpha_{AB} I T \tag{8.13}$$

The above equation shows that in order to have high heat transfer rates at low temperatures, either α_{AB} should be high and/or high currents should be used. However, high currents lead to high heat generation due to the Joulean effect.

Since the coefficients are properties of conducting materials, selection of suitable material is very important in the design of efficient thermoelectric refrigeration systems. Ideal thermoelectric materials should have high electrical conductivity and low thermal conductivity. Pure metals are not good due to their high thermal conductivity, while insulating materials are not good due to their low electrical conductivity. Thermoelectric refrigeration systems became commercial with the development of semiconductor materials, which typically have reasonably high electrical conductivity and low thermal conductivity. Thermoelectric refrigeration systems based on semiconductors consist of p-type and n-type materials. The p-type materials have positive thermoelectric power α_p, while the n-type materials have negative thermoelectric power, α_n. By carrying out a simple thermodynamic analysis it was shown that the temperature difference between hot and cold junctions (T_2-T_1), rate of refrigeration $\dot{Q}_l$ and COP of a thermoelectric refrigeration system are given by:

$$(T_2 - T_1) = \frac{(\alpha_p - \alpha_n)T_1 I - \dot{Q}_l - \frac{1}{2}I^2 R}{U}$$

$$\dot{Q}_l = (\alpha_p - \alpha_n)T_1 I - U(T_2 - T_1) - \frac{1}{2}I^2 R \qquad (8.14)$$

$$COP = \frac{\dot{Q}_l}{W} = \frac{(\alpha_p - \alpha_n)T_1 I - U(T_2 - T_1) - \frac{1}{2}I^2 R}{(\alpha_p - \alpha_n)(T_2 - T_1)I + I^2 R}$$

where $\dot{Q}_l$ is the rate of refrigeration (W) obtained at temperature T_1, W is the power input by the battery (W) and U is the effective thermal conductance between the two junctions. From the above expression it can be easily shown that in the absence of the two irreversible effects, i.e., conduction effect and Joulean effect, the COP of an ideal thermoelectric refrigeration system is same as that of a Carnot refrigerator. The temperature difference between the junctions will be maximum when the refrigeration effect is zero.

An optimum current can be obtained by maximizing each of the above performance parameters, i.e., temperature difference, refrigeration effect and COP. For example, differentiating the expression for COP with respect to I and equating it zero, we get the expressions for optimum current and maximum COP as:

$$I_{opt} = \frac{(\alpha_p - \alpha_n)(T_2 - T_1)}{R(\sqrt{1 + ZT_m} - 1)}$$

$$COP_{max} = \frac{\left(\frac{T_1}{T_2 - T_1}\right)\left(\sqrt{1 + ZT_m} - \frac{T_2}{T_1}\right)}{(\sqrt{1 + ZT_m} + 1)} \qquad (8.15a)$$

where Z is a property parameter called figure of merit and Tm is the mean of T_2 and T_1. The figure of merit Z is given by:

$$Z = \frac{(\alpha_p - \alpha_n)^2}{UR} \qquad (8.15b)$$

It can be shown that for best performance the figure of merit Z should be as high as possible. It is shown that Z is related to the thermal and electrical conductivities of the materials and the electrical contact resistance at the junctions. For a special case where both p- and n-type materials have equal electrical and thermal conductivities (σ and k) and equal but opposite values of thermoelectric power α, it is shown that the maximum figure of merit Z_{max} is given by:

$$Z_{max} = \frac{\alpha^2 \sigma}{k(1 + \frac{2r}{\rho L})} \tag{8.16}$$

where ρ is the electrical resistivity and L is the length of the modules.

8.2.7. Adiabatic demagnetization

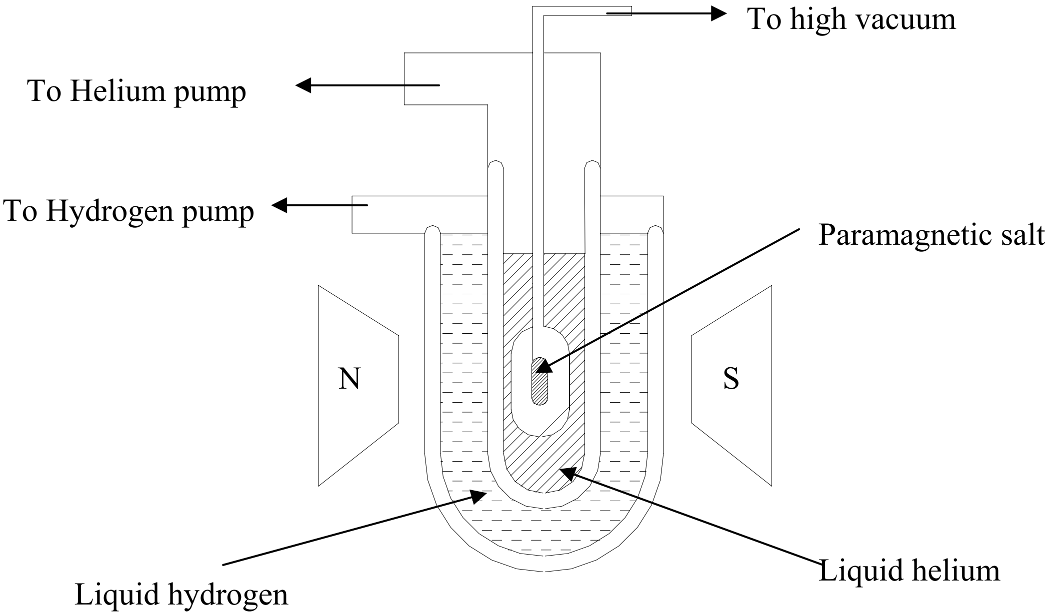

Fig.8.7. *Schematic of a setup depicting magnetic refrigeration*

Magnetic refrigeration is based on the magnetocaloric effect, discovered by E. Warburg in 1881. Similar to mechanical compression and expansion of gases, there are some materials that raise their temperatures when adiabatically magnetised, and drop their temperature when adiabatically demagnetised. Temperature very near the absolute zero may be obtained by adiabatic demagnetization of certain paramagnetic salts. Each atom of the paramagnetic salt may be considered to be a tiny magnet. If the salt is not magnetized then all its atoms or the magnets are randomly oriented such that the net magnetic force is zero. If it is exposed to a strong magnetic field, the atoms will align themselves to the direction of magnetic field. This requires work and the temperature increases during this process. If the salt is kept in a container surrounded by Helium, the heat will be absorbed by Helium. Now if the magnetic field is suddenly removed, the atoms will come back to the original random orientation. This requires work to be done by the atoms. If there is no heat transfer from surroundings, the internal energy of the salt will decrease as it does work. Consequently the salt will be cooled.

This process is used to achieve temperature near absolute zero. Paramagnetic salts like gadolinium sulphate are used. Magnetization involves alignment of electronic spin. Protons and neutron also have spins called nuclear spins, which can be aligned by magnetic field. This gives lower temperatures for a brief instant of time. This is however not macroscopic temperature but temperature associated with nuclear spin.

Questions:

1. What is refrigeration? How does it differ from cooling? (Answer)

2. Prove that the latent heat of vaporization (h_{fg}) is equal to

$$h_{fg} = \frac{RT^2}{P}\frac{dP}{dT}$$

assuming ideal gas equation of state for vapour. (Hint: Start from the fundamental derivation of Clausius- Clapeyron equation) (Solution)

3. The boiling point of a substance at 1 atm is 400K. Estimate the approximate value of the vapour pressure of the substance at 315 K. Assume:

$$\frac{\bar{h}_{fg}}{T_B} = 88 \text{ kJ/kg-mol K}$$ (Solution)

4. The vapour pressure of solid ammonia is given by:

$$\ln P = 23.03 - \frac{3754}{T}$$

while that of liquid ammonia by:

$$\ln P = 19.49 - \frac{3063}{T}$$

where P is in mm of mercury. What are the latent heats of sublimation (l_{sub}) vaporization (l_{vap}) ? (Solution)

5. Prove that Joule-Thompson coefficient, μ_{JT}, is equal to

$$\mu_{JT} = \frac{\left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right]}{c_P}$$

from basic laws of thermodynamics. Here v is the specific volume and c_P is the specific heat at constant pressure.

Also show that these will be no change in temperature when ideal gas is made to undergo a throttling process. (Solution)

6. Clarify whether the following statements are True or False :

1. Refrigeration is a spontaneous process. (Answer)
2. Refrigeration and cooling are the same. (Answer)
3. It is possible to produce cooling by addition of sodium chloride in water. (Answer)
4. Higher the normal boiling point higher is the molar enthalpy of vaporization. (Answer)
5. In a phase change system a substance of higher latent heat of phase change should be selected for compact systems. (Answer)
6. Sudden expansion of liquids and gases is isenthalpic if a turbine is used and isentropic if its done with a throttling device. (Answer)
7. The Joule Thompson coefficient (μ_{JT}) is the measure of deviation of real gas from ideal behaviour. (Answer)
8. Isenthalpic expansion of most gases lead to cooling as maximum inversion temperature is much above room temperature. (Answer)
9. Throttling at low pressure produces higher reduction in temperature compared to its throttling at high temperatures. (Answer)
10. See beck effect illustrates that if an EMF is connected in between two dissimilar conductors then one of the junction becomes hot while the other becomes cold. (Answer)
11. Temperatures close to absolute zero can be obtained by adiabatic demagnetization. (Answer)