Lesson 2

History Of Refrigeration – Development Of Refrigerants And Compressors

The objectives of the present lesson are to introduce the student to the history of refrigeration in terms of:

1. Refrigerant development *(Section 2.2)*:

   i. Early refrigerants *(Section 2.2.1)*
   ii. Synthetic fluorocarbon based refrigerants *(Section 2.2.2)*
   iii. Non-ozone depleting refrigerants *(Section 2.2.3)*

2. Compressor development *(Section 2.3)*:

   i. Low-speed steam engine driven compressors *(Section 2.3.1)*
   ii. High-speed electric motor driven compressors *(Section 2.3.1)*
   iii. Rotary vane and rolling piston compressors *(Section 2.3.2)*
   iv. Screw compressors *(Section 2.3.2)*
   v. Scroll compressors *(Section 2.3.2)*
   vi. Centrifugal compressors *(Section 2.3.3)*

At the end of the lesson the student should be able to:

i. State the importance of refrigerant selection
ii. List various refrigerants used before the invention of CFCs
iii. List various CFC refrigerants and their impact on refrigeration
iv. State the environmental issues related to the use of CFCs
v. State the refrigerant development after Montreal protocol
vi. List important compressor types
vii. List important landmarks in the development of compressors

2.1. Introduction:

The development of refrigeration and air conditioning industry depended to a large extent on the development of refrigerants to suit various applications and the development of various system components. At present the industry is dominated by the vapour compression refrigeration systems, even though the vapour absorption systems have also been developed commercially. The success of vapour compression refrigeration systems owes a lot to the development of suitable refrigerants and compressors. The theoretical thermodynamic efficiency of a vapour compression system depends mainly on the operating temperatures. However, important practical issues such as the system design, size, initial and operating costs, safety, reliability, and serviceability etc. depend very much on the type of refrigerant and compressor selected for a given application. This lesson presents a brief history of refrigerants and compressors. The emphasis here is mainly on vapour compression refrigeration systems, as these are the most commonly used systems, and also refrigerants and compressors play a critical role here. The other popular type of refrigeration system, namely the vapour absorption type has seen fewer changes in terms of refrigerant development, and relatively less number of problems exist in these systems as far as the refrigerants are concerned.

2.2. Refrigerant development – a brief history

In general a refrigerant may be defined as "any body or substance that acts as a cooling medium by extracting heat from another body or substance". Under this general definition, many bodies or substances may be called as refrigerants, e.g. ice, cold water, cold air etc. In closed cycle vapour compression, absorption systems, air cycle refrigeration systems the refrigerant is a working fluid that undergoes cyclic changes. In a thermoelectric system the current carrying electrons may be treated as a refrigerant. However, normally by refrigerants we mean the working fluids that undergo condensation and evaporation as in compression and absorption systems. The history that we are talking about essentially refers to these substances. Since these substances have to evaporate and condense at required temperatures (which may broadly lie in the range of $-100^{o}C$ to $+100^{o}C$) at reasonable pressures, they have to be essentially volatile. Hence, the development of refrigerants started with the search for suitable, volatile substances. Historically the development of these refrigerants can be divided into three distinct phases, namely:

i. Refrigerants prior to the development of CFCs
ii. The synthetic fluorocarbon (FC) based refrigerants
iii. Refrigerants in the aftermath of stratospheric ozone layer depletion

2.2.1. Refrigerants prior to the development of CFCs

Water is one of the earliest substances to be used as a refrigerant, albeit not in a closed system. Production of cold by evaporation of water dates back to 3000 B.C. Archaeological findings show pictures of Egyptian slaves waving fans in front of earthenware jars to accelerate the evaporation of water from the porous surfaces of the pots, thereby producing cold water. Of course, the use of "punkahs" for body cooling in hot summer is very well known in countries like India. Production of ice by nocturnal cooling is also well known. People also had some knowledge of producing sub-zero temperatures by the use of "refrigerant mixtures". It is believed that as early as 4th Century AD people in India were using mixtures of salts (sodium nitrate, sodium chloride etc) and water to produce temperatures as low as $-20^{o}C$. However, these natural refrigeration systems working with water have many limitations and hence were confined to a small number of applications.

W*ater* was the first refrigerant to be used in a continuous refrigeration system by William Cullen (1710-1790) in 1755. William Cullen is also the first man to have scientifically observed the production of low temperatures by evaporation of *ethyl ether* in 1748. Oliver Evans (1755-1819) proposed the use of a volatile fluid in a closed cycle to produce ice from water. He described a practical system that uses *ethyl ether* as the refrigerant. As already mentioned the credit for building the first vapour compression refrigeration system goes to Jakob Perkins (1766-1849). Perkins used *sulphuric (ethyl) ether* obtained from India rubber as refrigerant. Early commercial refrigerating machines developed by James Harrison (1816-1893) also used *ethyl ether* as refrigerant. Alexander Twining (1801-1884) also developed refrigerating machines using *ethyl ether.* After these developments, *ethyl ether* was used as refrigerant for several years for ice making, in breweries etc. Ether machines were gradually replaced by ammonia and carbon dioxide based machines, even though they were used for a longer time in tropical countries such as India.

Ethyl ether appeared to be a good refrigerant in the beginning, as it was easier to handle it since it exists as a liquid at ordinary temperatures and atmospheric pressure. Ethyl ether has a normal boiling point (NBP) of 34.5^{o}C, this indicates that in order to obtain low temperatures, the evaporator pressure must be lower than one atmosphere, i.e., operation in vacuum. Operation of a system in vacuum may lead to the danger of outside air leaking into the system resulting in the formation of a potentially explosive mixture. On the other hand a relatively high normal boiling point indicates lower pressures in the condenser, or for a given pressure the condenser can be operated at higher condensing temperatures. This is the reason behind the longer use of ether in tropical countries with high ambient temperatures. Eventually due to the high NBP, toxicity and flammability problems ethyl ether was replaced by other refrigerants. Charles Tellier (1828-1913) introduced *dimethyl ether* (NBP = 23.6^{o}C) in 1864. However, this refrigerant did not become popular, as it is also toxic and inflammable.

In 1866, the American T.S.C. Lowe (1832-1913) introduced *carbon dioxide* compressor. However, it enjoyed commercial success only in 1880s due largely to the efforts of German scientists Franz Windhausen (1829-1904) and Carl von Linde (1842-1934). Carbon dioxide has excellent thermodynamic and thermophysical properties, however, it has a low critical temperature (31.7^{o}C) and very high operating pressures. Since it is non-flammable and non-toxic it found wide applications principally for marine refrigeration. It was also used for refrigeration applications on land. Carbon dioxide was used successfully for about sixty years however, it was completely replaced by CFCs. It is ironic to note that ever since the problem of ozone layer depletion was found, carbon dioxide is steadily making a comeback by replacing the synthetic CFCs/HCFCs/HFCs etc.

One of the landmark events in the history of refrigerants is the introduction of *ammonia*. The American David Boyle (1837-1891) was granted the first patent for ammonia compressor in 1872. He made the first single acting vertical compressor in 1873. However, the credit for successfully commercializing ammonia systems goes to Carl von Linde (1842-1934) of Germany, who introduced these compressors in Munich in 1876. Linde is credited with perfecting the ammonia refrigeration technology and owing to his pioneering efforts; ammonia has become one of the most important refrigerants to be developed. Ammonia has a NBP of 33.3^{o}C, hence, the operating pressures are much higher than atmospheric. Ammonia has excellent thermodynamic and thermophysical properties. It is easily available and inexpensive. However, ammonia is toxic and has a strong smell and slight flammability. In addition, it is not compatible with some of the common materials of construction such as copper. Though these are considered to be some of its disadvantages, ammonia has stood the test of time and the onslaught of CFCs due to its excellent properties. At present ammonia is used in large refrigeration systems (both vapour compression and vapour absorption) and also in small absorption refrigerators (triple fluid vapour absorption).

In 1874, Raoul Pictet (1846-1929) introduced *sulphur dioxide* (NBP= 10.0^{o}C). Sulphur dioxide was an important refrigerant and was widely used in small refrigeration systems such as domestic refrigerators due to its small refrigerating effect. Sulphur dioxide has the advantage of being an auto-lubricant. In addition it is not only non-flammable, but actually acts as a flame extinguisher. However, in the presence of water vapour it produces sulphuric acid, which is highly corrosive. The problem of corrosion was overcome by an airtight sealed compressor (both motor and compressor are mounted in the same outer casing). However, after about sixty years of use in appliances such as domestic refrigerators, sulphur dioxide was replaced by CFCs.

In addition to the above, other fluids such as methyl chloride, ethyl chloride, iso-butane, propane, ethyl alcohol, methyl and ethyl amines, carbon tetra chloride, methylene chloride, gasoline etc. were tried but discarded due to one reason or other.

2.2.2. The synthetic CFCs/HCFCs:

Almost all the refrigerants used in the early stages of refrigeration suffered from one problem or other. Most of these problems were linked to safety issues such as toxicity, flammability, high operating pressures etc. As a result large-scale commercialization of refrigeration systems was hampered. Hence it was felt that "refrigeration industry needs a new refrigerant if they expect to get anywhere". The task of finding a "safe" refrigerant was taken up by the American Thomas Midgley, Jr., in 1928. Midgley was already famous for the invention of tetra ethyl lead, an important anti-knock agent for petrol engines. Midgley along with his associates Albert L. Henne and Robert R. McNary at the Frigidaire Laboratories (Dayton, Ohio, USA) began a systematic study of the periodic table. From the periodic table they quickly eliminated all those substances yielding insufficient volatility. They then eliminated those elements resulting in unstable and toxic gases as well as the inert gases, based on their very low boiling points. They were finally left with eight elements: carbon, nitrogen, oxygen, sulphur, hydrogen, fluorine, chlorine and bromine. These eight elements clustered at an intersecting row and column of the periodic table, with fluorine at the intersection. Midgley and his colleagues then made three interesting observations:

i. Flammability decreases from left to right for the eight elements
ii. Toxicity generally decreases from the heavy elements at the bottom to the lighter elements at the top
iii. Every known refrigerant at that time was made from the combination of those eight "Midgley" elements.

A look at the refrigerants discussed above shows that all of them are made up of seven out of the eight elements identified by Midgley (fluorine was not used till then). Other researchers have repeated Midgley's search with more modern search methods and databases, but arrived at the same conclusions (almost all the currently used refrigerants are made up of Midgley elements, only exception is Iodine, studies are being carried out on refrigerants containing iodine in addition to some of the Midgley elements). Based on their study, Midgely and his colleagues have developed a whole range of new refrigerants, which are obtained by partial replacement of hydrogen atoms in hydrocarbons by fluorine and chlorine. They have shown how fluorination and chlorination of hydrocarbons can be varied to obtain desired boiling points (volatility) and also how properties such as toxicity, flammability are influenced by the composition. The first commercial refrigerant to come out of Midgley's study is Freon-12 in 1931. Freon-12 with a chemical formula CCl_2F_2, is obtained by replacing the four atoms of hydrogen in methane (CH_4) by two atoms of chlorine and two atoms of fluorine. Freon-12 has a normal boiling point of 29.8^{o}C, and is one of the most famous and popular synthetic refrigerants. It was exclusively used in small domestic refrigerators, air conditioners, water coolers etc for almost sixty years. Freon-11 (CCl_3F) used in large centrifugal air conditioning systems was introduced in 1932. This is followed by Freon-22 ($CHClF_2$) and a whole series of synthetic refrigerants to suit a wide variety of applications.

Due to the emergence of a large number of refrigerants in addition to the existence of the older refrigerants, it has become essential to work out a numbering system for refrigerants. Thus all refrigerants were indicated with 'R' followed by a unique number (thus Freon-12 is changed to R12 etc). The numbering of refrigerants was done based on certain guidelines. For all synthetic refrigerants the number (e.g. 11, 12, 22) denotes the chemical composition. The number of all inorganic refrigerants begins with '7' followed by their molecular weight. Thus R-717 denotes ammonia (ammonia is inorganic and its molecular weight is 17), R-718 denotes water etc.. Refrigerant mixtures begin with the number 4 (zeotropic) or 5 (azeotropic), e.g. R-500, R-502 etc.

The introduction of CFCs and related compounds has revolutionized the field of refrigeration and air conditioning. Most of the problems associated with early refrigerants such as toxicity, flammability, and material incompatibility were eliminated completely. Also, Freons are highly stable compounds. In addition, by cleverly manipulating the composition a whole range of refrigerants best suited for a particular application could be obtained. In addition to all this, a vigorous promotion of these refrigerants as "wonder gases" and "ideal refrigerants" saw rapid growth of Freons and equally rapid exit of conventional refrigerants such as carbon dioxide, sulphur dioxide etc. Only ammonia among the older refrigerants survived the Freon magic. The Freons enjoyed complete domination for about fifty years, until the Ozone Layer Depletion issue was raised by Rowland and Molina in 1974. Rowland and Molina in their now famous theory argued that the highly stable chlorofluorocarbons cause the depletion of stratospheric ozone layer. Subsequent studies and observations confirmed Rowland and Molina theory on stratospheric ozone depletion by chlorine containing CFCs. In view of the seriousness of the problem on global scale, several countries have agreed to ban the harmful Ozone Depleting Substances, ODS (CFCs and others) in a phase-wise manner under Montreal Protocol. Subsequently almost all countries of the world have agreed to the plan of CFC phase-out. In addition to the ozone layer depletion, the CFCs and related substances were also found to contribute significantly to the problem of "global warming". This once again brought the scientists back to the search for "safe" refrigerants. The "safety" now refers to not only the immediate personal safety issues such as flammability, toxicity etc., but also the long-term environmental issues such as ozone layer depletion and global warming.

2.2.3. Refrigerants in the aftermath of Ozone Layer Depletion:

The most important requirement for refrigerants in the aftermath of ozone layer depletion is that it should be a non-Ozone Depleting Substance (non-ODS). Out of this requirement two alternatives have emerged. The first one is to look for zero ODP synthetic refrigerants and the second one is to look for "natural" substances. Introduction of *hydrofluorocarbons* (HFCs) and their mixtures belong to the first route, while the re-introduction of carbon dioxide (in a supercritical cycle), water and various hydrocarbons and their mixtures belong to the second route. The increased use of ammonia and use of other refrigeration cycles such as air cycle refrigeration systems and absorption systems also come under the second route. Both these routes have found their proponents and opponents. HFC-134a (synthetic substance) and hydrocarbons (natural substances) have emerged as alternatives to Freon-12. No clear pure fluid alternative has been found as yet for the other popular refrigerant HCFC-22. However several mixtures consisting of synthetic and natural refrigerants are being used and suggested for future use. Table 2.1 shows the list of refrigerants being replaced and their alternatives. Mention must be made here about the other environmental problem, global warming. In general the non-ODS synthetic refrigerants such as HFC-134a have high global warming potential (GWP), hence they face an uncertain future. Since the global warming impact of a refrigerant also depends on the energy efficiency of the system using the refrigerant (indirect effect), the efficiency issue has become important in the design of new refrigeration systems. Though the issues of ozone layer depletion and global warming has led to several problems, they have also had beneficial effects of making people realize the importance of environmental friendliness of technologies. It is expected that with the greater awareness more responsible designs will emerge which will ultimately benefit the whole mankind.

Refrigerant	**Composition**	**Normal Boiling Point (NBP) (°C)***	**Ozone Depletion Potential (ODP) (R11=1)**	**Global Warming Potential (GWP) (CO_2=1)**	**Retrofit or New**
Example Candidate Replacements for CFC-11					
CFC-11		*23.8*	*1.0*	*3800*	
HCFC-123		27.9	0.020	90	Both
HCFC-141b		32.2	0.110	630	New
HFC-245fa		15.3	0	900	New
n-pentane		36.19	0	0	Both
Example Candidate Replacements for CFC-114					
CFC-114		*3.78*	*0.8*	*9300*	
HCFC-124		-13.2	0.022	480	Both
HFC-134		4.67	0	1300	New
R600		-0.45	0	0	Both
Example Candidate Replacements for CFC-12					
CFC-12		*-29.79*	*1*	*8100*	
HFC-134a		-26.1	0	1300	New
R401A	R22/152a/124 (53/13/34)	-33.0/6.3	0.037	1100	Both
R409A	R22/124/142b (60/25/15)	-34.3/8.5	0.048	1400	Both
propane-ethane	R290/170 (43/57)	-31.9/7.9	0	3	Both
Example Candidate Replacements for HCFC-22					
HCFC-22		*-40.75*	*0.055*	*1700*	
R407C	R32/125/134a (23/25/52)	-44.0/7.2	0	1600	Both
R410A	R32/125	-52.7/<0.1	0	1900	New
	R23/32/134a	-43.0/10.2	0	1600	New
propane-ethane	R290/170 (95/5)	-49.3/7.9	0	3	Both
Example Candidate Replacements for R502					
R502	*CFC115/HCFC22 (48.8/51.2)*	*-45.6 azeo*		*5500*	
R404a	R125/143a/134a (44/52/4)	-46.5/0.8	0	3700	Both
R507	R125/143a (50/50)	-46.7 azeo	0	3800	Both
	R32/125/143a (10/45/45)	-49.7/0.9	0	3500	Both
propane-ethane	R290/170 (95/5)	-49.3/7.9	0	3	Both
Other Options - Natural Refrigerants					
Air			0	0	
Water			0	?	
Ammonia			0	0	
Carbon dioxide			0	1	

* or bubble point /temperature glide for mixtures. Temperature glide = $T_{dew} - T_{bubble}$

***Table 2.1**. Candidate refrigerants for replacing CFCs*

Q. Ethyl ether was the first refrigerant to be used commercially, because:
a) It exists as liquid at ambient conditions
b) It is safe
c) It is inexpensive
d) All of the above
Ans. a)
Q. Ammonia is one of the oldest refrigerants, which is still used widely, because:
a) It offers excellent performance
b) It is a natural refrigerant
c) It is inexpensive
d) All of the above
Ans. d)
Q. In the olden days Carbon dioxide was commonly used in marine applications as:
a) It has low critical temperature
b) Its operating pressures are high
c) It is non-toxic and non-flammable
d) It is odorless
Ans. c)
Q. Sulphur dioxide was mainly used in small refrigeration systems, because:
a) It is non-toxic and non-flammable
b) It has small refrigeration effect
c) It is expensive
d) It was easily available
Ans. b)
Q. Need for synthetic refrigerants was felt, as the available natural refrigerants:
a) Were not environment friendly
b) Suffered from several perceived safety issues
c) Were expensive
d) Were inefficient
Ans. b)
Q. The synthetic CFC based refrigerants were developed by:
a) Partial replacement of hydrogen atoms in hydrocarbons by chlorine, fluorine etc.
b) Modifying natural refrigerants such as carbon dioxide, ammonia
c) Modifying inorganic compounds by adding carbon, fluorine and chlorine
d) Mixing various hydrocarbons
Ans. a)
Q. The synthetic refrigerants were extremely popular as they are:
a) Environment friendly
b) Mostly non-toxic and non-flammable
c) Chemically stable
d) Inexpensive
Ans. b) and c)
Q. CFC based refrigerants are being replaced as they are found to:
a) Cause ozone layer depletion
b) Consume more energy
c) React with several materials of construction
d) Expensive
Ans. a)

2.3. Compressor development – a brief history

Compressor may be called as a heart of any vapour compression system. The rapid development of refrigeration systems is made possible due to the developments in compressor technologies.

2.3.1. Reciprocating compressors:

The earliest compressor used by Jakob Perkins is a hand-operated compressor, very much like a hand operated pump used for pumping water. Harrison also used a hand-operated ether compressor in 1850, but later used steam engine driven compressors in commercial machines. A small half horsepower (hp) compressor was used as early as 1857 to produce 8 kg of ice per hour. Three other machines with 8 to 10 hp were in use in England in 1858. In 1859, the firm P.N. Russel of Australia undertook the manufacture of Harrison's machines, the first compressors to be made with two vertical cylinders. The firm of Siebe brothers of England went on perfecting the design of the early compressors. Their first compressors were vertical and the later were horizontal. From 1863 to 1870, Ferdinand Carre of France took out several patents on diaphragm compressors, valves etc.

Charles Tellier used a horizontal single cylinder methyl ether compressor in 1863. These compressors were initially installed in a chocolate factory near Paris and in a brewery in USA in 1868. In 1876 the ship "Le Frigorifique" was equipped with three of Tellier's methyl ether compressors and successfully transported chilled meat from Rouen in France to Buenos Ayres in Argentina (a distance of 12000 km).

T.S.C. Lowe (1832-1913) started making carbon dioxide compressors in 1865, and began to use them in the manufacture of ice from 1868. However, the credit for perfecting the design of carbon dioxide compressor goes to Franz Windhausen of Germany in 1886. The British firm J&E Hall began the commercial production of carbon dioxide compressors in 1887. They started manufacturing two-stage carbon dioxide compressors since 1889. Soon the carbon dioxide systems replaced air cycle refrigeration systems in ships. Several firms started manufacturing these compressors on a large scale. This trend continued upto the Second World War.

A significant development took place in 1876 by the introduction of a twin cylinder vertical compressor working with ammonia by Carl von Linde. Similar to his earlier methyl ether compressor (1875) a bath of liquid mercury was used to make the compressor gas-tight. This ammonia compressor was installed in a brewery in 1877 and worked there till 1908. In 1877, Linde improved the compressor design by introducing a horizontal, double acting cylinder with a stuffing box made from two packings separated by glycerine (glycerine was later replaced by mineral oil). Figure 2.1 shows the schematic of Linde's horizontal, double acting compressor. This design became very successful, and was a subject of many patents. Several manufacturers in other countries adopted this design and manufactured several of these compressors. USA began the production of ammonia compressors on a large scale from 1880.

Raoul Pictet invented the sulphur dioxide compressor in 1874. The machine was initially built in Geneva, then in Paris and afterwards in some other countries. The compressor developed by Pictet was horizontal and was not lubricated as sulphur dioxide acts

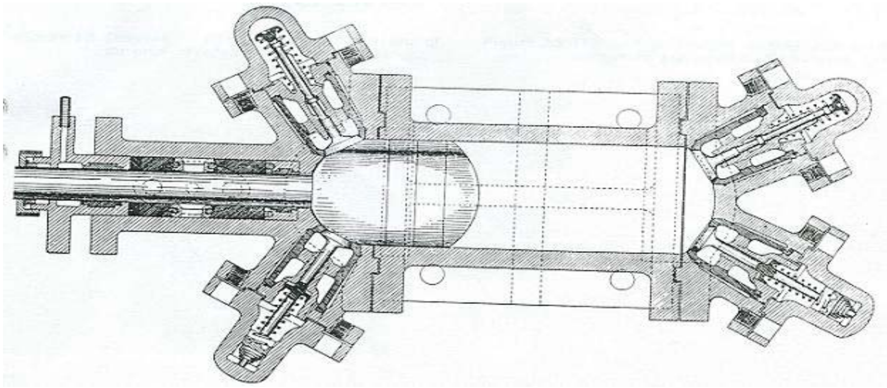

Fig.2.1. *Schematic of Linde's horizontal, double acting compressor*

as an auto-lubricant. As mentioned before, the sulphur dioxide system was an instant success and was used for almost sixty years, especially in small systems.

In 1878, methyl chloride system was introduced by Vincent in France. The French company Crespin & Marteau started manufacturing methyl chloride compressors from 1884. This continued upto the first world war. Escher Wyss of USA started making these compressors from 1913 onwards, right upto the Second World War.

At the beginning of 20th century, practically all the compressors in USA, Great Britain and Germany used either ammonia or carbon dioxide. In France, in addition to these two, sulphur dioxide and methyl chloride were also used. Compressor capacity comparison tests have been conducted on different types of compressors as early as 1887 in Munich, Germany. Stetefeld in 1904 concluded that there was no marked difference in the performance of ammonia, carbon dioxide and sulphur dioxide compressors.

Due to many similarities, the early compressors resembled steam engines in many ways. Like early steam engines, they were double acting (compression takes place on both sides of the piston). Both vertical and horizontal arrangements were used, the former being popular in Europe while the later was popular in USA. A stuffing box arrangement with oil in the gap was used to reduce refrigerant leakage. The crosshead, connecting rod, crank and flywheel were in the open. Initially poppet valves were used, which were later changed to ring-plate type. The cylinder diameters were very large by the present day standards, typically around 500 mm with stroke lengths of the order of 1200 mm. The rotational speeds were low (~ 50 rpm), hence the clearances were small, often less than 0.5 % of the swept volume. Due to generous valve areas and low speed the early compressors were able to compress mixture of vapour as well as liquid. Slowly, the speed of compressors have been increased, for example for a 300 kW cooling capacity system, the mean speed was 40 rpm in 1890, 60 in 1900, 80 in 1910, 150 to 160 in 1915, and went upto 220 in 1916. The term "high speed" was introduced in 1915 for compressors with speeds greater than 150 rpm. However, none of the compressors of this period exceeded speeds of 500 rpm. However, compressors of very large capacities (upto 7 MW cooling capacity) were successfully built and operated by this time. In 1905 the American engineer G.T. Voorhees introduced a dual effect compressor, which has a supplementary suction orifice opened during compression so that refrigerant can be taken in at two different pressures. As mentioned, the first two-stage carbon dioxide compressor was made in 1889 by J&E Hall of England. Sulzer Company developed the first two-stage ammonia compressor in 1889. York Company of USA made a two-stage ammonia compressor in 1892.

About 1890, attention was focused on reducing the clearance space between the piston and cylinder head (clearance space) in order to increase the capacity of the compressors. Attention was also focused on the design of stuffing box and sealing between piston and cylinder to reduce refrigerant leakage. In 1897 the Belgian manufacturer Bruno Lebrun introduced a rotary stuffing box, which was much easier to seal than the reciprocating one. A rotating crankshaft enclosed in a crankcase drove the two opposed horizontal cylinders. Many studies were also conducted on compressor valves as early as 1900. By 1910, the heavy bell valves were replaced by much lighter, flat valves. By about 1900, the design of stuffing box for large compressors was almost perfected. However, for smaller compressors the energy loss due to friction at the stuffing box was quiet high. This fact gave rise to the idea of sealed or hermetic compressor (both compressor and motor are mounted in the same enclosure). However, since the early electric motors with brushes and commutator and primitive insulation delayed the realization of hermetic compressors upto the end of First World War.

As mentioned, the earliest compressors were hand operated. Later they were driven by steam engines. However, the steam engines gradually gave way to electric motors. Diesel and petrol engine driven compressors were developed much later. In USA, 90% of the motive power was provided by the steam engine in 1914, 71% in 1919, 43% in 1922 and 32% in 1924. This trend continued and slowly the steam engine driven compressors have become almost obsolete. Between 1914 and 1920, the electric motor was considered to be the first choice for refrigerant compressors.

About 1920, high-speed compressors (with speeds greater than 500 rpm) began to appear in the market. The horizontal, double acting compressors were gradually replaced by multi-cylinder, vertical, uni-flow compressors in V- and W- arrangement, the design being adopted from automobile engine design. In 1937, an American compressor (Airtemp) comprised two groups of 7 cylinders arranged radially at both ends of 1750 rpm electric motor. These changes resulted in a reduction of size and weight of compressor, for example, a York 300 000 kcal/h compressor had the following characteristics:

Year	Refrigerant	No. of cylinders	Speed (rpm)	Cooling capacity per unit weight
1910	NH_3	2 cylinders	70	6.5 kcal/h per kg
1940	NH_3	4 cylinders	400	42 kcal/h per kg
1975	R22	16 cylinders in W-arrangement	1750	200 kcal/h per kg

All the compressors developed in the early stages are of "open" type. In the open type compressors the compressor and motor are mounted separately. The driving shaft of the motor and the crankshaft of the compressor are connected either by a belt drive or a gear drive. With the open type compressors there is always a possibility of refrigerant leakage from an open type compressor, even though the rotating mechanical seals developed reduced the leakage rate considerably. Since leakage cannot be eliminated completely, systems working with open type compressors require periodic servicing and maintenance. Since it is difficult to provide continuous maintenance on small systems (e.g. domestic refrigerators), serious thought was given to tackle this problem. A hermetic or sealed compressor was the outcome of this.

An Australian Douglas Henry Stokes made the first sealed or hermetic compressor in 1918. Hermetic compressors soon became extremely popular, and the rapid development of small hermetic compressors has paved the way for taking the refrigeration systems to the households. With the capacitor starting of the electric motor becoming common in 1930s, the design of hermetic compressors was perfected. In 1926, General Electric Co. of USA introduced the domestic refrigerator working with a hermetic compressor. Initially 4-pole motors were used. After 1940 the 4-pole motors were replaced by 2-pole motors, which reduced of the compressor unit significantly. Soon the 2-pole hermetic refrigerant compressor became universal. Gradually, the capacity of hermetic compressors was increased. Now-a - days hermetic compressors are available for refrigerating capacities starting from a few Watts to kilowatts. At present, due to higher efficiency and serviceability, the open type compressors are used in medium to large capacity systems, whereas the hermetic compressors are exclusively used in small capacity systems on a mass production. The currently available hermetic compressors are compact and extremely reliable. They are available for a wide variety of refrigerants and applications. Figure 2.2 shows cut view of a hermetic compressor.

***Fig.2.2**. Cut view of a hermetic compressor*

Other types of compressors:

*2.3.2.*Positive displacement type *(other than reciprocating):*

In 1919, the French engineer Henri Corblin (1867-1947) patented a diaphragm compressor, in which the alternating movement of a diaphragm produced the suction and compression effects. Initially these compressors were used for liquefying chlorine, but later were used in small to medium capacity systems working with ammonia, carbon dioxide etc.

Several types of rotary air compressors existed before the First World War, and this idea has soon been extended to refrigerants. However, they became popular with the introduction of Freons in 1930s. The first positive displacement, rotary vane compressor using methyl chloride was installed on an American ship “Carnegie”. However, a practical positive displacement, rotary vane compressor could only be developed in 1920. In Germany, F.Stamp made an ethyl chloride compressor of 1000 kcal/h capacity. In USA, Sunbeam Electric made small sulphur dioxide based rotary sliding vane compressors of 150 kcal/h capacity, rotating at 1750 rpm for domestic refrigerators. In 1922, Sulzer, Switzerland made “Frigorotor” of 1000 to 10000 kcal/h using methyl chloride. Sulzer later extended this design to ammonia for large capacities (“Frigocentrale”). Escher Wyss, also of Switzerland rotary sliding vane compressor “Rotasco” in 1936. These compressors were also made by Lebrun, Belgium in 1924 and also by Grasso (Netherlands).

A model of the rolling piston type compressor was made in 1919 in France. This compressor was improved significantly by W.S.F. Rolaff of USA in 1920 and M. Guttner of Germany in 1922. Rolaff’s design was first tried on a sulphur dioxide based domestic refrigerator. Guttner’s compressors were used with ammonia and methyl chloride in large commercial installations. Hermetic, rolling piston type compressors were made in USA by Frigidaire for refrigerant R114, by General Electric for ethyl formate and by Bosch in Germany for sulphur dioxide. In 1931, Vilter of USA made large rotary compressors (200000 kcal/h) first for ammonia and then for R12.

At present, positive displacement rotary compressors based on sliding vane and rolling piston types are used in small to medium capacity applications all over the world. These compressors offer the advantages of compactness, efficiency, low noise etc. However, these compressors require very close manufacturing tolerances as compared to reciprocating compressors. Figure 2.3 shows the schematic of a rolling piston compressor. The low pressure refrigerant from the evaporator enters into the compressor from the port on the right hand side, it gets compressed due to the rotation of the rolling piston and leaves the compressor from the discharge valve on the left hand side.

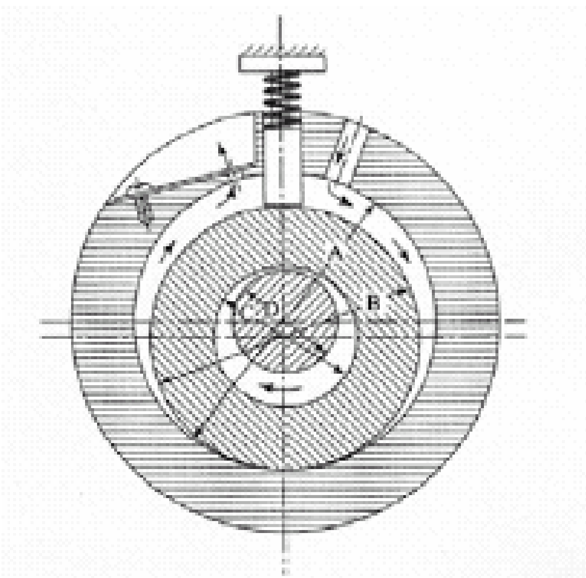

Fig.2.3. Schematic of a rolling piston type, rotary compressor

The screw compressor is another important type of positive displacement compressor. The screw compressors entered into refrigeration market in 1958, even though the basic idea goes back to 1934, by A. Lysholm of Sweden. The screw compressors are of twin-screw (two helical rotors) type or a single-screw (single rotor) type. The twin-screw compressor uses a pair of intermeshing rotors instead of a piston to produce compression. The rotors comprise of helical lobes fixed to a shaft. One rotor is called the male rotor and it will typically have four bulbous lobes. The other rotor is the female rotor and this has valleys machined into it that match the curvature of the male lobes. Typically the female rotor will have six valleys. This means that for one revolution of the male rotor, the female rotor will only turn through 240 deg. For the female rotor to complete one cycle, the male rotor will have to rotate 11/2 times. The single screw type compressor was first made for air in 1967. Grasso, Netherlands introduced single screw refrigerant compressors in 1974. The screw compressor (both single and twin screw) became popular since 1960 and its design has almost been perfected. Presently it is made for medium to large capacity range for ammonia and fluorocarbon based refrigerants. It competes with the reciprocating compressors at the lower capacity range and on the higher capacity side it competes with the centrifugal compressor. Due to the many favorable performance characteristics, screw compressors are taking larger and larger share of refrigerant compressor market. Figure 2.4 shows the photograph of a cut, semi-hermetic, single-screw compressor.

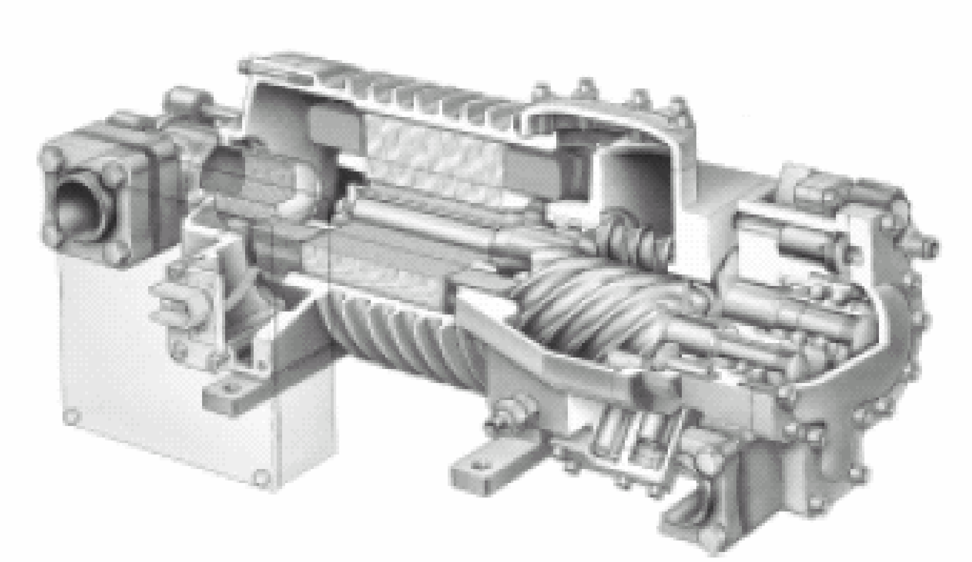

Fig.2.4. Cut view of a semi-hermetic, single-screw compressor

The scroll compressor is one of the more recent but important types of positive displacement compressors. It uses the compression action provided by two intermeshing scrolls - one fixed and the other orbiting. This orbital movement draws gas into the compression chamber and moves it through successively smaller “pockets” formed by the scroll’s rotation, until it reaches maximum pressure at the center of the chamber. There, it’s released through a discharge port in the fixed scroll. During each orbit, several pockets are compressed simultaneously, so operation is virtually continuous. Figure 2.5 shows gas flow pattern in a scroll compressor and Fig.2.6 shows the photograph of a Copeland scroll compressor. The principle of the scroll compressor was developed during the early 1900's and was patented for the first time in 1905. Although the theory for the scroll compressor indicated a machine potentially capable of reasonably good efficiencies, at that time the technology simply didn't exist to accurately manufacture the scrolls. It was almost 65 years later that the concept was re-invented by a refrigeration industry keen to exploit the potentials of scroll technology. Copeland in USA, Hitachi in Japan introduced the scroll type of compressors for refrigerants in 1980s. Scroll compressors have been developed for operating temperatures in the range of 45°C to +5°C suitable for cold storage and air conditioning applications. This scroll has also been successfully applied throughout the world in many freezer applications. Today, scroll compressors are very popular due to the high efficiency, which results from higher compression achieved at a lower rate of leakage. They are available in cooling capacities upto 50 kW. They are quiet in operation and compact. However, the manufacturing of scroll compressors is very complicated due to the extremely close tolerances to be maintained for proper operation of the compressor.

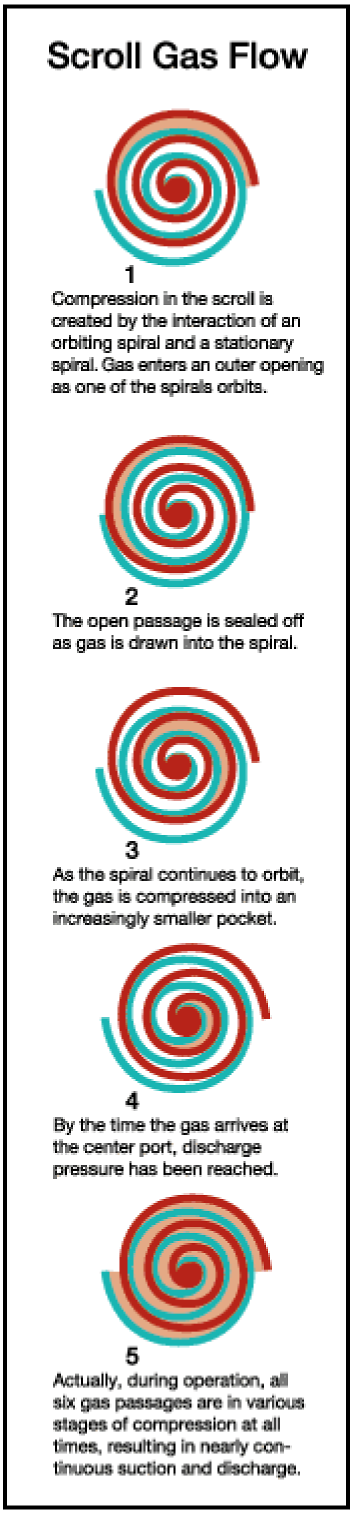

Fig.2.5. Gas flow in a scroll compressor

Fig.2.6. Photograph of a cut scroll compressor (Copeland)

2.3.3. Dynamic type:

Centrifugal compressors (also known as turbocompressors) belong to the class of dynamic type of compressors, in which the pressure rise takes place due to the exchange of angular momentum between the rotating blades and the vapour trapped in between the blades. Centrifugal were initially used for compressing air. The development of these compressors is largely due to the efforts of Auguste Rateau of France from 1890. In 1899, Rateau developed single impeller (rotor) and later multi-impeller fans. Efforts have been made to use similar compressors for refrigeration. In 1910, two Germans H. Lorenz and E. Elgenfeld proposed the use of centrifugal compressors for refrigeration at the International Congress of Refrigeration, Vienna. However, it was Willis H. Carrier, who has really laid the foundation of centrifugal compressors for air conditioning applications in 1911. The motivation for developing centrifugal compressors originated from the fact that the reciprocating compressors were slow and bulky, especially for large capacity systems. Carrier wanted to develop a more compact system working with non-flammable, non-toxic and odorless refrigerant. In 1919, he tried a centrifugal compressor with dichloroethylene ($C_2H_2Cl_2$) and then dichloromethane (CCl_2H_2). In 1926 he used methyl chloride, and in 1927 he had nearly 50 compressors working with dichloroethylene. The centrifugal compressors really took-off with the introduction of Freons in 1930s. Refrigerant R11 was the refrigerant chosen by Carrier for his centrifugal compressor based air conditioning systems in 1933. Later his company developed centrifugal compressors working with R12, propane and other refrigerants for use in low temperature applications. In Switzerland, Brown Boveri Co. developed ammonia based centrifugal compressors as early as 1926. Later they also developed large centrifugal compressors working with Freons. Till 1950, the centrifugal compressors were used mainly in USA for air conditioning applications. However, subsequently centrifugal compressors have become industry standard for large refrigeration and air conditioning applications all over the world. Centrifugal compressors developed before 1940, had 5 to 6 stages, while they had 2 to 3 stages between 1940 to 1960. After 1960, centrifugal compressors with a single stage were also developed. Subsequently, compact, hermetic centrifugal compressor developed for medium to large capacity applications. The large diameter, 3600 rpm machines were replaced by compact 10000 to 12000 rpm compressors. Large centrifugal compressors of cooling capacities in the range of 200000 kcal/h to 2500000 kcal/h were used in places such as World Trade Centre, New York. Figure 2.7 shows cut-view of a two-stage, semi-hermetic centrifugal compressor.

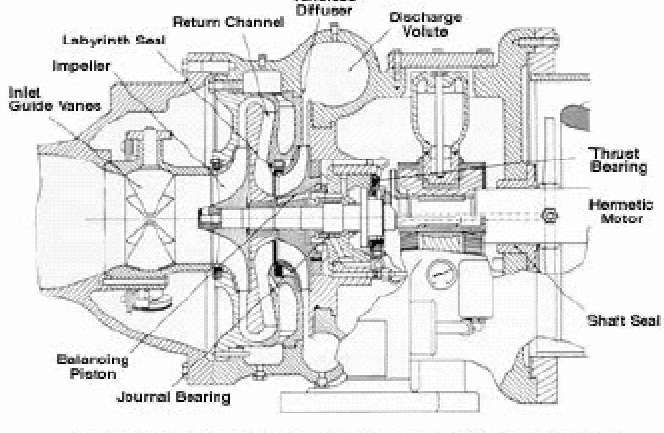

Fig. 2.7 Cut-view of a two-stage, semi-hermetic centrifugal compressor.

Q. The early refrigerant compressor design resembled:
a) Automobile engines
b) Steam engines
c) Water pumps
d) None of the above
Ans. b)
Q. The early compressors were able to handle liquid and vapour mixtures as they were:
a) Double acting, reciprocating type
b) Horizontally oriented
c) Low speed machines
d) Steam engine driven
Ans. c)
Q. The speed of the compressors was increased gradually with a view to:
a) Develop compact compressors
b) Reduce weight of compressors
c) Handle refrigerant vapour only
d) All of the above
Ans. a) and b)
Q. Hermetic compressors were developed to:
a) Improve energy efficiency
b) Overcome refrigerant leakage problems
c) Improve serviceability
d) Reduce weight
Ans. b)
Q. Open type compressors are used in:
a) Domestic refrigeration and air conditioning
b) Large industrial and commercial refrigeration systems
c) Only CFC based refrigeration systems
d) Only in natural refrigerant based systems
Ans. b)
Q. At present the reciprocating type compressors are most common as they are:
a) Rugged
b) Comparatively easy to manufacture
c) Offer higher energy efficiency
d) All of the above
Ans. a) and b)
Q. Which of the following are positive displacement type compressors:
a) Reciprocating compressors
b) Scroll compressors
c) Screw compressors
d) Centrifugal compressors
Ans. a), b) and c)
Q. Centrifugal compressors are used in:
a) Large refrigerant capacity systems
b) In small refrigerant capacity systems
c) Domestic refrigeration and air conditioning
d) All of the above
Ans. a)

2.4. Conclusions:

The compressor technology has undergone significant developments in the last hundred years. Almost all the compressors described so far have reached a high level of perfection. Today different compressors are available for different applications, starting from small hermetic reciprocating and rotary compressors for domestic refrigerators to very large screw and centrifugal compressors for huge industrial and commercial refrigeration and air conditioning applications. However, development is a never-ending process, and efforts are going on to develop more efficient compact, reliable and quiet compressors. Also some new types such as linear compressors, trochoidal compressors, acoustic compressors are being introduced in refrigeration and air conditioning applications. A brief history of refrigeration and air conditioning from the refrigerant and compressor development points of view has been discussed in the present lesson. The actual characteristics and performance aspects of some important refrigerants and compressors will be discussed in subsequent lessons.

Q. State briefly the impact of Freons (CFCs) on refrigeration and air conditioning

Ans.: Freons have contributed significantly to the widespread use of refrigeration and air condition systems as the systems using these refrigerants were thought to be safe, reliable and rugged. The rapid growth of domestic refrigerators and air conditioners all over the world can be attributed at least partly to the non-toxic, non-flammable and chemically stable nature of Freons. Of course, Freons are also responsible for the monopoly of few companies in refrigeration technology. Of late, the biggest impact of Freons could be their contribution to global environmental hazards such as ozone layer depletion and global warming.

Q. How do the natural refrigerants compare with the synthetic refrigerants?

Ans. Almost all the natural refrigerants are non-ozone depleting substances and they also have comparatively low global warming potential. Natural refrigerants generally offer good thermodynamic and thermophysical properties leading to energy efficient systems. They are also relatively inexpensive, and cannot be monopolized by few companies in the developed world. However, unlike synthetic refrigerants the natural refrigerants suffer from some specific problems related to toxicity, flammability, limited operating temperature range etc.

Q. What are the motivations for developing hermetic compressors? Why they are not used for large capacity systems?

Ans. Hermetic compressors were developed to take care of the problem of refrigerant leakage associated with the open type of compressors. By eliminating refrigerant leakage, the hermetic compressor based systems were made relatively maintenance free, which is one of the main requirement of small systems such as domestic refrigerators, air conditioners etc. Hermetic compressors are not used in large capacity systems, as they are not completely serviceable, they offer lower energy efficiency and compressor and motor cooling is difficult.