AIR CONDITIONING AND REFRIGERATION
Journal
The magazine of the Indian Society of Heating, Refrigerating and Air Conditioning Engineers

Issue : January-March 2004

Why are Screw Compressors Popular?

Over two centuries ago, refrigeration industry started with reciprocating compressors. Then came centrifugals followed by screw and scroll. Each type has its place, but the screw compressor has been gaining in popularity. The authors explain why this is so.

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Compressors are broadly classified as rotary and reciprocating, based on the motion of major moving parts. There is another way of classification as positive displacement and centrifugal depending on how the compression or higher pressure is achieved. Positive displacement compressors are those that create higher pressure by reduction of gas volume in the compression chamber. In the case of centrifugal compressors, the velocity head of gas at the tip of the impeller is converted into a higher pressure. A conventional multi-cylinder piston compressor is an example of positive displacement reciprocating compressor, while a normal centrifugal compressor is an example of rotary centrifugal type. Screw and scroll compressors are positive displacement rotary compressors . Each type has its merits and covers a range of compressors and capacities.

Suffice it to state at this stage that, screw compressors for commercial and industrial applications combine the advantages of reciprocating (being positive displacement) and centrifugal (being rotary) compressors.

History & Development of Screw Compressors

Twin screw compressors. The initial patented design of a screw compressor was by Lysholm in Sweden, seventy years ago (in 1934). This was developed by S.R.M

(Svenska Motor Mashina) and introduced in the refrigeration field in the late 1950s. This design had two screw rotors meshing into each other inside a close fitting casing.

The compression takes place by a volume reduction along the axis of rotors. The de-meshing and meshing of male rotor lobe and the female rotor flute cause suction and compression as many times as the driving motor revolutions per minute. The cycle is further explained in **Figure 1**.

- **Suction**

When the male rotor lobe and the female rotor flute begin to unmesh, the compression chamber is open to the suction side and a gas flow is led through the suction port (Figure 1-B); due to the rotary motion the chamber increase its volume and more gas is led into the chamber until this is not any longer open to the suction side.

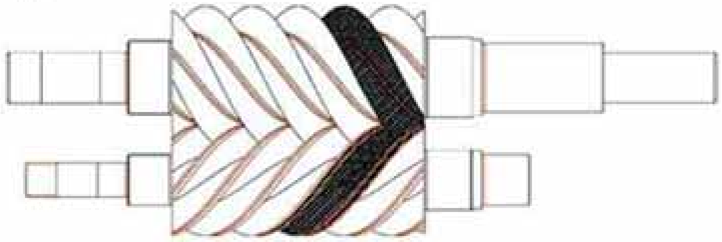

Figure 1-B: Chamber at end of suction phase

- **Compression**

With a further rotation, the volume of the compression chamber is reduced and at the same time it is moved along the axis toward the discharge port (Figure 1-C), increasing the pressure of the refrigerant contained in the chamber.

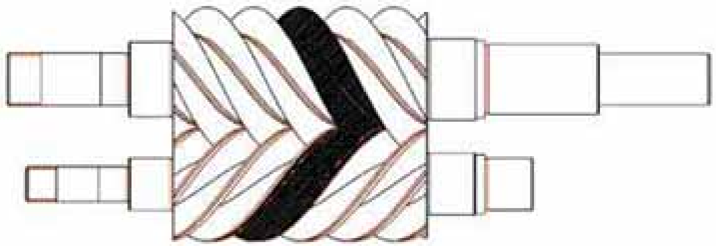

Figure 1-C: Chamber in compression phase

- **Discharge**

At a point, which is fixed by the housing geometry, the discharge port is uncovered and the compressed gas is discharged thanks to the further meshing of the lobe and the flute (Figure 1-D). Since the tooth ratio is 5/6 (5 lobes on the male rotor - 6 flutes on the female rotor) and the rotation speed is about 3000 rpm, there are 3000 x 5 = 15000 discharge processes every minute, resulting in a very low gas pulsation (a reciprocating compressor running at 1500 rpm should have 10 pistons to reach the same result).

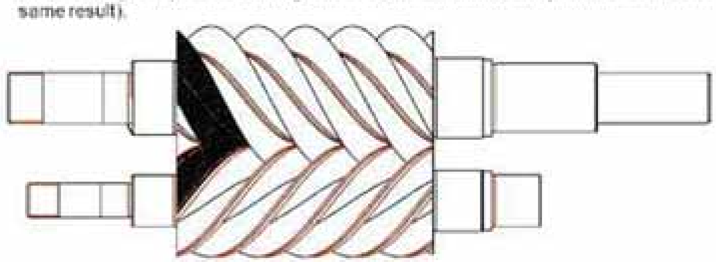

Figure 1-D: Chamber at beginning of discharge phase

Figure 1: Operating cycle inside a twin screw compressor

Over the next two decades, development took place in the areas of rotor profiles, slide valve for capacity control and super-feed porting, besides increasing the range from medium to high capacity. Even as these developments concentrated on larger sizes, particularly for refrigeration, it is only in the late 80s, that efforts were directed towards smaller size (swept volume) 'compact screws'. This development was crucial in addressing problems of smaller compressors with regard to cost and efficiency. Of particular interest is the satisfactory solution of 'leakage volume' and bringing into the compressor package a built-in oil separator, simplified capacity control and semi-hermetic drive. The details of how these were achieved are beyond the scope of this paper, but what resulted in the next 10 years was a volume surge particularly for the commercial air conditioning market that brought in volume builders' investment, further development, etc., which in turn brought down the price. Thus, the compact screw compressor pack came to be placed in the 'upward' spiral of volume sale that fed on itself (to reduce price and expand volume), brought in more manufacturers and pushed its range up towards centrifugals and down towards reciprocating to slowly displace and occupy their conventional range of capacities

Single screw compressors. The development work of a single screw compressor began in 1960 by Bernard Zimmern. The first decade saw a slow development in France for a range of portable and stationary air compressors upto 60 kW drive. By mid-seventies, new licensees in Japan and USA produced over 5,000 compressors of nearly 150,000 kW of installed brake power – many of these clocked over 10,000 hours of running.

It is around this period that two European compressor manufacturers of repute took up the license for this design and developed a single screw compressor for refrigeration. The British single screw compressor developed into a unique machine, winning several awards and laurels. Even as this manufacturer multiplied volumes and expanded the range all alone in Europe, subsequent licencees in USA and Japan brought this single screw design further acceptability and helped market penetration.The 1990s saw a development in compact screw range and brought into its fold many more manufacturers to give a volume thrust in the commercial air conditioning market.

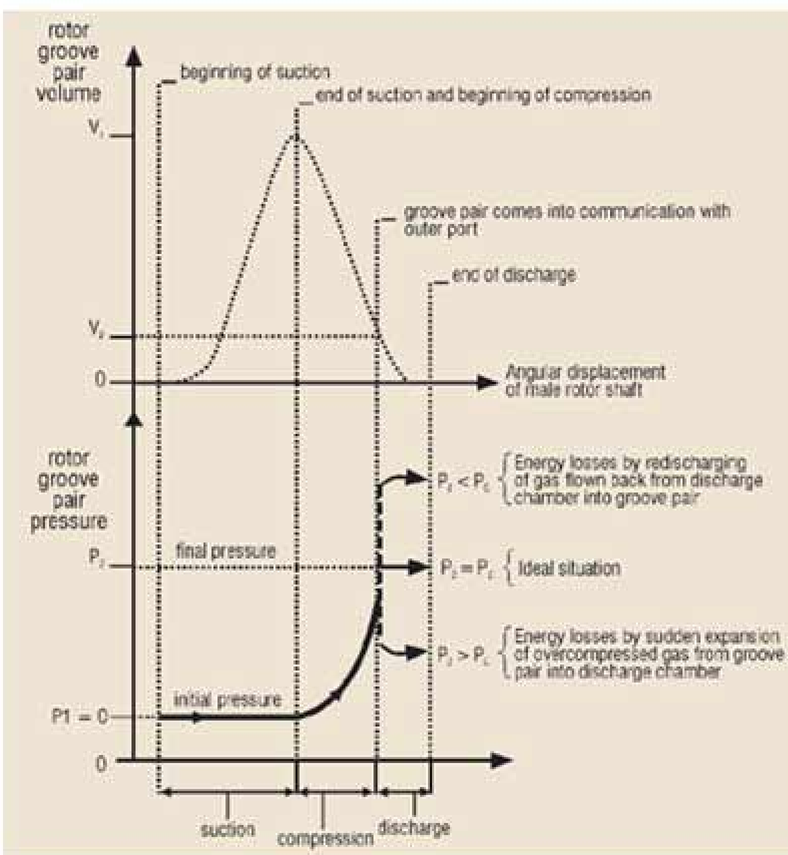

Figure 2: Over and under compression

Concepts and Features of Screw Compressors

Built-in volume (pressure) ratio. Screw compressors unlike recips, do not have suction and discharge valves (not stop valves !). In recips, as the piston moves down and allows the pressure over it to lower compared to suction manifold pressure, the gas gets in pushing up the suction valve plates. Again, as the cylinder pressure builds, when piston goes up, over discharge chamber pressure, the compressed gas overcomes the discharge valve plate resistance to pump out. In screw compressors, gas getting in and out of helical grooves of a rotor are through fixed ports located on either side. They have what is called a built-in "volume ratio" V1/ V2, where V1 is the volume at the rotor groove (pair) at the beginning of the compression and V2 is the volume of the same pair of grooves when the outlet part just comes into communication. This volume ratio is a 'builtin' feature for any screw compressor and relates to pressure ratio as $p_2/p_1 = (V_1/V_2)^\gamma$ where 'γ' is the adiabatic co-efficient of the refrigerant.

The significance of the volume ratio, VR (or the pressure ratio) lies in the fact that, for a given VR, the discharge port pressure is fixed irrespective of the condensing pressure imposed by the system. For screw compressors, therefore, an inefficiency factor to account for over or under compression, as explained in **Figure 2**, cannot be avoided.

All screw compressor manufacturers, provide standard built-in VRs by means of different slide valves (of different length and profile) to minimize the efficiency loss due to over / under compression for a range of pressure ratios.

Slide valve mechanism. Slide valves are used to optimize the operation for a range of pressure ratios. These slide valves are mainly provided to facilitate capacity control by opening a return port to suction chamber thus, delaying compression and reducing the suction volume. As the suction volume is reduced, in part load, in order to maintain the discharge port pressure closer to back (condenser) pressure, the discharge port area is reduced by the moving slide valve. The movement of slide valve in response to evaporator load, is by different mechanisms in different screw compressor designs such as an electric impulse motor or a Linear Variable Displacement Transducer – but operating through a hydraulic piston.

Economiser port. All screw compressors take advantage of the ability to accept vapour at an intermediate pressure. An external port (economizer port) is located close to the discharge end. This provision enables the system designer to use either an extra evaporator at intermediate pressure (for a side load) or to sub-cool the liquid refrigerant going to the main evaporator. The use of an economiser helps in increasing the system capacity at a small extra power consumption thus, improving the specific power consumption or C.O.P. The economizer would however, be in-effective at part load operations below about 85%.

Oil injection and cooling. All successful refrigeration screw compressors are oil injected type. Oil, in screw compressors, serves the purposes of lubrication, sealing of clearances and cooling of compressed refrigerant vapours besides external functions like slide valve positioning during capacity control. Oil management system is therefore very critical for proper operation of screw compressors. Oil cooling is done externally in different types of oil cooler or by internal liquid injection. Liquid injection cooling though simple and economical, costs dearly by way of capacity sacrifice and reduction in C.O.P. Oil separator, oil cooler, oil filters, pumps (if needed) and controls form part of an oil circuit which, although external to compressor, needs careful design and execution as sufficient flow of pure oil in controlled temperature is essential for trouble-free operation and long life of compressors.

Compressor drive. Most screw compressors are directly driven by a 2-pole motor (2,980 rpm @ 50 Hz.). Semi-hermetic version for commercial chillers are available upto 250 hp drive. It will be of interest to note that, natural gas engine drive has been increasingly deployed in view of a high saving in energy bills (30 to 60%). Engine drive is particularly suited to varying load in view of better part load characteristics of screw compressors with reduced speed.

The Uniqueness of Single Screw Compressors

Construction. The three rotating components comprise – the cylindrical main rotor in which are formed six-start, helically grooved screw threads with a spherical (hour-glass) root form meshing with two identical toothed wheels each having eleven teeth.

These wheels (or 'star rotors' as they are called owing to their shape), made of a special synthetic material, are located in a single plane diametrically opposite each other on either side of the main rotor with their axes at right angles to the main rotor axis. As the main rotor turns, it imparts a freely rotating motion to the star rotors.

The star rotors are supported by metal backings which, are cast in one-piece with the star rotor shafts. Although, they are located in place on their backings, the stars are allowed to 'float' a small amount in a rotational sense. This floating action, combined with the low inertia and negligible power transmission between the main rotor and star rotors, effectively absorbs any minute vibrations of the star / main rotor combination. The star rotor shafts are supported at each end by taper roller bearings.

The main rotor is a dynamically balanced component, manufactured from special cast-iron, keyed to the steel main shaft which, runs in rolling element main bearings. Where the shaft emerges from the casing, leaking of oil or refrigerant is effectively prevented by a specially designed mechanical seal.

The main rotor and star rotors are housed inside a one-piece, cast-iron casing. The inside of the casing has a somewhat complex shape but essentially consists of a cylindrical annulus which encloses the main rotor leaving a small clearance. Part of the annulus is a cut-away at the suction end to allow the star teeth to mesh with the main rotor flutes. The discharge ports (one for each star), positioned at the other end of the annulus, convey the compressed gas into the discharge manifold, formed by a web cast between the annulus and the walls of the casing – this web separates the casing into two pressure zones. Except for the discharge manifold, suction pressure prevails elsewhere in the casing.

Side covers are provided to allow easy access to the star rotors, star rotor shafts and bearings, without disturbing working tolerances. The discharge end cover can also be removed to inspect the capacity control mechanism. The compressor is provided with a choice of either top or bottom discharge; the unused connection is blanked off.

Some understanding of the inside details of the compressor can be seen from **Figure 3**.

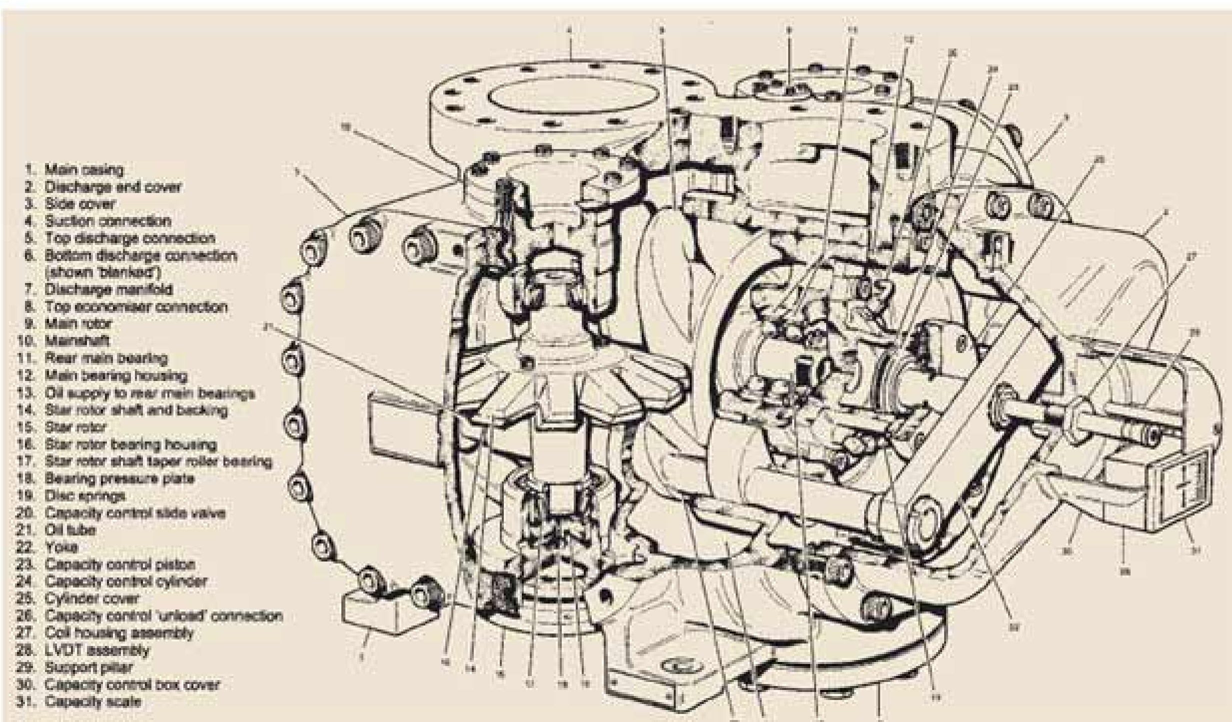

Figure 3: Inside details of a single screw compressor

Compression process. In the construction of the Hall screw, the helical flutes in the main rotor can be likened to the cylinders of a reciprocating compressor, the star rotor teeth taking the place of conventional pistons. Instead of using suction and discharge valves, gas flow in and out of the flutes (the cylinders) is controlled by fixed ports.

Gas enters the compressor through the suction connection and fills the available flutes. Rotation of the main rotor traps the gas in chambers formed by the flute walls, the cylindrical annular ring housing the main rotor and the star teeth. The small clearances around the star teeth are sealed with oil which is injected into the compressor during operation. As the main rotor turns, the star teeth act as stationary pistons in the moving flutes (the cylinders) and the gas is compressed until the discharge port is uncovered. Each flute is used twice per rotor revolution i.e. once by one tooth on each star. Further details of suction, compression and discharge process can be seen from **Figure 4**.

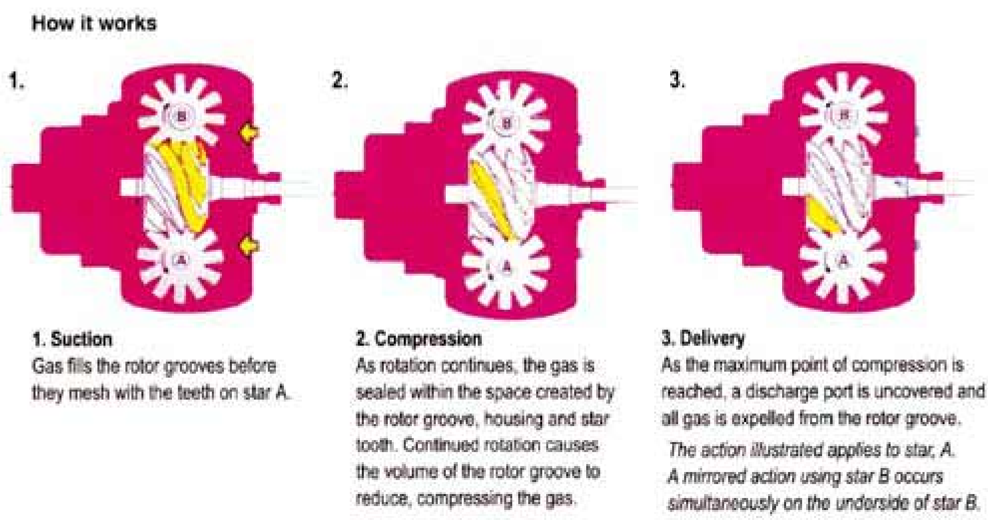

Figure 4: Operating cycle inside a single screw compressor.

Minimal bearing load. As the compression process happens exactly the same way on either side of rotor – and discharge takes place diametrically on opposite sides, radial forces on bearings balance out. Because the flutes terminate on the cylindrical surface of main rotor at the discharge end, it is possible to arrange that both ends of the main rotor are at suction pressure. This makes the thrust load nearly zero. Thus, apart from the weight of the rotor assemblies, only loading on the bearings arise from the gas pressure acting the 2 or 3 star teeth engaged with rotor flutes on either sides.

Capacity Control Slide Valve Operation

Slide valve operation. The best part load characteristics are achieved, if the design full load VR is maintained as the compressor's capacity is reduced.

Single screw compressors are fitted with a pair of slide valves, one for each half of the symmetrical compression process. These valves reduce pumping capacity by delaying the sealing of the flute volume together with the opening of discharge port, altering the effective length of the main rotor flutes. The valves not only permit step-less capacity control down to approximately 10% of full load, but also maintain the best possible VR over a wide capacity control range. Each slide valve is housed in a semicircular slot in the wall of the annular ring which, encloses the main rotor. As the slide valve travels axially from the full load position it uncovers a port which, vents part of the gas trapped in the main rotor flute back to suction before compression can begin. When the flute has passed beyond the port, compression commences with a reduced volume of gas. However, a simple bypass arrangement without any further refinement would produce an undesirable fall in the effective VR, which in turn causes under-compression and inefficient part load operation. To overcome this problem, the slide valve is shaped so that it reduces the discharge port area at the same time as the bypass slot is created.

Figure 5 shows one of the capacity control slide valves in two positions – fully loaded and at part load, the arrows on the diagram indicating the flow of gas.

Each half of the compressor is provided with its own slide valve system, these are operated simultaneously to maintain balanced gas loads and low bearing loads within the compressor. The position of the slot at the suction end of the slide and the position of the moving delivery port can both be chosen to give the desired full load VR, the appropriate ratio being selected according to the operating conditions. The following volume ratio slides are available for each compressor size : 2.2, 2.6, 3.5 and 4.9.

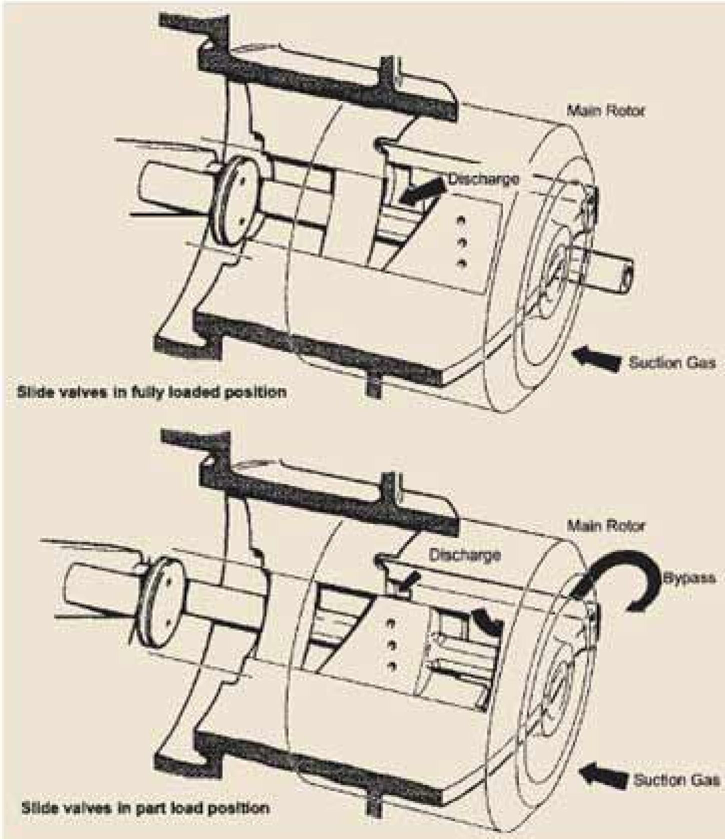

Figure 5: Slide valve operation

Slide valve actuation. The capacity control slide valves are joined together by a yoke which is connected to a hydraulic piston, housed inside a cylinder and mounted internally at the discharge end of the compressor. The motive force required to actuate the piston is derived from a supply of pressurised oil taken from the lubrication system.

Lubrication, sealing and cooling. Oil is supplied by a separate external oil support system at strategic points into the compressor. The oil performs four basic functions viz. bearing lubrication, sealing of clearances, cooling of compressed vapour and capacity control actuation.

Relative merits of Single Screw over Twin Screw Compressors

Having understood the common and specific features, operating principle and constructional details of single and twin screw compressors, let us proceed further to analyse the merits of single screw compressors over twin screw compressors.

Balanced compression – long bearing life. For reasons detailed earlier under "Minimal bearing load" the expected bearing life is over 100,000 hours.

Single piece casing. The advantages of this feature are :

- The design is considered as a pressure vessel, is stronger and simpler and the three way joints where the main casing meets the end (bearing) covers are done away with.
- All essential location dimensions are on the one casing component making it easier to maintain the required accuracy of positioning the rotor elements.
- The assembly procedure is easier because each star rotor can be positioned individually.
- Total access for inspection without disturbing the rotor assembly or any other part except side cover.
- For overhauling purposes and bearing or star replacement, the star assemblies can be removed individually.
- The main rotor assembly complete with the end seal is designed to be fitted as a sub-assembly so that all the moving parts are accessible without the need to remove the compressor from base or disturbing the pipe work.

Standard components. Except for rotors, all components that may need replacement, if ever (after 50,000 hours) such as bearings and shaft seal are from standard sources and can be locally procured.

Tolerance to liquid and marginal lubrication. The greatest advantage is the simple lubrication oil circuit. The quantity of oil circulated is also far less. In a twin screw, the rotor coupled to the motor drives the other rotor through the film of oil and hence the importance of the continuous oil supply. In a single screw, in the worst event of marginal lubrication, the non-metallic star would wear-off. This can be replaced at minimum cost and down time.

Screw vs. Recips

If the screw compressor population is growing rapidly, it is definitely in the place of reciprocating compressors. Although both belong to positive displacement category, reciprocating compressors are much more economical initial-cost-wise. Why reciprocating loses out to screws can be understood from the following comparison :

Efficiencies. The reciprocating and screw compressors differ vastly in regard to volumetric and isentropic efficiencies vs pressure ratio. While screw compressors have a steady (reasonably flat) characteristic, reciprocating have a drooping curve. This, of course, is due to clearance volume in reciprocating in the discharge valve assemblies.

On the other hand, the isentropic efficiency variation with respect to pressure ratio is just the opposite i.e. the screw compressors have a falling isentropic efficiency as the pressure ratio increases. This is mainly due to losses through leakage path between the rotor screw.

Lubrication oil. Screw compressors generally require higher viscosity oil as one of the main functions of oil here is in sealing the clearances. A minimum of ISO 68 grade is required.

Multi-staging. Screw compressors can operate for high pressure ratios in single stage due to oil cooling and lower discharge temperature. Reciprocating compressors require multi-staging for low temperature applications.

Economising. Screw compressors can take advantage of economiser port to improve C.O.P at or near full load.

Part load power consumption. There are differences in perception as to which of the two operate efficiently in part load. Unless the load matches the capacity step, the unloaded compressor can only match its evaporator capacity at a less-than-design suction pressure. This would increase the compression ratio and hence the power consumption.

Wear, tear and maintenance. The greatest drawback of recips is its number of moving parts per cylinder such as piston rings which are subject to continuous wear due to motion. Not only does this wear and tear need regular replacement, it also causes leakage past piston resulting in lower capacity and lower C.O.P as the machine gets older.

Unbalanced forces and moments. Reciprocating compressors require heavy foundations due to unbalanced forces and moments on the base. Because of its rotary motion, screw compressor packs need only load bearing level ground to position them.

High reliability. Screw compressor, because of the features and construction details explained earlier, is a highly reliable machine. It is very common for screw compressors to operate unattended in the refrigeration system on continuous basis for over 50,000 hours. Reciprocating compressors need to be opened periodically for maintenance and service. Every time a machine is opened, in spite of adequate care, one cannot rule out ingression of air and moisture into the system, which would in turn hamper the performance.

Conclusion

A year-on-year calculation of actual power consumption in an identical system where a screw compressor pack replaced a reciprocating compressor, indicated savings of about 30% in favour of screw compressor. This, in addition to mandatory maintenance required for reciprocating compressors makes the screw compressor's relative ownership cost much less.

With prices of screw compressors coming down in the Indian market (import duty getting reduced), even the initial cost difference is becoming marginal. No wonder screw compressors have started replacing reciprocating, particularly in the industrial refrigeration segment that looks for high reliability over a long period of time.

At the high end of the capacity spectrum, centrifugals are facing refrigerant related problems. Large capacity screw chillers have now penetrated the commercial air conditioning market. A lot of development work is taking place in large size screw compressors for this sector. An example is the prospect of large capacity (500 TR) hermetic screw for commercial chillers.

Screw compressors, thus, enlarge their capacity range gradually displacing reciprocating and centrifugals on either end of the spectrum.