A scroll compressor application in an air cooled condensing unit

Scroll Compressors

for Air Conditioning and Refrigeration Systems

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Introduction

The scroll compressor has emerged as the leading compressor technology, generally in 3 - 30HP range; primarily due to higher efficiency, lower sound, and better reliability. This article will give a brief outline of scroll history, design features, and manufacturing challenges. In addition, some information is presented on the latest trends in refrigerants. Finally a summary of future trends in the entire subject is proposed.

History

It may be surprising to some, but the first patent on the scroll form to be used to compress a fluid was in 1905. Both orbiting and co-rotating concepts were covered in this work. Over the years, there were other patents, but it was not until the early 1970s that the technology was applied to compress refrigerant gas. This was done by Trane and AD Little, a research company in Cambridge, Massachusetts, U.S.A. From that point, other companies such as Hitachi, Copeland, etc. became involved in the pursuit to make this a viable technology for our industry. The advent of precise CNC machining equipment in this era actually made the concept practical. Since then many companies have developed and contributed much to the design and manufacturing of scroll compressors.

Basics

Conventional scroll compressor parts are the fixed and orbiting scrolls

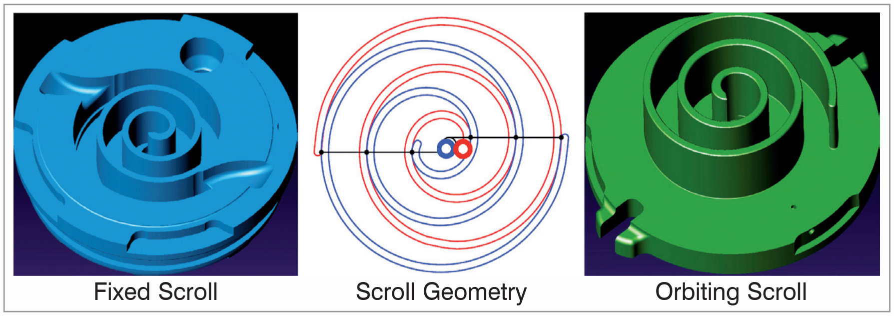

Figure 1: Scroll compressor parts

About the Author

Gene Fields graduated from MIT in 1973 with BS and MS degrees. He has extensive experience in air conditioning and compressors, having worked in companies like GE, Trane and Bristol Compressors in technology development of scroll compressors. He then moved on to Danfoss where he was responsible for the concept, design and manufacture of Nx Gen scrolls, and was appointed Director of Engineering and later the Global Engineering Head. Gene holds 26 patents in the field of scroll compressors.

(see *Figure 1*), and these are mathematical forms derived from the *involute of a circle*. Wrap a string around a spool of a given diameter, tie the end to a pencil, hold the string tight, and unwrap the string while drawing on a piece of paper. The circumference of the spool is the pitch of the spiral form. One scroll is a mirror image of the other, and forced to orbit in a circle based on the pitch and the thickness of each wall. Two crescent shaped pockets are formed by the contact of the two scroll forms and are continually reduced in volume as the orbit motion takes place. For the young academics, here's the displacement equation:

$$V_d = 2\pi H R_o (2Rg(\beta_e - 2\pi) + R_o)$$

Based on the geometry of the scroll involutes, there is an exact circular orbit path for one scroll with respect to the other. For this reason they are commonly called the fixed and orbiting scrolls. Unlike reciprocating, where compression to discharge occurs in ~1/2 revolution, the scroll is much smoother with >2 revolutions.

Design Concepts

Over the years, several basic concepts of scroll compressor have been successfully developed. Perhaps the primary challenge has been developing a means to hold the two scrolls together and seal the involute (spiral) tips against the floors of the opposite scroll member while compressing. Nature does not cooperate with compressing gas! The most significant of the Trane/ADL research was the tip seal, which is shown in *Figure 2*. The scrolls are set with a small clearance between the parts, and prevented from moving apart axially, due to the gas force. The tip seals simply extend to contact and seal the compression pockets. This technology is used in many scroll designs, but is probably best for larger commercial scrolls which have high PV loads. One advantage is that it seals and avoids leakage during compression very well, and requires no run-in time to achieve performance.

An alternative approach is called axial compliance, used less frequently but very effective (see *Figure 3*). In this concept one of the scrolls is designed to move up and down a small amount. An external force is then applied to the scroll with axial movement, to overcome the internal gas force attempting to split the scrolls apart. Even from the early R&D on scroll compressors, the use of gas pressure developed by the scrolls was proposed as the best method to apply this force. The gas force and axial movement scroll can be either the orbiting or the fixed.

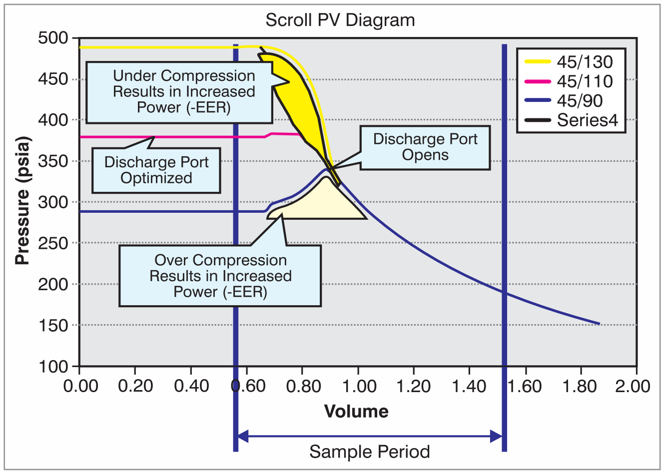

Figure 4: PV diagram of a scroll compressor

A very important feature is the design of Adaptive Gas Pressure Force (AGPF), which self adjusts the applied force as a function of both the condenser and evaporator conditions throughout the envelope. The PV diagram in *Figure 4* illustrates how this works, and why it is valuable. First of all, typical scrolls have no discharge valve like in reciprocating compressors. While it does not have the power losses associated with valves, it does present a challenge for all scroll compressors, since the compression ratio is fixed in a given design. Therefore depending on the condensing pressure at a given evaporator condition, the scroll can either have perfect match, over compression, or under compression. For this reason the AGPF can always apply the optimum force throughout the operating envelope.

The concept of axial gas force means the contact and sealing tips of the two scrolls actually wear-in as operation continues, which increases the performance. Perhaps more important is the ability to separate if incompressible liquid refrigerant enters the scrolls, which is a reliability benefit.

Orbiting Motion

In scroll compressors, the orbiting motion of one scroll is generated by an eccentric offset at the end of the drive shaft. In most scroll compressors, the eccentric offset is a very exact dimension based on the geometry of the scroll involutes (pitch, wall thickness). This offset

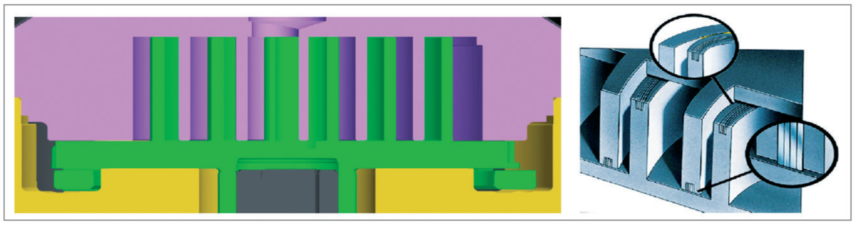

Figure 2: Tip seal

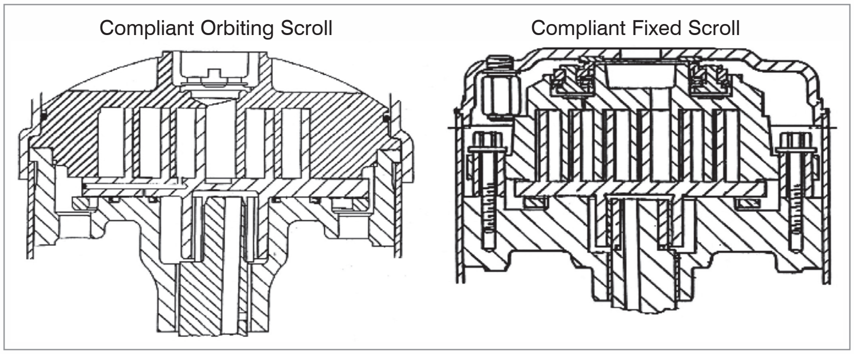

Figure 3: Axial compliance

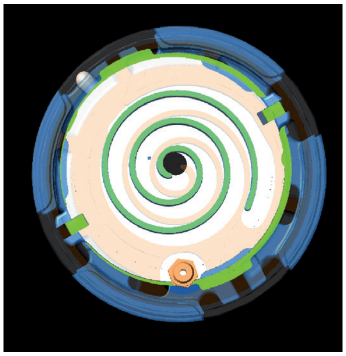

Figure 5: Orbiting motion

becomes the journal inside the orbiting scroll bearing and rotates the part on this circular path. This description is commonly called a *fixed offset*, which is used by most scroll manufacturers, and requires close tolerance in most of the machined parts. However there are scroll compressors that utilize *radial compliance*. This feature allows the eccentric offset which drives the orbiting scroll, to be self adjusting in the offset. The benefit of this mechanism is that centrifugal force of the orbiting scroll and the involute geometry determine the circular orbit path, rather than it being defined by the fixed offset of the shaft. Radial compliance provides numerous benefits, which include great tolerance to liquid and manufacturing tolerances. Finally, there is another very important function that must be provided for either type of offset. When the scrolls orbit together and compress gas, they must be maintained in perfect alignment with respect to their x and y axes of origin. This function is provided by the Oldham coupling, which allows orbiting motion but no rotating motion.

Scroll Optimization

As described above, it is very important to match the built-in compression ratio of the scroll to the intended application because of over and under compression losses. This optimization in the scroll can have significant effect on system efficiency. For example, in the US residential HVAC market the average ambient temperatures are lower, and the scroll products have lower compression ratio to match. In higher ambient temperature areas like India, this ratio must be significantly higher to provide reasonable efficiency and maintain reliability. Medium temperature refrigeration is another example. The heat pump market is growing rapidly in some parts of the world, since it offers much lower cost operation than conventional fuels. In the US the air-to-air HP/AC market is quite large and is handled well with the lower ratio scroll. However there is now much demand for more aggressive heat pump systems that can also produce hot water and other heating benefits. For these applications, the scroll must be designed with other features. These include a discharge valve (like a reciprocating compressor), which prevents under-compression or backflow. Vapor injection can be used to boost capacity in the lowest temperatures, and liquid injection can cool the scroll discharge to allow operation at these very high ratios, and *Figure 6* explains the application.

This type of scroll is therefore similar to a low temperature refrigeration product. In addition, there are special heat pump scrolls that have additional valves to avoid over-compression during the cooling cycle, and this product will become very attractive in the AC/HP market.

Manufacturing

The manufacturing of a scroll compressor has significant challenges, and the greatest of these is the machining of the fixed and orbiting scroll parts. Regardless of the various concepts described above, the accuracy required is in the micron level. Most scroll compressors for HVAC use iron castings for these parts, with intricate CNC programming for the detailed form. However, next to scroll machining the most challenging is the alignment and securing of the bearing components to the shell of the compressor. Obviously bearing alignment with the rotating shaft is most important to reliability as well as performance. In reciprocating compressors, the machined and assembled alignment of the compressor section is self contained inside the hermetic shell. In scroll compressors the alignment must incorporate the hermetic shell either directly or indirectly as the frame of the assembly. Returning to the previous topic, radial compliance is considered by the author to be manufacturing's best friend.

Reliability and Applications

When scroll compressors were first introduced in the 1980s, their reliability was not as good as the mature reciprocating product. The inherent advantages of less moving parts, no valves, and more evenly distributed bearing loads were obvious; and over the years scroll has acquired the best overall reliability because of much focus.

Liquid refrigerant can cause problems in two ways. It can migrate and wash the lubricant from the bearings which can cause failures, and this has been addressed very well with the relatively new polymer type bearings. These can operate for extended periods with marginal lubricant. In addition, liquid can cause breakage of the scroll parts because it is incompressible. As mentioned earlier, this can be virtually eliminated with radial compliance. Finally we

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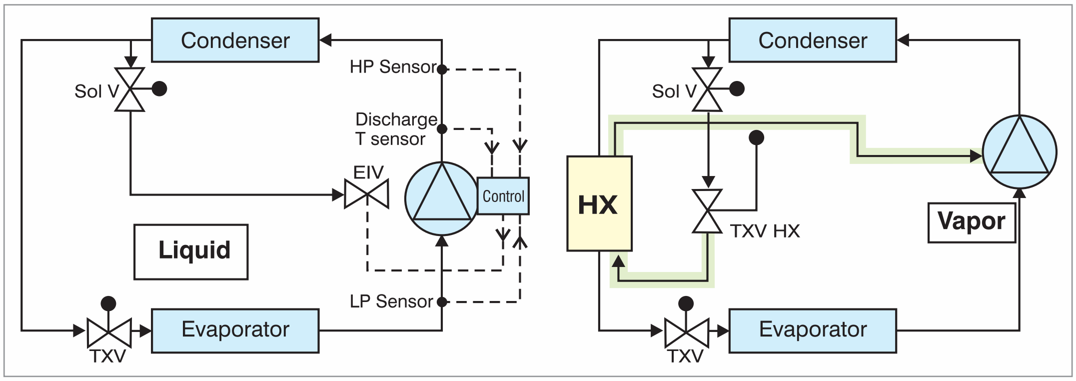

Figure 6: Liquid injection and vapour injection

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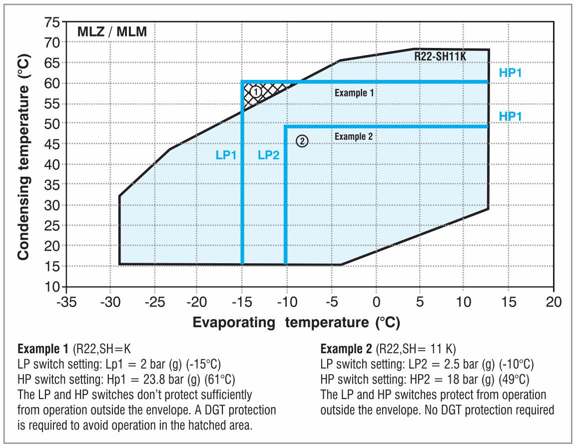

Figure 7: Need for high temperature protection

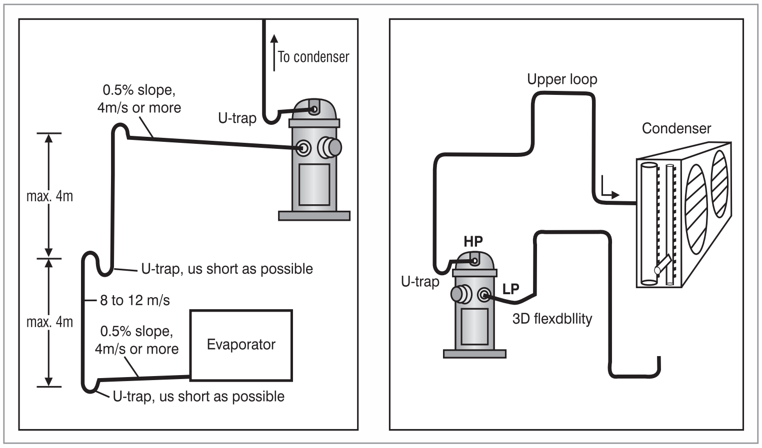

Figure 8: Interconnecting piping designed to minimize vibration and prevent migration of oil and refrigerant

have the greatest reliability challenge for scrolls, and this is tolerance to very high ratio, low mass flow conditions. This will generate very high temperatures, lose oil to the system, and eventually fail the compressor. For this reason, it is always best to apply either low pressure sensing or high temperature sensing. Other than designs specifically for these very high ratios, as in low temperature refrigeration or extended heat pump range, they must be avoided. *Figure 7* shows the need for high temperature protection. In addition here is a simple guide for the importance of proper design of interconnecting piping to minimize vibration as well as prevent migration problems with oil and refrigerant (see *Figure 8*).

In addition, there are faults in the system that are challenging for scrolls. These *thermal fault* conditions are: loss of refrigerant charge, 3ϕ mis-wire (reverse rotation), blocked TXV, and evaporator fan failure if TXV is used. While it is imperative that system applications follow the published guide for a compressor, the trend in our industry has been for the compressor design to become more tolerant to bad conditions. We have done this very well by applying the strategy of *test to fail*, where we have created special life test facilities to evaluate extreme loads, flooded start, liquid transient slugs, loss of refrigerant charge, condenser fan failure, evaporator fan failure, TXV failure, start-stop, high ratio, 3ϕ mis-wire, etc. We also evaluate our competitor's scroll compressors in life testing, to help identify strengths and weaknesses. Our goal is to be the most tolerant to application issues, and gain the reputation for the best reliability in the business.

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Table 1: Overview of alternate refrigerants

• HFC (R410A, R404A, R407c, R134a) ◦ High efficiency ◦ Safety is good ◦ Low cost impact ◦ High GWP	• US OEM's ~100% R410A • Most of Europe moving R410A • Northern Europe R407C • Asia emerging to R410A
• HC (R290, R600a, R1270, etc) ◦ High efficiency (R290 heat pumps) ◦ Low GWP ◦ Similar pressures to HFC ◦ Highly flammable	• Europe leading effort • Doubtful US will ever adopt
• CO2 (R744) ◦ Non-toxic, non- flammable ◦ Low GWP ◦ High pressures, high cost, compatibility	• Very limited applications only
• NH3 (R717) ◦ High efficiency, zero GWP ◦ Toxic & flammable ◦ High cost impact	• Very limited applications only
• Emerging Refrigerants	
◦ HFO (1234yf, 1234ze) • Similar, lower pressures to HFC • Low GWP • Flammable, high cost, many unknowns	• Minimal work by large OEM's in US • Testing in Europe
◦ R32 • Lower GWP than R410A • Higher efficiency • Moderately flammable	• Much interest in China • Little interest in US • Some testing in Europe

Refrigerant	R22	R134a	R404A	R410A	R717 (NH_3)	R744 (CO_2)	R290 (propane)
Efficiency	🙂	🙂	😐	🙂	🙂	😐*/🙂**	🙂
Safety	🙂	🙂	🙂	🙂	☹️	🙂	☹️
Environment (ODP, GWP)	☹️	☹️	☹️	☹️	🙂	🙂	🙂
Pressure & temperature	🙂	🙂	🙂	😐	🙂	☹️	🙂
Chemical properties	☹️	🙂	🙂	🙂	☹️	😐	🙂
Economic aspects	🙂/☹️***	🙂/☹️***	🙂/☹️***	🙂/☹️***	☹️	😐	😐
Availability	🙂	🙂	🙂	🙂	🙂	🙂	🙂
Typical applications	All	light commercial, commercial, A/C	commercial	commercial, heat pumps, A/C	commercial & industrial refrig-eration	light commercial, commercial, in-dustrial, transport, HP	domestic, light commercial, commercial, heat pumps

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Refrigerants

The goal to better protect the environment from harmful effects of refrigerants has led to much change in the past decades, and the rate of change is even greater. First the Montreal Protocol addressed the Ozone Depletion Potential (ODP) by the move to eliminate HCFCs (R12, R22, etc.), and this has been adopted for new equipment sale in much of the world, by moving to HFCs (R410A, R407C, etc). Then came the Kyoto Protocol to address the Global Warming Potential (GWP), which meant that even HFCs were not the final answer. Therefore while some parts of the world are still working to switch to the HFC refrigerant, others are actively working on refrigerants which address both of these harmful effects. While these are the facts, *Table 1* gives an overview of the options being evaluated, as well as a good summary of the metrics for each.

Summary and Conclusions

Although the concept of scroll compression is more than 100 years old, their production for HVAC is still in development. Every manufacturer is focused on new refrigerants, higher efficiency, lower cost, better reliability, new materials, and providing special benefits for enhanced system performance.

A summary for the best new refrigerant in all categories is simple: there is no single one. The HCs, like R290 (propane) offer very high efficiencies. While the HCs and emerging refrigerants have some benefits, all of these have the potential issue of flammability and it will be interesting to see how this progresses. The high pressure of CO_2 drives the cost out of range for conventional HVAC, and ammonia has both flammability and toxicity problems. China is seriously evaluating R32, even with its moderate flammability and it will be interesting to see how this unfolds. The R&D of these new refrigerants is important and must continue; however it is the opinion of the author that the move to R410A for AC and R404A for Refrigeration are probably the best alternatives for India at this time.

The thrust to reduce cost in compressors has been evident in the past decade where virtually all manufacturers have facilities in developing countries. While this can present challenges to maintain quality, it will happen. While this addresses labor cost, it does little for raw materials and this is the best opportunity for scroll design. With the greater tolerance to liquid, increased strength of components, and advances in new materials, the future will likely provide smaller, lower weight scrolls for the same capacity. Since much of the valuable IP has now expired, this will probably bring more competition into scroll manufacturing, which will add to this effect. Finally, high-speed variable speed could become the product of the future, if cost effective.

In general, the efficiency in a scroll compressor is limited by leakage in the compression and orbiting friction losses. While many advances have been made in these areas, it is doubtful that the scroll mechanism can produce significantly higher isentropic efficiencies. There are possibilities with the motor, but there can be significant cost penalties. Of course, the DC variable speed motor is the ultimate at this time. Therefore the future of HVAC system efficiency will depend on regulations in various parts of the world, and this in turn will require closer design integration between the compressor and the system.

In particular, for much of the world, the total energy (seasonal) usage of the HVAC system is driving focus on part load efficiency. For this strategy, the compressor's isentropic efficiency is not as important as the ability to reduce capacity on demand. Various methods of achieving this are in use today, and include multiple manifold of compressors, discrete step modulation, digital pulse modulation, and variable speed. Of all these concepts to reduce capacity, variable speed, especially with permanent magnet DC motor offers the highest system efficiency. While there are some challenges for the compressor design, the major challenge for the product is how to reduce the cost of the electronic drive and compressor combination. Scroll is the ideal compressor for this technology. In addition, another equally important system efficiency rating is the peak load, which drives the capacity demand of power generation. For this requirement there are optimizations that can be done in scroll design, but the potential gain is less than with seasonal efficiency. A third rating is used in some countries, like the US, for the heat pump cycle of AC/HP systems. Optimizing for this can be counter to what is required for the other rating strategies. Therefore it is a challenge for the scroll design to achieve the benefits for all strategies of energy consumption.