

Scroll Compressors

**High Efficiency Compression for Commercial and
Industrial Applications**



**Carrier Corporation
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INTRODUCTION

What is a scroll compressor? According to ASHRAE’s HVAC Systems and Equipment Handbook (ASHRAE 2020, Chapter 34), “Scroll compressors are orbital motion, positive-displacement machines that compress with two interfitting, spiral-shaped scroll members.” A reader understands ASHRAE’s brief, written description more readily when he or she understands the conceptual simplicity of how a scroll compressor really operates. But understanding how a scroll compressor works always inspires the thought: “It’s so simple! I wish I had thought of that.” This paper’s purpose is to explain how scroll compressors work, their operating principles, and their applications. It also discusses scroll compressor performance, efficiency, and reliability.

ASHRAE classifies scroll compressors as *orbiting* positive-displacement compressors. For practical purposes, however, scroll compressors are frequently considered *rotary* machines, a class that includes twin-screw, single-screw, moving vane and rolling piston compressors. ASHRAE’s classification may be technically more exact, but the distinction is not compelling in the HVAC marketplace. Orbiting scroll compressors and rotary twin-screw compressors are both viable, positive-displacement technologies in commercial applications such as air-cooled water chillers. The rotary-like movement of their

compressing elements distinguishes them both from the linear movement of pistons in reciprocating compressors, and the spinning action of centrifugal compressors.

Scroll Compressor History and Development

Although the idea of a scroll compressor is not new, scroll compressors themselves are a relatively new technology. The first scroll compressor patent dates back to 1905. Léon Creux, a French engineer, developed the first scroll compressor design that was literally ahead of its time. Not until the early 1970s had precision machining technology advanced sufficiently to make a working prototype possible. Development continued, primarily in Japan and the United States, and widespread introduction to HVAC and refrigeration applications began in the mid-1980s. Today, scroll compressors are found in many commercial and residential applications.

Screw compressors, in contrast, have a much longer history, but their actual adaptation to HVAC applications is not as old as might initially be thought. The first patent awarded for a screw compressor is dated 1878, but the first modern twin-screw compressor did not appear until 1935. Screw compressors found their first uses in industrial applications and did not move into the HVAC arena until late in the twentieth century.

OPERATING PRINCIPLES

Geometry of a Scroll

By definition, a *volute* is a turn or twist about a center. A *volute* is a spiral. A *spiral* is a circular curve: the locus of a point moving with an ever increasing radius about a fixed center. A spiral may have one or more volutions, as shown in Figure 1.

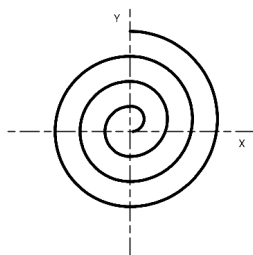


Fig. 1. A Simple Spiral

There are many different kinds of spirals, each defined by variations of a basic mathematical equation. The fundamental spiral form is the Spiral of Archimedes, which is defined by the simple equation: $r = a\theta$, where r is the radius from a fixed center, a is a constant and θ is the angle (in polar coordinates). Other variants include the hyperbolic spiral, parabolic spiral, logarithmic spiral and involute spiral.

If we add a third dimension to a simple spiral, the result is a coiled plane similar in appearance to a rolled strip of paper. Ancient scribes rolled written parchments onto wooden spools for storage and safekeeping, which is where we derive the term *scroll*.

Of particular interest to scroll compressor design is the *involute spiral*, shown in Figure 2. An involute spiral is a spiral with a continuously variable radius measured from the circumference of a base circle centered on a fixed axis. The curve can be visualized as the end point of a tightly pulled cord unwinding from a cylinder.

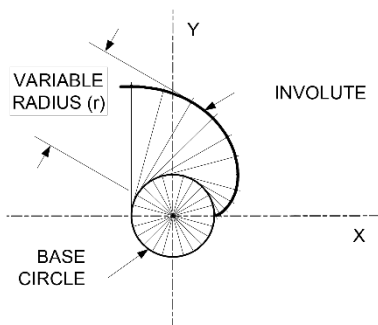


Fig. 2. The radius of an involute spiral is measured from the circumference of a base circle

The shape of an involute permits opposing machine elements to mesh so that the bearing faces roll against one another rather than slide (e.g., gear teeth). This reduces friction and wear, and produces a constant angular-velocity ratio during meshing. The involute geometry of identical meshing scroll vanes creates a rolling action at tangential points and minimizes sliding.

The Scroll Set

The *scroll* is the fundamental compressing element in a scroll compressor. Conceptually, it is a freestanding strip of metal machined into the form of an involute spiral, bound on one edge by a solid flat base. A *scroll set* uses two scrolls with identical geometry. One scroll is inverted, rotated 180 degrees, and inserted into the gaps of the second scroll as shown in Figure 3.

In most scroll compressors, the unit frame holds the upper scroll stationary. An eccentric motor shaft moves the lower scroll in an orbital pattern. A specially designed coupling, called an Oldham coupling, holds the lower scroll at a fixed angular position, preventing rotation and allowing radial movement in an orbital path.

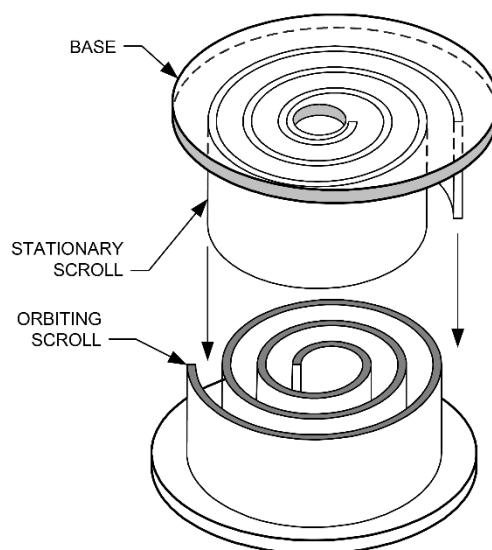


Fig. 3. A scroll set is made up of two identical scrolls—one scroll is inverted and rotated 180 degrees to intermesh with the opposite scroll

Compression Process

When assembled, the flanks of the upper and lower scroll vanes form crescent-shaped pockets. As the lower scroll orbits, the sealing points (tangent points) on the vane flanks migrate inward, pushing crescent-shaped pockets toward the involute center. As the pockets move, they decrease in volume and consequently compress the trapped gas. Figure 4 shows a sequence of orbits, and the movement and variation of the trapped gas pockets.

In Figure 4, the first orbit begins with the ends of both scrolls fully open, allowing the interstitial space to fill with low-pressure refrigerant gas (Position A). The lower scroll's orbit eventually closes the first pockets of refrigerant gas (Position C). As the first orbit ends, the first pair of crescent-shaped pockets have migrated inward to a middle position, and the scroll's outer ends begin opening again to admit more low-pressure refrigerant gas (Position D). The second orbit pushes the first gas pockets toward the center of the scroll set, continually decreasing the gas volume and increasing the gas pressure. The third orbit begins with the

crescent-shaped pockets just outside of the scroll set center. As the third orbit continues, the inner ends of the vanes break contact (Position J), admitting the compressed gas to the center discharge port. The third orbit continues the compression cycle, discharging high-pressure refrigerant gas (Position L).

It is important to note the symmetry of the scroll and the crescent-shaped pockets. The shape and position of both pockets described in the above paragraph are symmetrical and diametrically opposed to each other through the complete compression cycle (e.g., 3 orbits). The natural symmetry in the scroll set balances radial gas forces against the vanes, providing a smooth compression cycle. Moreover, each orbit begins the compression cycle anew so that at any given time there are three pairs of symmetrical crescent-shaped pockets at low-, medium-, and high-pressure conditions, as shown in Figure 5 (on page 6). Between Positions A and L on Figure 4, compression is a smooth and continuous process without vibration or strong pulsations as in reciprocating compressors.

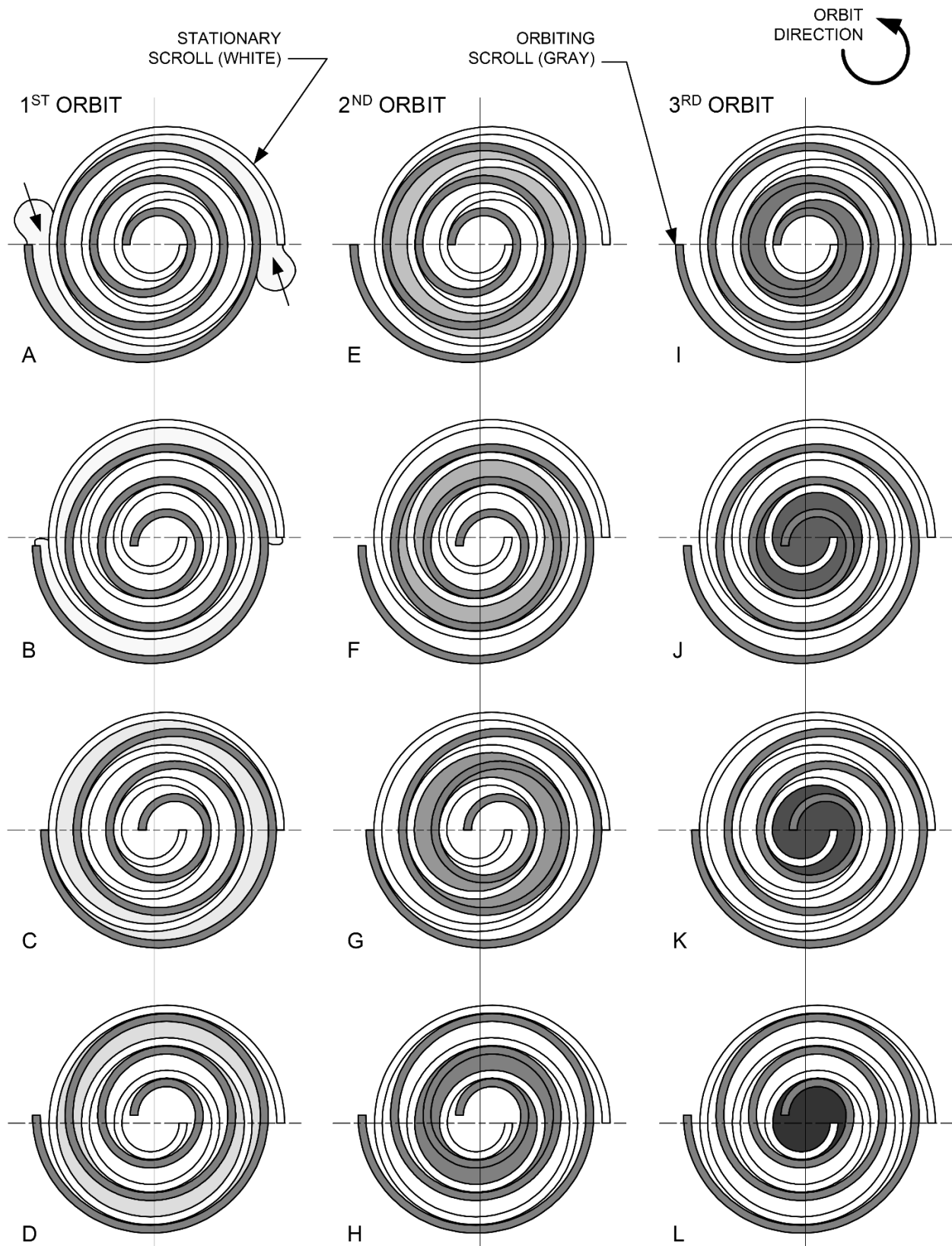


Fig. 4. The complete compression cycle requires several orbits to move refrigerant gas from the low-pressure suction condition (at Position A) to the high-pressure discharge condition (at Position L)

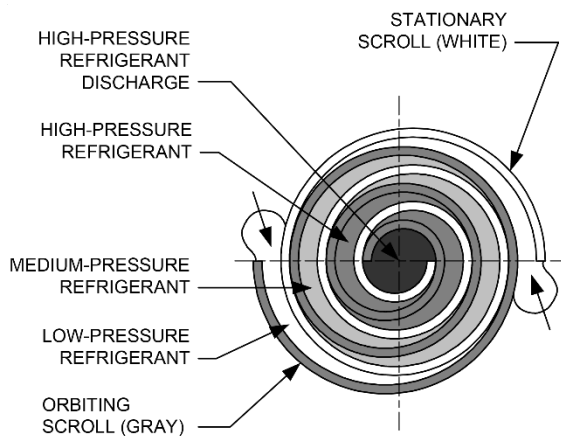


Fig. 5. Because the compression process is continuous, at any given time the scroll vanes contain pockets of low, medium, and high-pressure refrigerant gas

Compliance

Some scroll compressor manufacturers have adopted the term *compliance* to describe the orbital path between the upper and lower scrolls in a compressor. A *radially compliant* compressor allows the orbiting scroll to follow a flexible path that is defined by its contact with the stationary scroll (much the same as a cam and follower). An “unloader” bushing installed between the orbiting scroll and the motor shaft absorbs variations in orbit radius created by machining and assembly discrepancies. *Axial compliance* refers to the ability of the orbiting and stationary scrolls to separate axially. In a *non-compliant* compressor, the orbiting scroll follows a fixed path where the orbiting and the fixed scrolls never touch. Carrier and Danfoss refer to this as a *controlled orbit* design. The geometric relationship between the scrolls in a controlled orbit compressor is constant under all operating conditions.

The decision to make a compressor with scrolls that contact each other or scrolls in a contact-free controlled orbit follows the method used to seal the scrolls.

Sealing Techniques

Compressor performance is directly related to internal leakage and mechanical losses. Each crescent-shaped pocket of refrigerant gas trapped between the scroll vanes naturally tries to find a place of equilibrium. If the gas on one side of a vane is at a higher pressure than the gas on the other side, the high-pressure gas will seek a path to the low-pressure side. In a scroll compressor, there are only two leakage paths: radial

and axial.¹ Figure 6 shows that *radial* leakage occurs between the flanks of the scroll vanes where an advancing high-pressure crescent-shaped pocket attempts to leak back into the following pocket of lower pressure gas. *Axial* leakage occurs between the scroll vane tip (the free involute scroll edge) and the baseplate of the opposite scroll. Axial leakage is generally considered more critical than radial leakage (ASHRAE 2020).

Leakage increases power consumption, reduces compressor capacity, and diminishes efficiency.

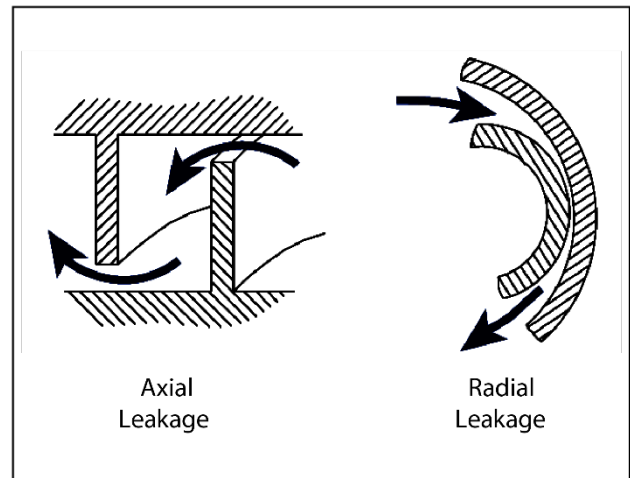


Fig. 6. Radial leakage occurs between adjoining flanks of scroll vanes, and axial leakage occurs between vane tips and base of opposite scroll

Radial Sealing

Compliant compressors use contact between the orbiting and the fixed scrolls as the sealing mechanism. However, radially compliant compressors may not have uniformly effective sealing at all contact points when new. These designs require a “wear-in” period to equalize contact on all surfaces. Contact makes compliance mandatory.

Controlled orbit compressors, in contrast, rely on an ultra-precise scroll profile to ensure scroll flank tightness. Computer-controlled machine tools create precise surface geometry, maintaining tolerances measured in microns (one micron is 1×10^{-6} meters, or 0.000039 inches). The vane flanks never touch.

¹ As a comparison, rotary twin-screw compressors have at least three leakage paths: a) axially between mesh of the male and female lobes, b) radially between the lobe edges and the housing, and c) between the rotor ends and the housing.

Tolerances are so precise that a thin oil film seals the gap and provides a lubricating surface for the orbiting scroll to pass over with no friction or wear. Since the controlled orbit concept never allows mechanical contact between the flanks, compliance is unnecessary and the compressor maintains a fixed geometry over the life of the scroll set.

Axial Sealing

Compliant designs depend on contact between the vane tips and the opposite baseplate. Axial flexibility is necessary to provide allowances for thermal growth and wear. Some manufacturers use gas pressure to load the stationary scroll against the orbiting scroll.

Controlled orbit compressors maintain dynamic contact between the orbiting vane tips and the stationary baseplate with floating seals. Grooves machined into the vane tips hold seal elements that “float” between the vane and the opposite baseplate as shown in Figure 7. Refrigerant gas pressure loads the seals against baseplate for proper dynamic contact during operation. Contact forces are very small, which, combined with reduced contact surface area, substantially reduces friction losses and increases efficiency.

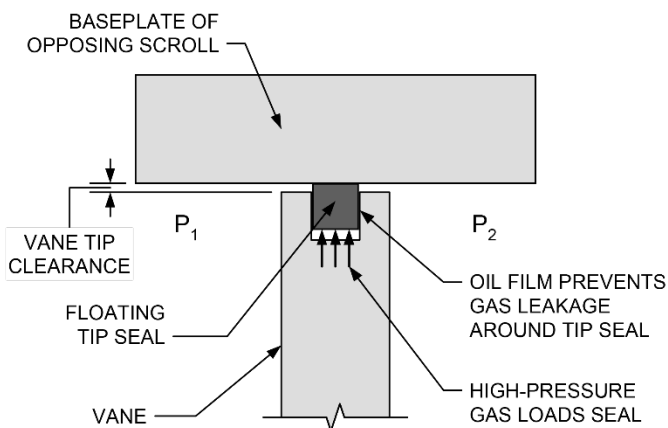


Fig. 7. Scroll compressors with controlled orbit designs use floating seals installed in machined grooves in the vane tips

CONSTRUCTION AND OPERATION

Scroll compressors are fully hermetic. The scroll set, coupling, counterweights, motor, and bearings are assembled in a cylindrical, welded steel shell. Most scroll compressors for refrigeration and HVAC service have a vertical orientation with the scroll sets mounted on the upper end of motor shaft as shown in Figure 8.

Although there are variations in construction between manufacturers, the fundamental features are similar.

The descriptions below highlight features of the Performer[®] controlled orbit scroll compressor used in Carrier's AquaSnap[®] air-cooled chillers.

Shell

The Performer scroll compressor shell is a cylindrical vessel, oriented vertically, and divided into a low-pressure and a high-pressure end. The largest volume of the shell operates at the refrigerant suction pressure and contains the motor, oil pump, and the moving components of the scroll set. A relatively small high-pressure area lies above the compressor's stationary scroll and acts as a discharge muffler to reduce gas pulsation sound and vibration.

Cool refrigerant suction gas enters large suction shell via the lower connection. Gas velocity drops substantially in the shell, allowing lubricant and any small amounts of liquid refrigerant to separate from the gas. In a Performer scroll compressor, all of the suction gas passes upward through the motor on its way to the scroll set. The small amount of oil carried to the compressor as a mist entrained in the refrigerant gas provides the necessary lubrication for sealing the scroll vanes. Compressed gas discharges through a check valve into the high-pressure dome and then exits the compressor shell through a discharge connection.

The lower portion of the shell serves as an oil and liquid reservoir. The Performer compressor's high capacity sump enables operation in systems with long pipe runs and large refrigerant charges.

Performer scroll compressors also use a centrifugal force-driven oil pump that distributes lubricant to the bearings and drive coupling through a diagonal channel drilled in the motor shaft, as shown in Figure 9.

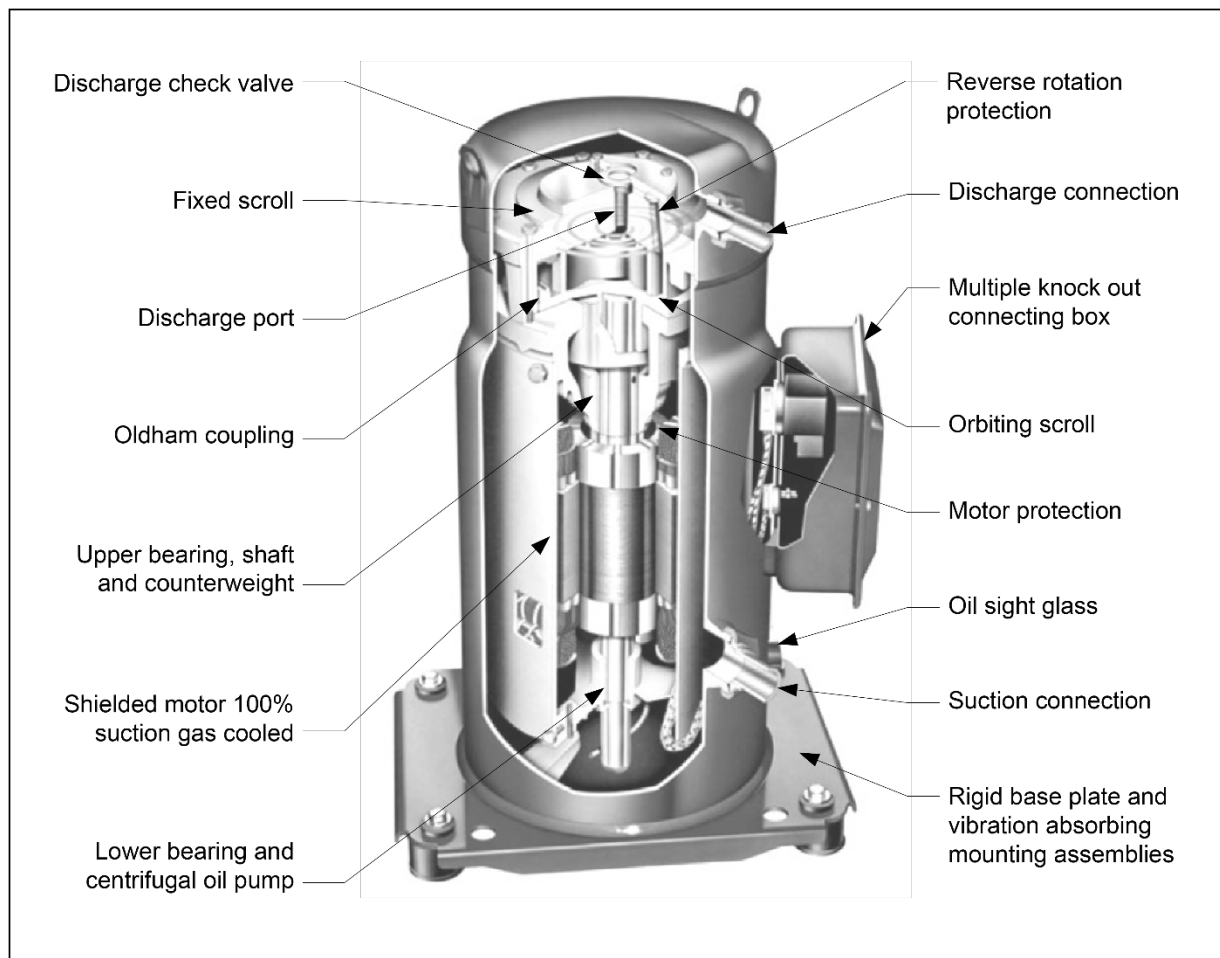


Fig. 8. A Fully Hermetic Scroll Compressor

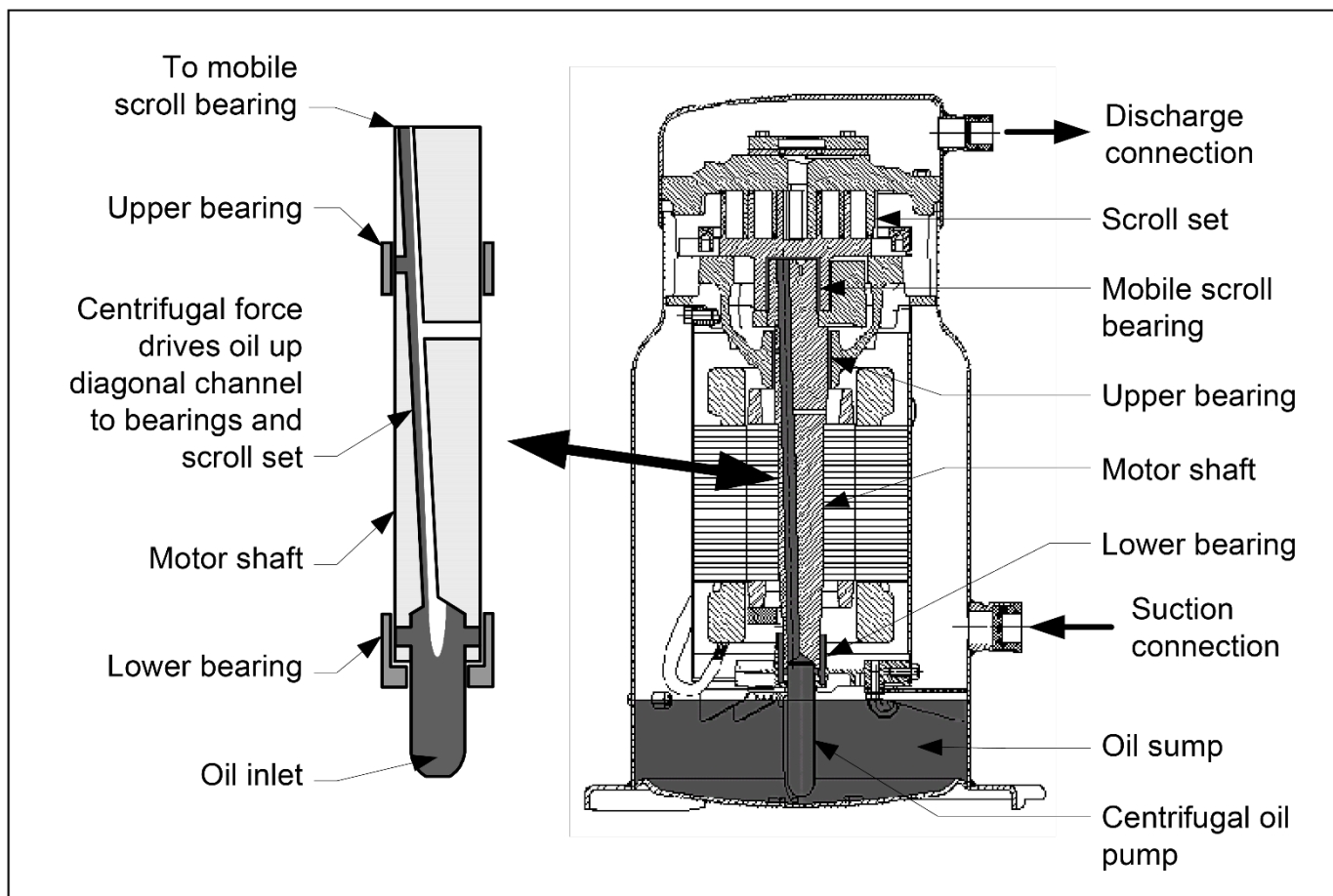


Fig. 9. Using a vertical orientation, the Performer® scroll compressor shell serves as a large oil sump that gives it excellent liquid handling capability

Motor and Crankshaft

A fully hermetic, 100% suction gas-cooled, squirrel cage induction motor drives the compressor.

Suction gas cooling prolongs motor life by ensuring the motor stays at a stable, low temperature. The motor also serves as a barrier between any liquid refrigerant that may migrate through suction line to compressor at shutdown.

Liquid refrigerant stays in the compressor shell. Upon startup, liquid refrigerant must pass through the motor before reaching the compression area of the scroll set. The presence of liquid raises the refrigerant gas pressure drop through the motor. That, combined with heat from the motor, causes liquid refrigerant to evaporate before reaching the scrolls. Suction gas cooling also eliminates any need for external cooling.

The motor shaft, referred to as the crankshaft, transmits the rotary motion of the motor to the orbital motion of the lower scroll. The crankshaft also carries the counterweights necessary to balance the compressor mechanism. Two oil-lubricated sleeve bearings align the

crankshaft—one below and one above the motor. The lower bearing is lightly loaded and the upper bearing carries the bulk of the compression load.

Scrolls

Scrolls are individually machined from carbon steel blanks that are cast into the basic scroll form. High-speed, computer-controlled milling machines produce the precise surface geometry necessary to create identical scrolls. Modern metalworking equipment, using no-lag digital controls, produces contour accuracy with a high quality surface finish (residual roughness $R_a < 0.7 \mu\text{m}$).

A hydrodynamic thrust bearing supports the orbiting scroll and resists the axial forces imposed by compressed gas between the scrolls. Proper bearing design and lubricant selection are important elements in obtaining the best possible compressor efficiency.

The scroll design, including the involute height and diameter proportions, is optimized for each different refrigerant. Geometric proportions of the scroll set increase uniformly for larger capacity compressors.

Currently, the practical capacity limit for a single scroll compressor is 25 tons, although manufacturers are conducting research to develop larger units.

Seals

Controlled orbit scroll compressors have seals at the vane tips. There are two types of seals commonly used. The first design uses multiple, narrow, metallic strips installed with the flats laid side-to-side (like a laminate) as shown in Figure 10. The second design uses a single graphite element set into the tip groove. In both cases, the seal element floats in the tip groove enabling seal effectiveness to remain uniformly high under continuously changing pressure and temperature.

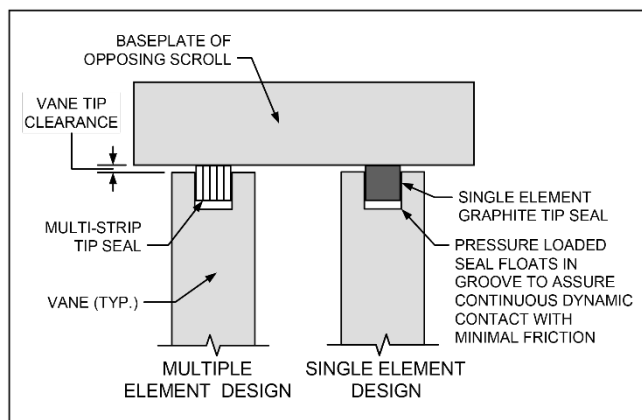


Fig. 10. Vane tip seals used in controlled orbit scroll compressors have less contact area and less friction than compliant compressors where vane tip and base of opposite scroll are in contact

Compressor Protection

Scroll compressor protection is conceptually straightforward and similar to other types of compressors. Fundamentally, scroll compressors must be protected against overpressurization, overheating, reverse rotation, and slugging. Carrier combines the scroll compressor protection features into a *Scroll Protection Module* that mounts in a housing on the side of the compressor shell.

High-Pressure Switch

High-pressure switches must be standard equipment for compressors meeting UL requirements. In a system with multiple refrigeration circuits, such as that in an air-cooled chiller, each circuit must have a separate high-pressure switch to protect against over-pressurization. The switches must be wired in series so that a high-pressure incident stops the entire system.

High Temperature Limit

An internal temperature sensor protects the compressor from potentially damaging high temperatures. In Performer scroll compressors, the sensor mounts

internally so that it will be influenced by both the motor temperature and the discharge gas temperature. A rise in temperature to 220°F (104°C) causes the high-limit switch to initiate a compressor shutdown.

Discharge Check Valve

A check valve mounted on the compressor discharge connection (near the top of the compressor shell) prevents reverse rotation in the compressor at shut down. An external check valve has slightly lower pressure drop than an internal check valve and provides improved protection against backflow.

When the compressor stops, high-pressure gas trapped in the crescent-shaped pockets between scrolls will leak back to the suction side. This lets the compressor start unloaded, which reduces starting current, torque, and mechanical stresses.

Crankcase Heater

Refrigerant liquid may accumulate in the oil sump of hermetic scroll compressors. To prevent slugging liquid refrigerant into the compressor during startup, manufacturers have traditionally used an electric heater that energizes when the compressor stops. The heater warms the oil sump to boil liquid refrigerant (not the oil) so that only refrigerant gas is present during startup. On Performer scroll compressors, the heater mounts externally on the shell bottom.

Other Means of Compressor Protection

Compressor protection is not always achieved internally to the compressor. Carrier applies additional, external safeguards to assure safe, reliable compressor operation. For instance, in AquaSnap air-cooled chillers, the Scroll Protection Module (SPM) houses a “communicating” circuit board that continually exchanges operating information with the chiller’s main control panel.

Software elements provide the following compressor protection features:

- *Single-Phase Protection.* The chiller main control panel continuously examines the three-phase power source entering the unit. Upon the loss of any one phase, the chiller control system interrupts the power source to the unit. Loss of a phase in a three-phase system causes reverse rotation in the compressors.
- *Startup Protection.* Using information from the SPM(s), the chiller control system monitors compressor suction and discharge pressure in the first few seconds of startup. If compressor fails to achieve a differential pressure (e.g., discharge pressure increases less than 10 psig), or if the discharge pressure decreases, compressor stops.

- *Excessive Starts.* The chiller cycles compressors on and off to achieve a defined leaving chilled water temperature set point. The AquaSnap chiller control software uses an *adaptive deadband* to automatically increase or decrease the deadband around the set point. This ensures that a compressor never starts more than 12 times in any given hour. Excessive starts can cause overheating in the motor.
- *Compressor Operating Parameters.* Every scroll compressor has defined operating parameters, that is, acceptable combinations of suction and discharge pressure (suction and discharge temperature) in which it was designed to perform continuously and reliably. Operation outside the acceptable parameters can damage the compressor. The AquaSnap chiller control system has the parameters, referred to as the *operating map*, programmed into the unit software. The chiller control system uses the operating map to stage compressors on and off within acceptable parameters, and to continuously monitor overall refrigerant circuit performance.

EFFICIENCY AND PERFORMANCE

There are two ways to think of compressor efficiency: a) the individual, thermodynamic efficiency of a compressor alone, or b) the efficiency of the compressor as it performs in a system. The first method is a useful measure for compressor designers; the second has more meaning for building owners and HVAC designers.

Compressor designers customize scroll compressors for each different refrigerant, isolating on the compressor's individual performance. Variations in scroll geometry, shell design, oil selection and other features optimize the compressor-refrigerant combination.

Chiller designers focus on the efficiency of the overall system. Carrier's Model 30RC AquaSnap air-cooled chiller operates with R-32 and has full-load EER values up to 11.0 and IPLV (Integrated Part Load Value) up to 19.0.

APPLICATIONS

Manufactured in a variety of sizes up to 44 tons, scroll compressors have found their way into a variety of refrigeration and HVAC applications. In the "refrigeration" category, scroll compressors have been successfully used for bulk milk cooling, truck transportation, marine containers, and grocery display cases. The residential and light commercial air-conditioning segment, a huge success story for scroll compressors, was one of the first HVAC applications to

employ scroll compressors. Heavy commercial HVAC applications quickly followed suit and employed scroll compressors in unitary (rooftop) systems, heat pumps, water chillers for process and building cooling, and large split system condensing units. The transportation industry has also joined the scroll movement and has successfully applied efficient and reliable scroll compressors to automotive air-conditioning. Scroll compressors are also commonly used for compressed air and oil-less compressed air service.

Carrier introduced the model 30RC AquaSnap air cooled scroll chiller, shown in Figure 11 and 12, in 2023 and produces units in capacities between 10 and 250 tons. The smallest size has a nominal 4 and 6 ton compressor. At the opposite end of the size spectrum, the 250 ton chiller has six nominal 42 ton compressors on two equally sized refrigeration circuits.



Fig. 11. Carrier Model 30RC AquaSnap air-cooled chiller, 10 to 60 tons



Fig. 12. Carrier Model 30RC AquaSnap air-cooled chiller, 60 to 250 tons

All model 30RC chillers come with one or two independent refrigerant circuits, and the maximum number of compressors per circuit is three. The individual compressor sizes on a given circuit can be mixed (e.g., a 10 ton paired with a 12.5 ton compressor) similar to that shown in Figure 13.



Fig. 13. Scroll compressors piped together on a common refrigerant circuit

RELIABILITY

Scroll compressors have a successful history in HVAC applications and have proved their reliability to be as good or better than other technologies. Since their introduction, millions of scroll compressors have seen successful service worldwide in food and grocery refrigeration, truck transportation, marine containers, and residential and light commercial air-conditioning.

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**CARRIER CORPORATION
SYRACUSE, NEW YORK**