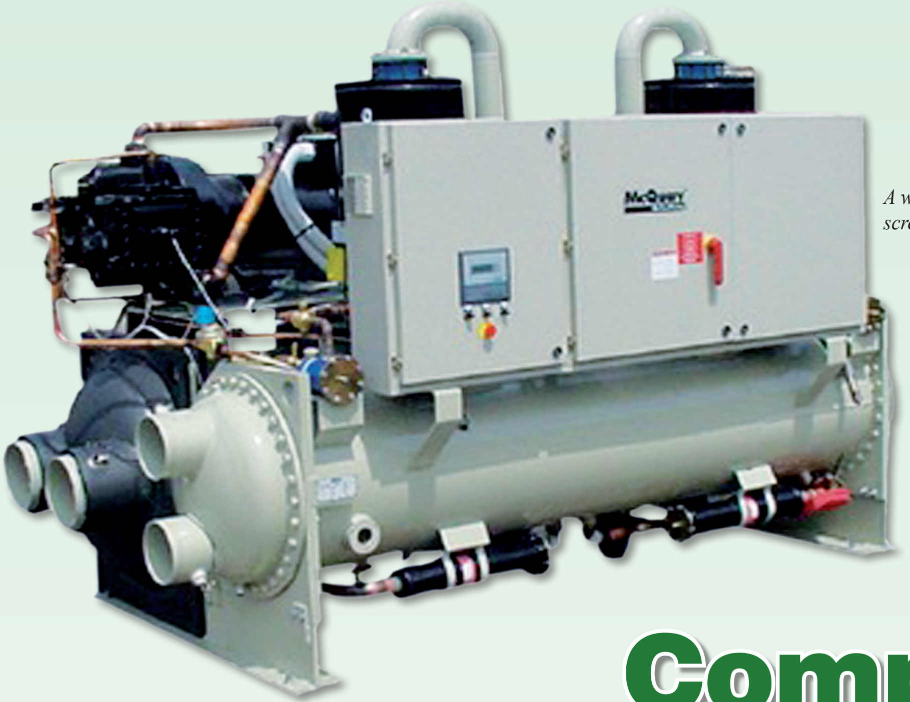

A water-cooled chiller with two screw compressors

Screw Compressors & Chillers

– History of Development

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Current annual production of screw compressors for refrigeration and air conditioning applications is approximately 140,000 units, more than 10-fold the annual production volume of centrifugal compressors. Screw compressor production has more than doubled over the past 10 years. Looking back over the history of large-capacity air conditioning equipment, the centrifugal chiller has maintained its status as the main stream of commercial and industrial air conditioning since Dr. Willis Carrier first commercialized it in 1922. Now, however, screw compressors have also come to play a key role rivaling centrifugal compressors of medium- and large-size air conditioning chillers and refrigeration equipment. At present, major air conditioning and refrigeration equipment manufacturers around the world manufacture their own screw compressors. In addition, almost all compressor manufacturers that have traditionally produced and sold reciprocating compressors now also produce screw compressors.

Screw compressor, with its fundamental theory established in the 1870s, was initially put into practical use in the 1930s, and screw compressors for refrigeration applications went into production in the 1960s. It was not until 1980, however, that the current models of semi-hermetic compressor for chillers were commercialized for air conditioning applications and their use began to expand sharply. This article traces the technical development of compressors and products they are used in for refrigeration and air conditioning applications as well as potential future developments.

Early Stage of Development

The principles of screw compressors were already established and patented in Germany by the 1870s, but rotor manufacturing technology posed an obstacle and no products were actually commercialized. A half-century later in the late 1930s, Sweden-based SRM made further advances in rotor theory practically and successfully commercialized an air compressor for use in gas turbines. This screw compressor was developed in order to get around the surging issue that arose with centrifugal compressors. It was called a twin screw compressor (*Figure1*) since it was composed of two rotors of male and mating female rotor. It would take another 10-odd years, however, to create a rotor machining tool capable of precision processing.

SRM, the developer of this compressor, first licensed the technology to UK-based Howden in 1946 and then went on to conclude licensing agreements with other companies around the world. This marked the beginning of global screw compressor production. SRM continued to file patent applications, and as of 2008, SRM still had been making licensing agreements with more than 50 companies worldwide.

In the beginning, screw compressors were of dry-running types that did not inject oil with timing gears to couple two rotors, but oil-injected air compressors were developed in the 1950s.

Compressors for refrigeration applications were commercialized in the 1960s. This marks the beginning of screw refrigeration units and screw compressors for chiller applications, a lag of about 40 years after the commercialization of centrifugal chillers. This also marks the appearance of large, rotating-type refrigerant compressors that took the place of reciprocating compressors.

The first screw compressors developed by SRM featured a symmetrical rotor profile, but along with analysis and processing technology advances, compressor improvements in the 1970s led to development of asymmetrical rotor profiles which reduced the blow holes and clearances between two rotors. These advances improved compressor efficiency, and the asymmetrical rotor profile forms the basic structure of current screw compressors.

Meanwhile, in the 1960s a French inventor by the name of Bernard Zimmern, developed what is known as the single screw compressor at his own company named Omphale in Paris, and he later founded the company Single Screw Compressor Inc. (SSCI) in Norwalk, Connecticut in order to expand his technology into the United States. Differing from the twin screw concept developed by SRM, the basic configuration consists of one main screw rotor and mating two gate rotors made of engineered plastic that mesh with the grooves in the main rotor to compress gas.

With this structure, the main rotor is pressure balanced and there is no deflection of main rotor arising from pressure load. This helps to keep meshing action with gate rotor in higher precision, in other words very tight clearance, as well as smaller bearing load.

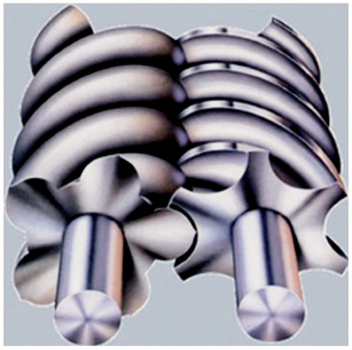

Figure 1 : Twin screw rotor

When the single screw configuration was initially developed, four basic configurations were envisioned, which featured the four combinations of main rotors with a flat or cylindrical shape and gate rotors with flat- or cylindrical-shape. The present-day configuration combines a cylindrical main rotor and mating two flat gate rotors *(Figure 2)*. This compressor was initially commercialized from air compressor, and as with SRM's twin screw compressor, the basic concept and technology were licensed to manufacturers around the world that then developed and produced compressors under their own design technologies.

Along with U.S. and European manufacturers, in the Japanese air conditioning and refrigeration industry Daikin and Mitsubishi Electric also entered into licensing agreements.

Following slightly behind twin screw compressors, single screw compressors for refrigeration applications were put into practical use from the 1970s.

To summarize, there are two main types of modern-day screw compressors, namely twin rotor and single rotor configurations, and they are used in a wide range of refrigeration and air conditioning applications.

Shifting to Rotating Type Compressors

Figure 2 : Single screw rotor

While reciprocating compressors had been the main compressor type for refrigeration and air conditioning equipment, from the late 1960s to the early 1970s the trend shifted to rotating-type compressors. While reciprocating compressors possessed advantages in terms of performance, wide operating range, and easy in maintenance, rotating-type compressors offered many advantages not possible with reciprocating compressors, including fewer parts, compactness, low vibration, and high rotating speeds. Production of rotating-type compressors became possible thanks to advances in high-precision machining technology. Room air conditioners (RACs) and packaged air conditioners (PACs) began to use rotary compressors in the 1970s, while scroll compressors were increasingly commercialized from the 1980s. Production of screw compressors mainly for refrigeration equipment began earlier, in the latter half of the 1960s.

While the fundamental technology underlying screw compressors was established, in the refrigeration and air conditioning field the use of screw compressors was initially limited to refrigeration equipment and specialized large capacity heat pump chillers. U.S.-based Dunham-Bush had already developed a large-capacity screw chiller for air conditioning by the 1960s, but it did not eclipse the position held by centrifugal chillers. The main reasons included efficiency – screw compressors could not outperform reciprocating or centrifugal compressor efficiency under air conditioning conditions – and the cost increases that came with managing the oil lubrication.

Screw compressors require more oil for injection than other compressors to prevent metal contacts with two rotors and to fill the clearance by oil between rotors. This has the benefit of reducing leakage loss due to the hydraulic seal, and at the same time the oil is highly effective in reducing the compressor discharge temperature under higher pressure ratio conditions in particular. On the other hand, the use of oil also requires a more complex structure in the compressor unit, including a large oil separator to separate the oil from the discharge gas. A bigger oil pump is needed to inject the oil and oil-related accessories such as oil cooler and valves are also required. These extra equipment and accessories raised costs and made screw chillers less competitive than other chillers already in the market. However, screw chillers also offered several advantages in large-capacity refrigeration units and heat pump applications not available with typical reciprocating chillers. Screw chillers could operate readily under the conditions of high-pressure ratios, had little vibration due to the rotational operation, had more compact compressors, and offered fine-tuned stepless control.

Screw chillers were therefore first commercialized mainly for large refrigeration units and air-cooled heat pumps with larger capacity of more than 100 hp.

Even today screw compressors are widely used in industrial gas compressors and refrigeration units. *Figure 3* shows an example of a compressor unit used in a refrigeration application.

Application to AC Chillers

In the 1970s, chiller compressors for air conditioning applications were divided into two types: semi-hermetic reciprocating compressors for systems under 100 RT in capacity and centrifugal compressors for systems over 100 RT. This trend continued into the 1980s. That is mainly because the reciprocating compressors with capacity over 100 hp became exceedingly large and their parts are too bulky and heavy to handle.

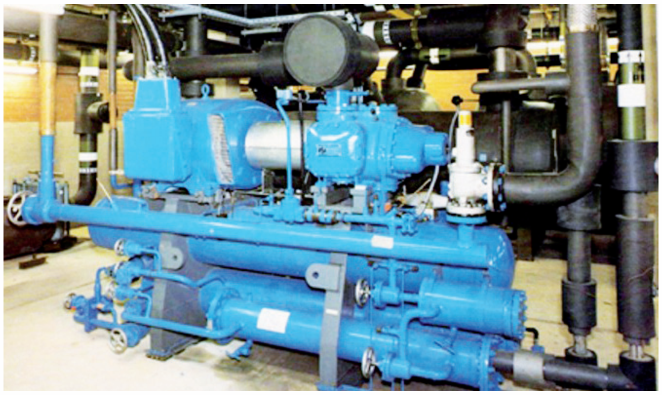

Figure 3 : Screw compressor unit

Meanwhile, small-capacity centrifugal chillers had technical difficulty in terms of performance and cost. Based on the principles of rotating type screw compressors, it was predicted from early stage of 1960s that the screw was to be suited to the capacity range between these two divergent compressors technologies.

As already stated, however, the complexity of the equipment that screw compressors require, including the oil separator and related accessories for oil injection, meant that the technology could not outperform centrifugal or semi-hermetic reciprocating compressors in terms of costs and compactness, nor could screw technology offer superior competitive efficiency.

Breakthrough Achieved in Japan

A breakthrough came in the early 1980s when Japan-based Hitachi developed a semi-hermetic screw compressor that used R22 refrigerant, then developed a series of chillers that mounted this compressor. The major purpose of this development was to replace the semi-hermetic reciprocating compressors that at the time were used in chillers up to 120 hp with screw compressors *(Figure 4)*. Japan has regulations on high-pressure gases and various legal restrictions on installations of chillers with capacity exceeding 120 hp, meaning that very few reciprocating chillers were above this capacity. The reciprocating compressors used in chillers came in three basic models of 40, 50, and 60 hp. At the time, these compressors were used in all types of chillers, including water-cooled chillers as well as air-cooled and heat pump chillers. These reciprocating compressors were in the small capacity range when considering the original screw compressor capacity.

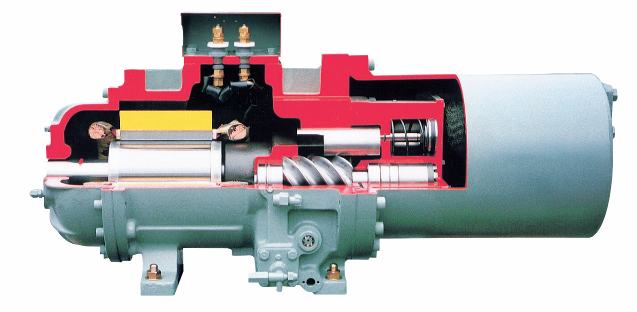

Figure 4 : Semi-hermetic twin screw compressor from Hitachi

The first screw compressors were semi-hermetic twin screw configurations, followed by a single screw compressor developed by Daikin. Chillers (water-cooled, air-cooled, heat pump) were then developed and released with single screw compressors. This marks the beginning of the growth of screw compressors for the air conditioning chiller segment. At the time, however, there were no plans to use screw compressors in the area dominated by small-capacity centrifugal compressors. This is because of the previously mentioned restrictions on chillers with capacity exceeding 120 hp in Japan. After these semi-hermetic screw compressors were released, they were extended to use for refrigeration condensing units.

The concept of this semi-hermetic screw compressor technology also influenced Asian and European markets to become the global *de facto* standard.

Technology to Surpass Reciprocating Compressors

The merits of rotating-type screw compressors to use for chillers have been well understood for a long time, but several issues also needed to be addressed. The first was achieving performance equivalent to reciprocating compressors, and the second was eliminating or making more compact the extra devices screw compressors required for oil injection in order to achieve costs on par with reciprocating compressors.

Screw performance is significantly affected by leakage from the clearances between rotors and parts.

As screw compressors become smaller, the leakage volume for the basic displacement of the compressor, in other words the relative leakage volume, tends to become larger, therefore

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the volumetric efficiency tends to fall. To resolve this problem, a new rotor profile with little leakage was developed that radically differed from the conventional rotor profile.

The second technical issue of compactness was addressed by fundamentally redesigning the oil injection system that was unique to screw compressors. First, the oil injection volume was reduced, which also required reducing the area of the oil sealing. This was made possible in large part thanks to the development of a new high-precision rotor profile that minimized the clearances between rotors. This development drastically reduced the volume of oil injection and allowed a smaller oil separator to be designed and integrated with the compressor. This screw compressor was specifically designed for the limited operating conditions of air conditioning applications, making it possible to eliminate the oil cooling equipment while keeping the discharge temperature within limits. And new synthetic oil was developed, which maintained proper viscosity even at higher temperatures. An oil pump was also not used, but the oil was supplied by the pressure difference, which led to a more compact compressor design.

Since this compressor was specifically designed for air conditioning application and had limited motor power range, the standard semi-hermetic motor configuration normally cooled by suction refrigerant in reciprocating compressors could be adopted, and the electric motor was integrated with the compressor. With this, there was now a screw compressor for air conditioning applications that could compete against conventional reciprocating compressors.

What made these developments possible were advanced simulation technology, which was rapidly emerging at the time during 1970s and 1980s, and high-precision machining technology. These technologies not only led to the optimized rotor profile, but were also applied to analysis of casing pressure and thermal deformation as well as optimization of all clearances between parts and part profiles. The same can be said about smaller rotary and scroll compressors that were developed around that time.

Substitute for Centrifugal Chillers

Following development in Japan, screw compressor development took off in the United States in the 1980s. Then in 1987, Trane released a water-cooled screw chiller in capacities from 70 to 125 RT. It also constructed a plant just for manufacturing screw compressors and chillers.

From this time, screw compressors have occupied a key position in the air conditioning field in the United States.

As mentioned, semi-hermetic screw compressor development in Japan was aimed at replacing reciprocating compressors of 120 hp or smaller, while in the United States, screw compressor development first focused on water-cooled chillers and worked into the centrifugal chiller segment. In other words, in the United States where high-pressure gas regulations differed, screw compressors were used not only to replace reciprocating compressors under 120 hp but rather focused to replace centrifugal compressors in the small capacity centrifugal chiller segment.

Figure 5 : Carrier's tri-roror screw compressor

Therefore, the U.S. and Japanese development concepts were not the same for screw chillers. But, the philosophy of shifting reciprocating compressor to rotating type was the same. The basic U.S. design was intended to replace centrifugal compressors with screw compressors. For this reason, a flooded-type heat exchanger with high efficiency was used. With this, going into the 1990s, more and more major U.S. manufacturers also started focusing on screw compressor development and they were developed in larger capacities.

Currently, the largest screw compressor is approximately 500 RT.

Screw compressors that were subsequently developed were used in large-capacity air-cooled chillers.

Subsequent Technology Development

Along with single and twin screw compressors, going into the 2000s, simulation technology was further advanced. In addition, a variety of rotor profiles were developed and improvements made in both design and manufacturing to achieve higher precision through dynamic thermal stress and deformation analysis of the rotors and casing. Key areas for screw compressor that were the subject of technology development around this time were (1) application of inverters – variable-frequency drive (VFD), (2) a new tri-rotor structure (*Figure 5*), and *(3)* practical application of variable volume ratio (Vi).

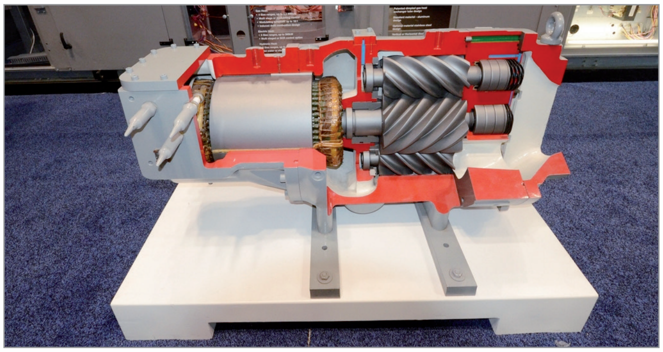

Figure 6: A large-capacity chiller with a tri-rotor compressor

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Inverter drive had been used as an option for compressors in the past, but around this time screw compressors began to be released only with inverter drive. Inverter scroll and rotary compressors for RAC and PAC applications had already become the mainstream and permanent magnet motors had also been commercialized. Penetration of inverter screw compressors followed slightly behind these developments.

The falling cost of large-capacity inverters contributed significantly to this development. Conventional screw compressor capacity control was achieved by moving a slide valve attached to the rotor to open and close a bypass passage, which adjusted the discharge gas volume by releasing refrigerant vapor under compression on the suction side. This method, however, results in bypass gas flow loss.

Future Screw Potential

The biggest features of screw compressors are the absence of surge and limitations in pressure on lift that occur with centrifugal compressors. Air conditioning systems are now required to be increasingly efficient and are also diversifying from simple air conditioning operation to offer heat recovery, ice thermal storage, and water-source and geothermal heat pumps. Under these types of conditions, it becomes increasingly important to have a wide operating envelope without limitations on lift.

Moreover, another feature of screw compressors is their ability to use various kinds of refrigerants without requiring significant design changes. With centrifugal compressors, it is necessary to design the shape of the impeller and the rotation for respective refrigerant characteristics, resulting in more time and money needed for development. Over the past 20 years, in fact, screw compressors have gone from using R22 refrigerant to using R407C, R134a, R404A and NH_3 as well as HFO refrigerant in the testing stage without major design changes. As such, no matter what refrigerant is developed in the future, screw compressors will have the major advantage of flexibility in applications and operating conditions. As new air conditioning equipment and systems continue to be developed and released in the market, the flexibility that screw compressors offer will be a key asset.

There is an optimum capacity range for screw compressors depending on the feature that is the focus – whether it is efficiency, cost, application, or refrigerant. However, the optimum range is always shifting with various technological advances. In recent years, large-capacity scroll compressors in the range of 50 and 60 hp have been developed and are entering into the current capacity range of screw compressors. At the same time, screw compressors are also stretching into the traditional range of centrifugal compressors and are nowadays used in the capacity range of water-cooled chillers from 100 RT to 300 RT extending to 550 RT.

Therefore, it becomes important to carefully assess the various technologies available at the time and select the optimum compressor for the proper operating conditions. ❖