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The Different Types of Cooling Compressors

White Paper 254

Revision 0

by Paul Lin
Victor Avelar

Executive summary

There is much confusion in the marketplace about different compressor types and their characteristics. In this paper, each of these compressors is defined, benefits and limitations are listed, and practical applications of each are discussed. With this information, an educated decision can be made as to most appropriate compressor for a given need.

Introduction

A compressor acts as the “heart” of a refrigerant-based mechanical cooling system. Its functions include drawing in the cool vaporized refrigerant that carries the heat energy from the evaporator coils, compressing it from a low pressure and temperature to a high pressure and temperature, and pushing it around the refrigeration loop for the purpose of heat rejection. For more information on fundamentals of the refrigerant-based mechanical cooling system, see White Paper 57, *Fundamental Principles of Air Conditioners for Information Technology*.

In data center environments, the compressor type not only impacts first cost and operational characteristics of the cooling system (i.e. performance, reliability, lifespan, noise, etc.) but also impacts the capacity requirements of upstream power distribution equipment and generators, required to support the cooling system. However, the various compressor types and their attributes often cause confusion for data center managers and operators. For example, it is widely believed that there are only two types of compressors, namely “constant speed” and “variable speed”. These two commonly used terms do not correctly describe many of the compressors available and cannot explain the characteristics of each of the compressor types.

Further adding confusion, vendors routinely produce models with similar names, but with very different performance characteristics. White Paper 257, *Difference Between Variable Speed and Variable Capacity Compressors and Why It’s Important* shows an example with quantitative analysis. Much of this confusion goes away if the different types of compressors are properly identified.

This paper classifies the compressor types in the marketplace today, describes their structure, theory of operation, benefits, limitations and applications, along with comparisons showing capacity, efficiency, and cost differences.

Compressor types

Compressors are sometimes described by the following characteristics:

- Drive speed (constant speed or variable speed)
- Number of stages (single-stage, two-stage, or multi-stage)
- Drive types (motor, engine, belt, or chain, etc.)
- Structure (open type, semi-hermetic and hermetically sealed)
- Cooling method and medium (air-cooled, water-cooled, or oil-cooled)
- Lubricating method (splash lubricated, forced lubricated, or oil-free)

However, the above characteristics cannot distinguish the commonalities or unique characteristics among the different compressor types, which leads to confusion for data center managers and operators. In fact, the most typical classification is based on the compressor theory of operation, such as positive displacement and dynamic (see **sidebar** for detailed explanations).

Figure 1 shows the typical classification of compressor types based on their theory of operation. Not all types, but most of the common types are listed here. This paper discusses five compressor types which are commonly installed in data center cooling systems (in green). The following sub-sections defines each compressor type, and lists the benefits, limitations and applications of each compressor type in details.

Positive displacement vs. dynamic

Positive displacement means that the cool vapor refrigerant is compressed to a high pressure and temperature via a chamber whose volume can change. For example, the motion of a piston in a cylinder chamber, or the rotation of a vane in a cylinder chamber, or the rotation of two matching helical screws inside of a casing, etc.

Dynamic means that the cool vapor refrigerant is compressed to a high pressure and temperature by adding kinetic energy via a rotating component. For example, a spinning impeller, or a rotating blade, etc.

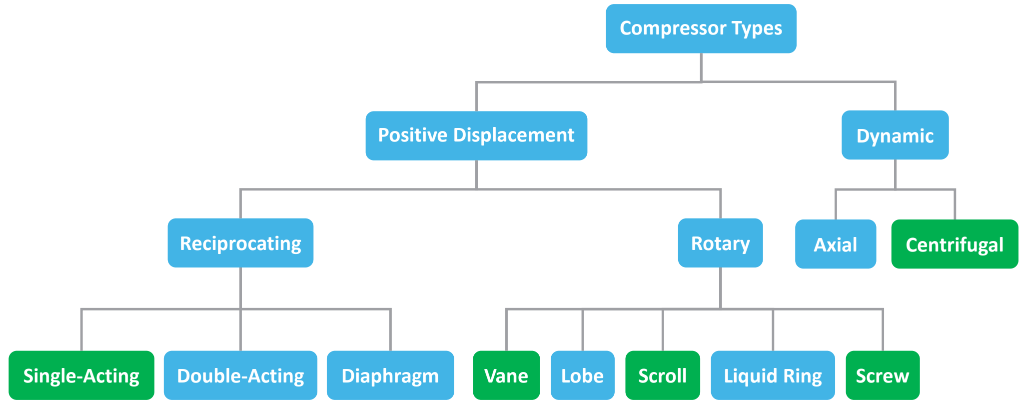

Figure 1
Classification of cooling compressor types based on the theory of operation (Green shows the compressor types commonly installed in data center environments)

Reciprocating compressor (single-acting)

A reciprocating compressor is also called a piston compressor which adopts the back and forth piston motion in a cylinder synchronized with suction and discharge valves to compress the vaporized refrigerant from a low pressure and temperature to a high pressure and temperature (shown in **Figure 2**). The motion of the piston is achieved via a crankshaft which converts motor rotations to piston reciprocations.

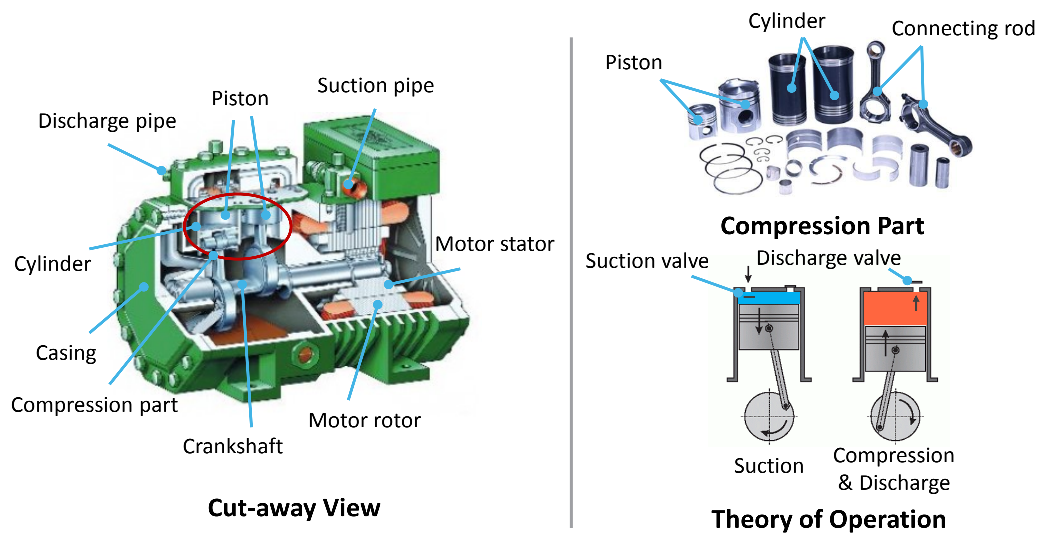

Figure 2
An example of reciprocating single-acting compressor (serviceable semi-hermetic)

Each operation cycle includes three actions: suction, compression and discharge. Each crankshaft rotation can achieve these three actions in sequence; as a result, the gas displacement is discontinuous which causes vibration. The total theoretical gas displacement depends on the size of each cylinder, cylinder quantity, and the rotating speed of the crankshaft. However, the actual gas displacement is also determined by the volume efficiency which depends on clearance volume (see **sidebar**), resistance of suction and discharge valves, leakage between the piston and cylinder, etc.

Clearance volume

Due to the complex shape of the compression parts, when the piston reaches top dead center at the end of the compression stroke, there is still a small volume left which is filled with compressed vapor refrigerant. This leftover volume is called clearance volume. The clearance volume losses a portion of cylinder volume for suction which reduces the compressor efficiency.

Depending on the location of the working fluid, the reciprocating compressor can be sub-classified as single-acting or double-acting. Single-acting means that the refrigerant acts only on one side of the piston while double-acting means the working fluid acts on two sides of the piston. The diaphragm compressor in **Figure 1** is normally used to compress hydrogen and natural gas and is not discussed in this paper.

The reciprocating single-acting compressor can also be sub-classified other ways, such as:

- **Structure** (open type, serviceable semi-hermetic, bolted serviceable semi-hermetic, and welded hermetic)
- **Cylinder arrangement & quantity** (laid out like the letter V, W, Y, S, etc.)
- **Operating temperature** (low, medium and high)

Open and serviceable semi-hermetic reciprocating compressors can be disassembled for service in the field while welded hermetic is unserviceable. The welded hermetic type can be designed to a small cooling capacity (e.g. 1/2 ton or 1.8kW) while the open type can be designed to a large cooling capacity (e.g. a hundred of tons or 350kW).

The capacity of the reciprocating compressor can be adjusted through quantity of working cylinders, cylinder unloading (via suction bypass or cutoff), and inverter drive. In order to increase the operating boundary of the cooling system, two-state compression or a cascade system can be used. The compressor performance like capacity and efficiency are also determined by the refrigerant type, and the refrigerants with lower global warming potential (GWP) values and lower ozone depletion potential (ODP) values are recommended for environmental benefits. The following lists the benefits, limitations, and applications of this compressor type.

<u>Benefits</u>

- Broad applications: this compressor type is capable of compressing a wide range of gases such as refrigerant, hydrogen, natural gas, etc. As a result, it can be used in different industries such as building, refrigeration, mining, metallurgy, etc.
- Broad capacity range: welded hermetic compressors can be designed to a very small capacity which is normally used for residential freezers. Open and serviceable semi-hermetic compressors can be designed to a hundred tons (350 kW) for residential and commercial air conditioning applications.

<u>Limitations</u>

- Low energy efficiency: this compressor type suffers from higher losses as a result of clearance volume, resistance due to suction and discharge valves, and gas leakage between the piston and cylinder.
- Sensitive to liquid slugging inherent with this design (see **sidebar** for details).
- Compared with other compressor types discussed below, it normally has larger dimensions and greater weight per unit capacity.
- Difficult to maintain due to complex structure.
- Vibration due to discontinuous gas displacement.

Liquid slugging

If there's liquid in cool vapor refrigerant, the liquid can damage the moving components like the piston. This is known as liquid slugging. Some strategies are used to separate the liquid from the cool vapor refrigerant to avoid wet stroke and enhance the compressor reliability.

<u>Applications</u>

Based on the characteristics of the reciprocating compressor, it can be used in the following applications:

- Household refrigerator and freezer with welded hermetic type
- Residential and commercial air conditioning and refrigeration applications (open, semi-hermetic and welded hermetic)

Rotary-vane compressor

A rotary-vane compressor is also known as a rotary piston compressor because the function of the vane is similar to that of a piston (shown in **Figure 3**). The fixed casing is known as a cylinder. The vane splits the space between the cylinder and the rolling piston into two sections (suction and discharge). As the rolling piston rotates, these two volumes are increased and decreased to achieve gas suction, compression and discharge. This compressor type can also be sub-classified by the drive speed (constant and variable) and number of vanes. Each operation cycle includes five actions: start, suction, compression, discharge and end. Each crankshaft rotation can achieve these five actions by average. The capacity can be adjusted through cylinder unloading or inverter drive.

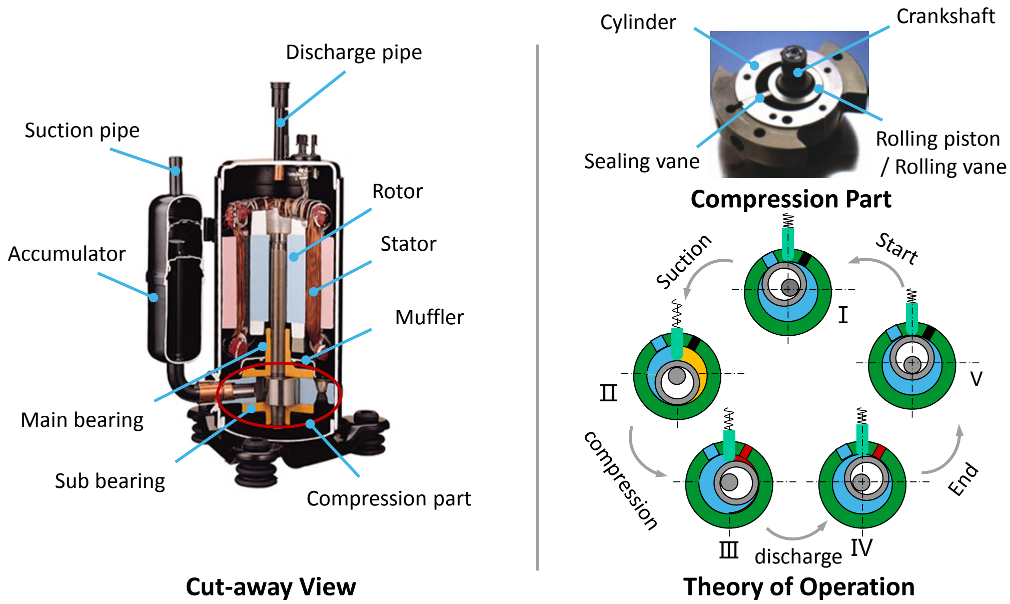

Figure 3
An example of rotary-vane compressor (single vane)

Benefits

Compared with the reciprocating compressor, the rotary-vane compressor has:

- Higher efficiency due to less losses from clearance volume and discharge valve resistance.
- Smaller dimensions and lighter weight per unit capacity (40%-50% savings).
- Less vibration, less components, and higher reliability because there is no conversion from rotations to reciprocations.

Limitations

Compared with other compressors discussed below, rotary-vane compressor has:

- Smaller capacity, normally below 5 tons (18kW) due to the limitation of its structure.
- lower reliability due to more components.
- Lower energy efficiency due to the losses from clearance volume, dis. valve.

Applications

- Appliances such as household refrigerators and freezers
- Residential air conditioning and heat pump products below 5 tons (17.6 kW)

Rotary-scroll compressor

Compared with rotary-vane compressor, a rotary-scroll compressor is used to compress larger volumes of gaseous refrigerant to a higher pressure and temperature via a fixed and orbital scroll (shown in **Figure 4**). The cool vapor refrigerant is drawn in from outside the fixed scroll, then compressed in between the fixed and the orbital scroll, and finally the compressed refrigerant is discharged from the center of the fixed scroll with a continuous displacement. The rotary-scroll compressor can be sub-classified by the drive speed (constant and variable).

Each operation cycle includes three actions: suction, compression, and discharge. However, some constant speed compressor designs adjust their cooling capacity by lifting or separating one of the scrolls intermittently from its normal operating position based on the amount of thermal load to adjust its cooling capacity. The less load, the more time the scrolls remain separated, preventing refrigerant compression. This method is not a variable speed compressor, but a variable capacity compressor, which is less efficient than the real variable speed compressor. A common industry term used to describe this type of compressor is digital scroll compressor. For more information on this topic, see White Paper 257, *Difference Between Variable Speed and Variable Capacity Compressors and Why It's Important*.

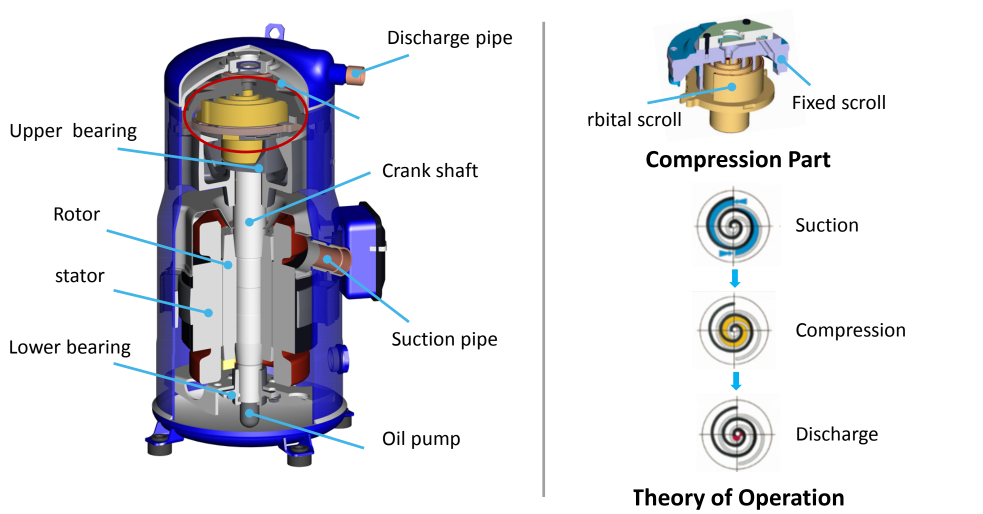

Figure 4
An example of rotary-scroll compressor

Benefits
Compared with the reciprocating and rotary-vane compressors, a rotary-scroll compressor has the following benefits:

- Higher reliability due to simpler structure and less components
- Higher efficiency due to less losses because it requires neither suction nor discharge valves, meanwhile there is no clearance volume.
- Less vibration and less surging due to continuous gas displacement through the sweeping motion of the rotors.

Limitations
Compared with the rotary-screw and centrifugal compressors discussed below, the rotary-scroll compressor has lower efficiency and smaller capacity.

Applications
This compressor type is normally used for commercial air conditioning and refrigeration applications which requires compressor capacity from 5 to 10 tons (18-35 kW).

Rotary-screw compressor

A rotary-screw compressor uses rotors to compress larger volumes of gaseous refrigerant to a high pressure and temperature (shown in **Figure 5**). The compression is performed by male and female rotors that reduce the refrigerant gas volume as they rotate. Cool vapor refrigerant enters from the suction port, is forced by the meshing rotors through the threads as the screws rotate, and exits at the discharge port with high pressure and temperature. The rotary-screw compressor can be sub-classified by the quantity of screws (single, twin and multi). The capacity can be adjusted through an inverter drive.

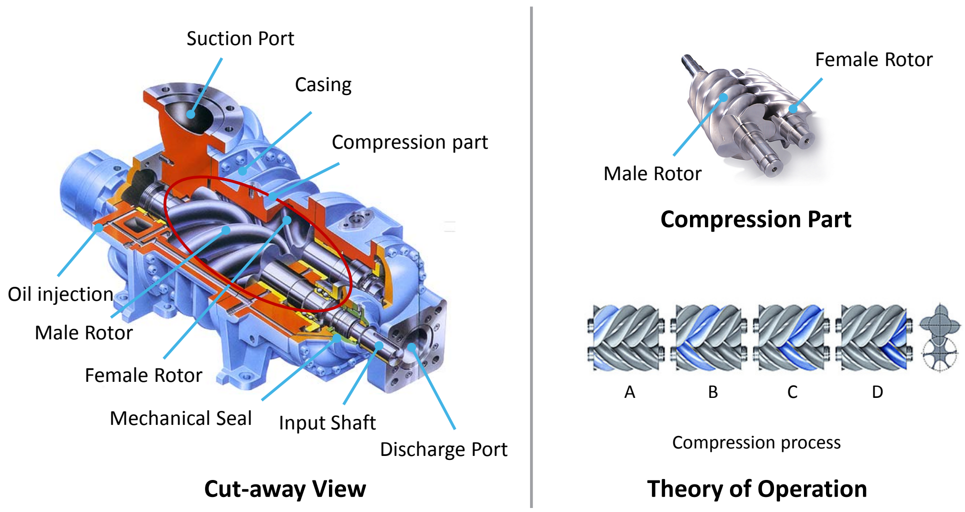

Figure 5
An example of rotary screw compressor (twin screw)

Benefits
Compared to the compressors discussed above, the rotary-screw compressor has the following benefits:

- Simpler structure, less components, larger capacity, and higher efficiency
- Less vibration and less surging due to continuous gas displacement via the sweeping motion of the rotors.
- Better adjustment in cooling capacity without causing unstable operation, which is sometimes an issue with centrifugal compressors
- Less sensitive to liquid slugging but long-term liquid slugging will impact the reliability of the compressor

Limitations

- Impractical to design to a capacity below 20 tons (70 kW), due to the rotor processing technology.

Applications
Screw compressors have been developed to compete with large reciprocating and small centrifugal compressors in both air conditioning and refrigeration markets. It is used for commercial and industrial air conditioning and refrigeration applications with a capacity range from 20 to 750 tons (70-2,637 kW).

Centrifugal compressor

A centrifugal compressor is also called a turbo or a radial compressor which compresses refrigerant to a high pressure and temperature by adding kinetic energy to the cool vapor refrigerant via rotating impellers (shown in **Figure 6**). The cool vapor refrigerant is forced to pass into and through the impeller, and the impeller forces the fluid to spin faster and faster. The high-speed refrigerant gas is then forced to pass through the diffuser where the refrigerant gas volume expands as its speed decreases. This process converts the kinetic energy of the high-speed low-pressure gas to a low-speed higher-pressure gas. The higher the impeller speed, the higher the pressure. Unlike the reciprocating piston compressor that has different actions for every stroke (i.e. suction, compression, discharge), centrifugal compressors perform these actions continuously and concurrently. The capacity can be adjusted through an inverter drive and inlet guide vane.

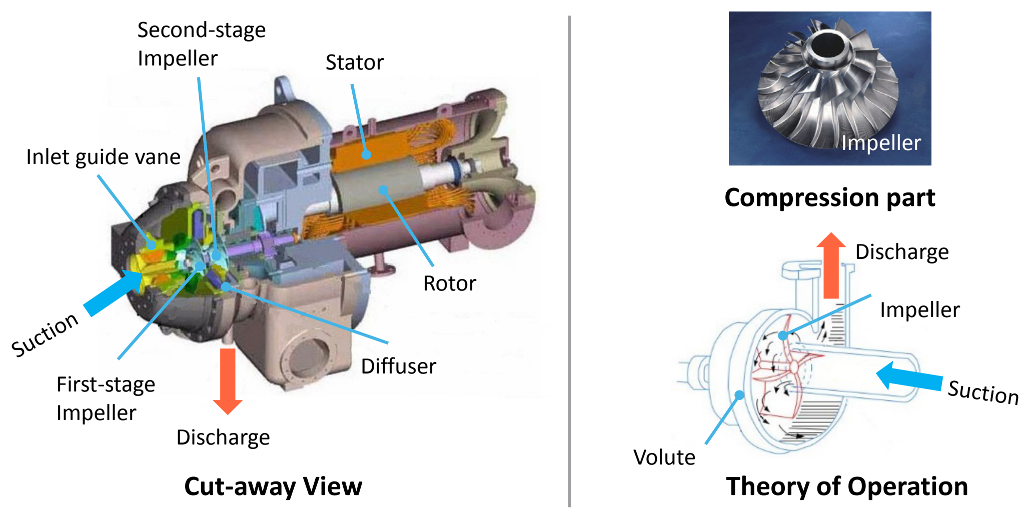

Figure 6
An example of a centrifugal compressor (two-stage)

A centrifugal compressor can also be sub-classified by the number of stages (single-stage, two-stage and multi-stage) and lubricating method (splash lubricated, forced lubricated, or oil-free). The oil-free type adopts friction-free magnetic bearings. As a result, there are no mechanical wear surfaces, which enhances the efficiency, reliability, reduces the noise level, and the maintenance cost.

<u>**Benefits**</u>
Compared with other compressors discussed in this paper, a centrifugal compressor has the following benefits:

- Largest capacity which can be up to 10,000 tons (35,000 kW) per unit.
- Higher efficiency under partial loads which is typical of data center loads.
- Higher heat transfer coefficient in evaporator and condenser due to oil-free refrigerant.
- Compact structure and lighter weight per unit capacity. 80%-90% weight reduction and about 50% footprint reduction compared to the reciprocating compressors.
- Higher reliability and lower maintenance cost because there are less components exposed to wear and tear.
- Less vibration due to continuous gas displacement.
- Multiple energy resources can be used for driving the compression, i.e. electrical motor, steam turbine, or gas turbine.

Surging

Surging means a gas flow reversal in the compressor from discharge to suction side. When the exiting head is greater than the compressor pumping head, the gas refrigerant will flow back and forth between the compressor and condenser. This unstable condition can damage the chiller bearings and drive shaft. As a result, the capacity of a centrifugal compressor should be specified based on the load conditions.

Limitations

- Capital cost premium, but lower operation cost offsets the increased investment.
- Requirements for higher quality material, higher precision machining, and higher quality manufacturing.
- Impractical to design to a capacity below 20 tons (70 kW) due to the impeller's high rotation speed. Also, it's difficult to manufacture an impeller with small diameters (e.g. not smaller than 200mm) due to processing technology.
- Larger unit capacity requires larger circuit breaker and wiring.
- Surging more likely to occur under light load conditions (see **sidebar**).

Applications

A centrifugal compressor is best suited for large cooling applications above 200 tons (700 kW), and is the most popular compressor type for commercial and industrial air conditioning and refrigeration systems. It competes with screw compressors and large reciprocating compressors.

Summary of compressor types

The different compressor types have attributes that make them more or less suitable for different applications. The attributes like cooling capacity, efficiency, reliability, price, etc. are key selection factors to consider. **Figure 7** shows the capacity and application comparisons between different compressor types discussed in this white paper. Note that some lower-capacity compressors like rotary-scroll can also be used in larger equipment when paralleled to achieve larger capacities, and may only be cost effective up to certain capacity limitations.

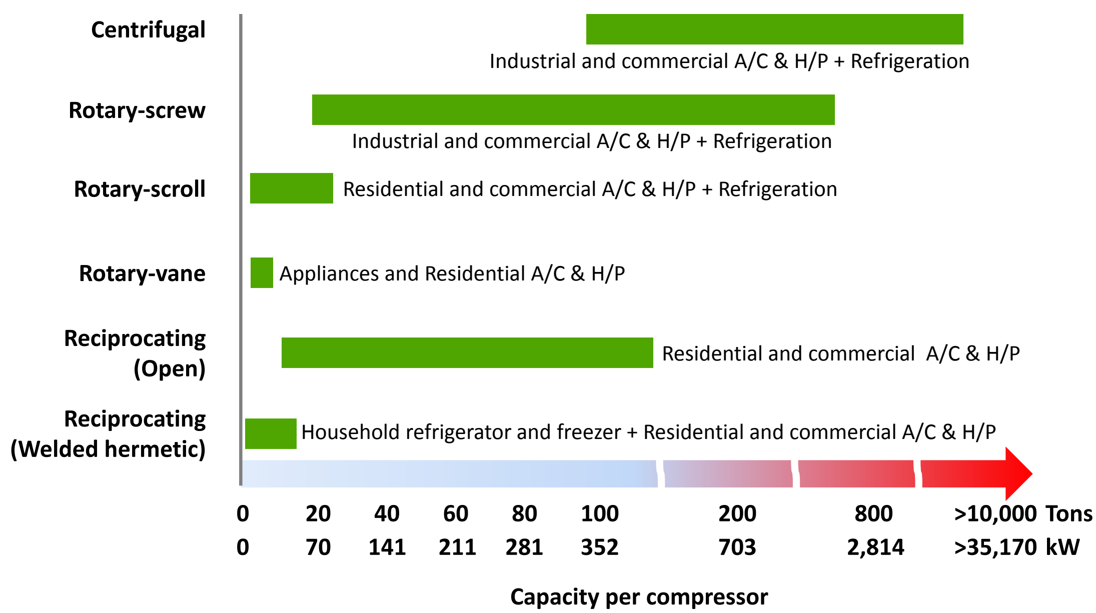

Figure 7
Capacity and applications of different compressor types
A/C: Air Conditioning
H/P: Heat Pump

Table 1 shows a summary of characteristics of the five compressor types discussed in this white paper.

Table 1

Compressor characteristics

Compressor Types		Cost per kW	Efficiency	Vibrations	Manufacturing accuracy	Input power per unit
Positive displace-ment	Reciprocating Single-acting	Low	Low	High	Easy	Low - High
	Rotary-vane	Medium	Medium	Moderate	Difficult	Low
	Rotary-scroll	Medium	High	Moderate	Difficult	Low
	Rotary-screw	High	Very high	Lowest	Very difficult	High
Dynamic	Centrifugal	High	Very high	Lowest	Very difficult	High

Conclusion

Various compressor types are appropriate for different uses, and no single compressor type is ideal for all applications. The intent of this paper is to contrast the benefits and limitations of the various compressor types on the market today.

Significant differences in compressor designs offer theoretical and practical benefits for different purposes. Nevertheless, the compressor is just one of four basic components of an air conditioner. The compressor type, cooling system configuration (e.g. condenser, evaporator), control, etc. will determine the ultimate performance achieved in a particular application. For more information on the types of cooling systems, see White Paper 59, *The Different Technologies for Cooling Data Centers*.

About the author

Paul Lin is a Senior Research Analyst at Schneider Electric's Data Center Science Center. He is responsible for data center design and operation research, and consults with clients on risk assessment and design practices to optimize the availability and efficiency of their data center environment. Before joining Schneider Electric, Paul worked as the R&D Project Leader in LG Electronics for several years. He is now designated as a "Data Center Certified Associate", an internationally recognized validation of the knowledge and skills required for a data center professional. He is also a registered HVAC professional engineer. Paul holds a master's degree in mechanical engineering from Jilin University with a background in HVAC and Thermodynamic Engineering.

Victor Avelar is the Director and Senior Research Analyst at Schneider Electric's Data Center Science Center. He is responsible for data center design and operations research, and consults with clients on risk assessment and design practices to optimize the availability and efficiency of their data center environments. Victor holds a bachelor's degree in mechanical engineering from Rensselaer Polytechnic Institute and an MBA from Babson College. He is a member of AFCOM.

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