Miniature BLDC Rotary Refrigeration Compressors

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Extremely small, high-performance rotary refrigeration compressors—the size of a child’s fist and weighting only 1.3 to 1.5 lbs—are produced in the U.S. and available around the world. Current models produce as much as 360 to 455W of cooling under standard ASHRAE conditions, using a single cylinder configuration. Compatible with various refrigerants and running on 12, 24 48VDC, etc. or AC power through a AC-DC conversion, the new compressors are starting a new trend in various compact mobile cooling systems as well as small foot-print countertop appliances with cooling or ice making capabilities.

On the 100th anniversary of the seminal patent by Willis Haviland Carrier, who is credited with starting the era of modern air conditioning and refrigeration, Aspen Compressor opened its first manufacturing plant to produce the world’s smallest production refrigeration compressors in Somerset, Ky., in 2006.

One might look back in the future and say the year 2006 was the beginning of a new era of energy-efficient “distributed cooling.” This means supplying cooling only where, when and only to the extent needed, and it is becoming more desirable from the viewpoint of the most efficient use of energy. A good example would be cooling individual workers in a large manufacturing space only where and when it is needed, obviating the need to air-condition the entire manufacturing space. Another good example would be cooling individual server racks or heat generating components in the server racks on demand instead of cooling the entire rooms/spaces housing the servers. A third example would be to provide cooling to individual seats in a sports stadium, either as a premium service, in a high temperature region, or only if a seat is occupied by a spectator and cooling is turned on by the occupant. The new efficient and compact compressors and their successors will make distributed cooling practical for many applications.

Figure 1 demonstrates the compactness of the new miniature compressors. Refrigeration compressors powered by direct current (DC) electrical energy have traditionally been very bulky and expensive, and only used in limited number of mobile refrigeration systems, where batteries or vehicle alternators are the source of power. The total number of conventional brushless DC (BLDC) compressors produced today for the worldwide market is relatively small (~1

Numerous refrigerated appliances can benefit from the size and weight reduction of a compressor. Some of the relevant refrigerated appliances are listed below:

- Beer Dispensers
- Beverage Carts
- Beverage Dispensers/Refrigerated Cabinets/Refrigerated Commercial Refrigerators/Freezers
- Cooled Display Cases
- CounterTop Appliances/Refrigerated Drawers/Refrigerated
- Household Appliances
- Ice Cream Cabinets/Dispensers
- Ice Storage Bins/Chests
- Marine Refrigerators
- Medical Product Storage
- Milk Coolers/Dispensers
- Mini Air Conditioners
- Mini-Bars
- Overstocking of Personal computers
- Portable Spot Coolers
- Reach-In Freezers
- Refrigerated Buffet Units
- Solar-Powered A/C & Refrigerator
- Vaccine/Medical Transport
- Wine Coolers
- Yogurt/Smoothie/Slush Machines
million) when compared to the vast number of AC driven compressors: reciprocating, rotary, and scroll types largely used in refrigerated appliances and air conditioners. But recent developments such as the emergence of solar power, and to a lesser extent hybrid and electric vehicles, have provided added impetus to the entire field of DC-powered small refrigeration systems. The result is that mobile refrigeration and portable cooling have been re-energized, creating new opportunities for innovative appliances of various kinds.

In 2007, a year after the opening of the Somerset Plant, the first series of new BLDC, hermetic rotary refrigeration compressors shown in Figure 1 was introduced to the world market. The development of the new compressors got started through a grant from the U.S. Dept. of Defense in the aftermath of the first Persian Gulf War. The Pentagon wanted to address the high number of heat-related casualties and electronic equipment failures experienced by the U.S. military during the desert campaign. A compact battery-powered refrigeration system was needed and this required a compressor that was small and light enough for a man-mounted cooling system, yet which could deliver sufficient cooling to protect soldiers and first responders from heat stress.

The design that eventually evolved over a 10-year development period was the rolling piston compressor shown in Figure 1. A year-long accelerated life tests in-house and subsequent endurance tests at third party test facilities demonstrated that the miniature compressors could match large-production rolling piston compressors in life expectancy and reliability: 5 years in refrigerators and 10 years in air conditioners.

### Dimensions

The compressors are just over 2.0 inches in diameter, about 3.0 inches in height, and weigh just 1-1/4 to 1-1/2 pounds. The pump part is of a single cylinder, rolling piston design with a displacement of 1.4cc, or 1.9cc and is powered

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>R134a, 404A, etc.</th>
</tr>
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<tbody>
<tr>
<td>Lubricating Oil</td>
<td>Polyol ester oil</td>
</tr>
<tr>
<td>Compressor Type</td>
<td>Single Cylinder Rotary (Rolling Piston)</td>
</tr>
<tr>
<td>Displacement</td>
<td>1.4cc or 1.9cc per revolution</td>
</tr>
<tr>
<td>ASHRAE Cooling Capacity</td>
<td>360 or 455W, respectively</td>
</tr>
<tr>
<td>Speed</td>
<td>Variable (2100 – 6500 RPM)</td>
</tr>
<tr>
<td>Motor</td>
<td>Brushless, Sensor-less DC, Rare-earth PM</td>
</tr>
<tr>
<td>Nominal Input Voltage</td>
<td>12, 24, or 48V DC</td>
</tr>
<tr>
<td>Maximum Current</td>
<td>9.5, 9.5 and 7 A, respectively</td>
</tr>
<tr>
<td>Allowable In-rush Current (50 milliseconds)</td>
<td>25, 25 and 15A, respectively</td>
</tr>
<tr>
<td>Evaporator Temperature Range</td>
<td>-18 to +24°C</td>
</tr>
<tr>
<td>Condenser Temperature Range</td>
<td>27 to 71°C</td>
</tr>
<tr>
<td>Maximum Compression Ratio</td>
<td>8:1</td>
</tr>
<tr>
<td>UL versions, currently available</td>
<td>1.4 or 1.9cc, 24V</td>
</tr>
</tbody>
</table>

Table 1 Compressor Specifications.
by a high-torque, high efficiency brushless DC motor. The motor is controlled with a sensor-less drive, and is easily adapted to variable speed operation between 2,100 and 6,500 rpm for efficient and load following operation. It could also provide rapid cool-down and precise control of temperature. The noise level data show that at 90cm, the levels vary from mid 60db for standard production models to ~50db for special low noise models. Users have agreed that the sound levels are quite reasonable and acceptable in many products for the extremely compact design. Table 1 provides a summary of specifications for the line of compressors.

<table>
<thead>
<tr>
<th>Type</th>
<th>Competing Reciprocating Compressor (left)</th>
<th>Aspen’s Rotary Compressor (right)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerant</td>
<td>R-134a</td>
<td>R-134a</td>
</tr>
<tr>
<td>Volume, cu.in.</td>
<td>130</td>
<td>11</td>
</tr>
<tr>
<td>Displacement per revolution, cc</td>
<td>2.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Weight, lbs.</td>
<td>9.5</td>
<td>13</td>
</tr>
<tr>
<td>Speed, RPM</td>
<td>2,000-3,500</td>
<td>2,100 – 6,500</td>
</tr>
<tr>
<td>Capacity (ASHRAE), W (Btu/h)</td>
<td>252 (860)</td>
<td>360 (1230)</td>
</tr>
<tr>
<td>Volumetric Cooling Capacity Denat. Btu/cu.in (ratio)</td>
<td>6.6 (1)</td>
<td>112 (17)</td>
</tr>
<tr>
<td>Weight Cooling Capacity Denat. Btu/cu.in (ratio)</td>
<td>90.5 (1)</td>
<td>946 (10.5)</td>
</tr>
</tbody>
</table>

Table 2. Comparison between the new miniature compressor and a widely used DC-driven reciprocating compressor with 30 percent less cooling capacity.

Figure 2 (left): Cooling Capacity Vs. Pressure Ratio at 6,000 RPM
Figure 3 (right): Volumetric Efficiency vs. Pressure Ratio at 6,000 RPM

Figure 4. Size Comparison between the New Miniature Compressor (1.4cc displacement) and a widely used DC driven Reciprocating Compressor with 30% Less Cooling Capacity.

A Cautionary Note to first time users of the miniature compressors
This is ironically one of unintended consequences of a successful introduction of an extremely compact compressor that can generate so much cooling!

The following mistake is made on more occasions than we would like to count: in the excitement and rush of trying to incorporate our miniature compressors into refrigeration system, new or old, even experienced refrigeration engineers/technicians tend to overlook or ignore the fact that our compressors come with only 21cc of POE oil inside. In the case of the conventional DC compressors, the oil contained in the compressor is ~ 150 to 200cc and even if 10 percent of the oil is lost to the balance of the system, there would be sufficient amount of oil left for lubricating the compressor.

It is quite important to know however that, depending on the overall size of the refrigeration system, a significant or major portion of the oil from the miniature compressors may go out with the discharged refrigerant and may never return to the compressor with the returning refrigerant. One must not forget to replenish the oil that would be lost to the balance of the cooling system. Otherwise, the miniature compressor would malfunction rapidly due to lack of lubrication oil.
An independent evaluation of the 1.4cc 24V compressor was performed at Purdue University. That evaluation included measurement of cooling capacity, coefficient of performance (COP), and volumetric and overall isentropic efficiencies. Volumetric efficiencies were found to range from 73 percent to 90 percent, while the overall isentropic efficiency varied from 44 percent to 70 percent. Cooling capacity was measured from 163 W to 489 W, while the COP varied from 2.1 to 7.4, as shown in Figures 2 & 3. Volumetric and isentropic efficiencies of the mini-compressor as reported in the referenced Purdue technical paper were in fact higher than those found in two other compressors (one reciprocating and one linear), which had similarly been miniaturized for size reduction purposes.

The testing at Purdue described above was performed with R134a as the primary refrigerant, which at this time is a popular choice refrigerant in North American markets. There has however been considerable interest in the use of hydrocarbons such as R290 (propane) and R600 (isobutane), which have been widely and successfully used in Europe. In the U.S., two industry giants, General Electric and Unilever, announced plans to incorporate hydrocarbon refrigerants into their products, showing the possible start of an industry trend. These refrigerants will be tested and evaluated soon in the miniature compressor, and it is believed that they will perform quite well.

Now that the performance and physical characteristics of this device have been described, we can now turn our attention to what this compressor means to the appliance designer. For its small size and low weight, the cooling capacity is very high. In fact, it can impart more cooling than many reciprocating compressors ten times larger in size and weight. Depending on ambient and evaporator temperatures, it can generate up to 1,800 BTU/h, enough to perform well in many refrigerated appliances. In a recent test with a 7.0 cubic foot commercial refrigerator/freezer, the compressor was able to maintain a minus 20ºF evaporator temperature and a refrigerator
compartment temperature below 40°F at 110°F ambient. These findings strongly suggest that the miniature compressor has sufficient capacity to cool many types of small appliances, whether they’re mobile or stationary.

Figure 4 shows the comparative sizes of the miniature compressor with a reciprocating DC compressor with 30 percent less capacity that has been widely used around the world for a long time. It is almost inconceivable to most people at first glance that the small compressor on the right (1.3 lbs and 11 cu.in.) actually has a 30 percent higher capacity than the larger compressor on the left (9.5 lbs and 130 cu.in)!

Comparison of key performance parameters is also shown in Table 2. For appliance designers, an important but seldom used (since they were pretty much all the same) parameter is that of cooling power density, both volumetric and weight.

The new rotary compressor has 17 times the cooling power for the same volume, and 10.5 times the cooling power for the same weight. An obvious conclusion to be drawn from this realization is that a large space and weight savings can be achieved using the miniature compressor. Such factors have historically been prized in mobile refrigeration systems only. Now, even though highly unusual for a DC-powered compressor, due to the weight and volume, the miniature compressors are being considered in various stationary applications, such as household countertop appliances; beverage dispensers; ice makers; ice cream machines, coffee machines, etc., where the small compressor size is highly desired to make the footprint of the appliance small.

When the miniature compressor is used in a refrigeration system together with a high-performance condenser and evaporator, the complete refrigeration system can be incorporated within a package as small as 100 in³ (1.64 liter). This allows a major space reallocation in the cabinet, namely much less volume for the refrigeration system and considerably more volume for product storage space. There’s also a weight reduction of approximately 10 lbs (4.54 kg) just from the use of mini-compressors. But for the most part, the space savings are usually considered more important than weight savings in most refrigerated appliances.

A small vapor compression cooling system using the miniature compressor would have even larger performance and efficiency advantages over thermoelectric coolers often used in various products in the absence of small compressors before. Above the cooling capacity range of 100W, the vapor compression based system will be far superior to the thermoelectric systems: ¼ to ½ the weight and volume, and 1/3 to ½ the power consumption compared to the thermoelectric systems.

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Where No Cooling System Has Gone Before
The miniature compressor is also an enabling technology for cooling various products that have yet to be conceived and developed.

Figure 5 shows various examples of appliances and cooling systems utilizing the miniature compressors.

In Figure 5.a, three miniature compressors are seen placed on a palm of a hand to emphasize their extraordinarily compact sizes.

Figures 5.b through 5.h show various appliances utilizing mini-compressors being sold or under development that we can show without violating the confidentiality agreements. These examples demonstrate that the miniature compressors are being looked at and used in many applications: military, electronics, industrial, commercial, medical, recreational, and household uses.

Extremely compact refrigeration compressors are already being introduced in many new applications that did not even exist, or were not feasible before and, as time goes by, their usage could usher in an era of super-efficient micro scale distributed cooling.

Reference: