QUIET, COMPACT, AND EFFICIENT ROTARY COMPRESSORS SUITABLE FOR COUNTERTOP AND HOUSEHOLD APPLIANCES

Presented are test data showing 55dBA-to-41dBA noise reduction without requiring much increase in casing size, if any, during development of the first generation quiet single-cylinder miniature rolling piston compressors which will be introduced to the worldwide market in January 2014. Full implementation of new patent pending measures for noise and vibration reduction will further lower the noise and vibration levels in subsequent models. These quiet miniature rotary compressors are intended for compact countertop appliances, refrigerators, smart distributed cooling, heating and other HVAC devices, etc. It is anticipated that by having achieved the respectably low noise level of 41dBA in the first generation models, and going lower in the future models, the speed of adoption for the highly efficient and compact rotary compressors will be accelerated resulting in tangible benefits in terms of more efficient and compact appliances for the end users, and reduction in global energy use by and carbon footprint of these ubiquitous appliances and cooling devices.

For cooling applications such as refrigerators, countertop beverage dispensers, freezers, coolers and air conditioners for automobiles, buses, trucks, ships, low noise and low vibration levels emanating from the compressor are required by the end users at the same time a very small compressor size and extremely low weight would be highly sought after. Compared to conventional reciprocating compressors which are used most prevalently in the refrigeration applications, inherently compact rolling piston compressors (the most widely used rotary compressors) would be more reliable in many applications, much lower in volume and weight, and significantly higher in thermal and mechanical efficiency.

Table 1 shows comparison of performance and other key parameters of an existing miniature BLDC compressor (A), semi-compact rotary BLDC compressor (B) and a reciprocating BLDC compressor (C): Compressor A is a current standard model 1.4cc miniature rotary compressor produced in the US without any noise/vibration mitigation measures. It is the smallest and lightest rotary compressor in production in the world. Compressor B, a semi-compact rotary compressor with a patented design, that has been in production in Taiwan, since 2006 and sold around the world, falls in the middle in comparison to very compact Compressor A and very large Compressor C originally from Germany and now China. Compressor B is one of the quietest rotary compressors available to date with the noise level of ~42 dBA at 90cm but it achieves reduction of noise and vibration at the expense of added weight and volume. Compressor C, a very quiet BLDC reciprocating compressor, is the most widely used BLDC reciprocating compressor in the world similar in design to most widely used AC driven compressors for household refrigerators. It has a relatively large housing

compared to Compressors A and B to accommodate conventional method of noise and vibration reduction such as long and flexible discharge line with spring cladding for support and damping, springs and dampers on support points, plastic bumpers, etc.

Table 1. Comparison of a state-of-the-art compact BLDC rotary compressor with a semi-compact BLDC rotary compressor and a large conventional BLDC reciprocating compressor

Comp. Designation / **Parameteres**	**A**	**B**	**C**
	Compact BLDC rotary compressor, without noise/vibration reduction measures	**Semi-Compact Rotary BLDC compressor with large mass & stator mounted to the top flange to reduce noise/vibration**	**BLDC reciprocating compressor with large housing for conventional noise/vibration reduction measures**
Manufacturer	**Aspen Compressor, USA**	**Teco Compressor, Taiwan**	**Danfoss, Germany**
Model number	**14-12-1101**	**KSDC010LJC KXY**	**BD35F**
Displacement, cc/rev.	**1.4**	**1.0**	**2.0**
Cooling Capacity, W	**360**	**145**	**234**
Comp. Weight, lbs	**1.45**	**3.20**	**9.50**
Comp. Volume, in^3	**11**	**24**	**130**
Height with tube, in.	**3.5**	**5.4**	**8**
Max. Diameter, in.	**2.2**	**2.4**	**8**
Gravimetric Cooling capacity Density, W/lb	**249**	**45**	**23**
Relative Ratio	**11**	**2.0**	**1.0**
Volumetric Cooling Capacity Density, W/in^3	**33**	**6.1**	**1.8**
Relative Ratio	**18**	**3.4**	**1.0**
Noise Level, dBA, 90cm	**55 @60 Hz**	**42 @68 Hz**	**35 @60 Hz**

To summarize Table 1: in terms of cooling capacity per compressor volume, Compressor A (miniature BLDC rotary compressor) is better than Compressor B by a factor of 6, and better than Compressor C by a factor of 18. In terms of cooling capacity per compressor weight, Compressor A is better than Compressor B by a factor of 5.5, and better than Compressor C by a factor of 11. The Compressor C represents the most common BLDC compressor sold in the world and the Compressor B represents one of the quietest semi-compact compressors.

Figure 1 shows the comparison of cooling capacity and COP between the compact miniature rotary BLDC compressor (Compressor A) and the most widely used large BLDC reciprocating compressor (Compressor C). It shows that the cooling capacity of the Compressor A is higher than that of Compressor C by 37% to 87% over the evaporator temperature range shown. It also shows that COP of the compact rotary BLDC compressor (Compressor A) delivering the same cooling capacity as the larger reciprocating compressor (Compressor C) at various evaporator temperatures is 56% to 100% higher depending on the operating conditions.

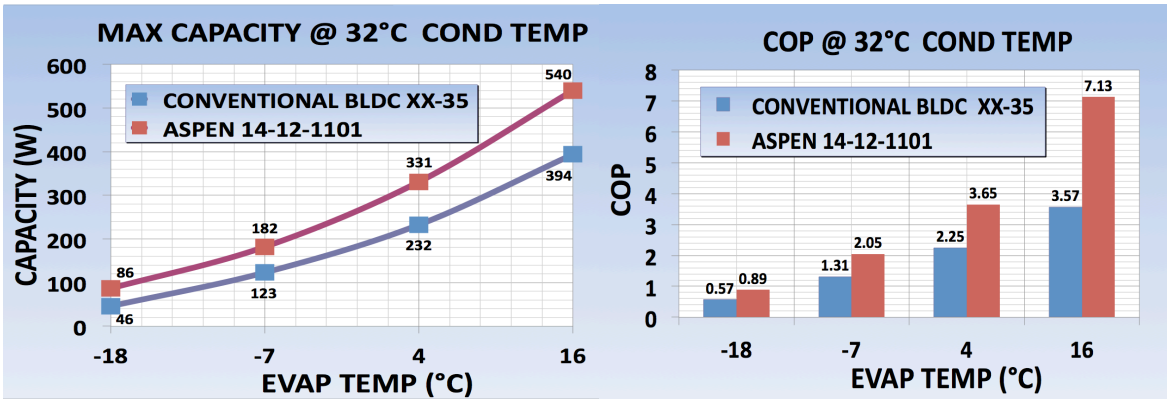

Figure 1. Miniature Rotary Compressor vs. Reciprocating Compressor

It is quite obvious from the comparison in Table 1 and Figure 1 that compact rotary compressors would be by far the best compressors to use in many applications because of their higher efficiency, extremely smaller size and much lower weight compared to the existing and widely used reciprocating or semi-compact rotary compressors. However, due to the higher noise and vibration, the rolling piston compressors have been generally relegated to outdoor units for air conditioning applications where high efficiency is much desired but very low noise and vibration are not absolutely required. Therefore, rotary compressors have not found the widespread use in household appliances that constitute a major refrigeration market, or even in the transportation vehicles due to their high noise levels. If their noise and vibration can be reduced even to a moderate level of 40 dBA, the use of rolling piston compressors in household appliances such as refrigerators would become widespread. For example, use of the compact BLDC

rotary compressors would result in a higher energy efficiency rating, so-called "Energy Star" rating, and lead to potentially a significant volume reduction of a so-called "Dog House" that currently houses a much larger (up to 18 times) sized compressor in a household refrigerator. If the "Dog House" can be reduced in size, the useful internal volume of a refrigerator increases by the same amount for the same external size refrigerator. There is a strong market incentive to reduce the noise and vibration of a rolling piston compressor so long as it can be achieved without compromising the key advantage of the compact size of the rolling piston compressor.

Due to the eccentric shaft and unbalanced pressure loads during the rotation of the eccentric shaft, single cylinder rolling piston compressors tend to create a relatively high levels of noise in the motor section and also in the pump assembly section in addition to the customary fluid borne noise mostly from the discharge. There is not much space to install conventional noise and vibration damping mechanisms within a compact rotary compressor.

Previously, there has not been a quiet compact rotary compressor with a respectably noise level of 40 dBA at 90cm @ 60Hz while keeping the low weight and small size intact. The closest one has been Compressor B in Table 1 which is still considered too large for wide scale use. Compressor B in Table 1 uses a massive top flange (weighing as much as 270g for a compressor compared to a miniature rotary compressor which has a top flange weighing only 30g) acting also as a holder for the stator thereby separating the stator from the casing by a physical gap, and utilizes a relatively massive metal components such as heavy bottom flange, heavy cylinder, and tall casing. The Teco semi-compact rotary compressor, with the noise level of ~42 dBA weighs about ~2.5 times heavier and bulkier than the quiet miniature compressor while delivering only 40% of the cooling capacity. In short, there has been no known success to drastically reduce the noise of a rolling piston compressor without resorting to large increases in volume and/or weight.

Truly compact, lightweight, low-noise/low-vibration rolling piston compressors, with the volumetric cooling capacity similar to that of Compressor A, would be able to penetrate the largely untapped home appliance and other large scale markets displacing the larger, not so efficient but much quieter, semi-compact rotary compressor such as Compressor B, or very large conventional reciprocating compressors such as Compressor C.

As a result of the lack of viable options for effective noise reduction to date without affecting the size, the noise reduction level achieved to date in state of the art compact rotary compressors are ~50 for twin cylinder and ~55 to 58 dBA for single cylinder and they are not sufficiently low enough to be used in household appliances as evidenced by the dirth of their use in these applications

despite many advantages of rotary compressors over conventional state of the art reciprocating compressors such as their extremely compact size and much higher efficiency.

A new patent pending, compact, in-casing noise and vibration mitigation method eminently suitable for a compact rotary compressor was developed in 2013 to ensure quiet operation for the normally noisy compressor. The new noise mitigation system will be especially useful for refrigeration systems where compact size, high efficiency, high power density is prized as well as low noise and vibration.

Table 2 shows comparison of performance and other key parameters of two new quiet BLDC compressors, D and E next to the original three compressors A, B, and C listed in Table 1. To repeat, Compressor A is a current standard production model 1.4cc compact rotary compressor without any noise/vibration mitigation measures. The compressor B, a rotary compressor with a patented design, that has been in production and sold around the world, is semi-compact in comparison to other large alternatives like Compressor C. It is one of the quietest rotary compressors available to date with the noise level of ~42 dBA at 90cm but it uses a quick and easy means of reducing noise and vibration at the expense of added weight and volume as well as the first articulated add-on component. The new quiet Compressors D and E are pre-production model 1.9cc and 1.4cc compact miniature rotary compressors with approximately 50% of the key features of patent pending noise reduction methods incorporated. It is to be noted that most of the increases shown in Table 2 in weight and volume for Compressors D and E over Compressor A are to accommodate a larger/higher efficiency/higher torque motor used to meet higher cooling requirements under extremely harsh operating conditions in the battlefield or tropical climates and also to increase the pressure rating of the casing to accommodate a higher pressure refrigerant, 410a.

In summary, in terms of cooling capacity density per compressor volume, the new low noise compact miniature rotary compressors D and E, are better than Compressor C (reciprocating) by a factor of 15 to 19, and better than Compressor B (semi-compact rotary) by a factor of 4.4 ~ 5.6, respectively. In terms of cooling capacity per compressor weight, the low noise compact rotary compressors, D and E, are better than Compressor C by a factor of 8.4 ~ 10, and better than Compressor B by a factor of 4.2 ~ 5.0. Compressors D and E, incorporating two of the four key features of the patent pending advanced noise suppression techniques, represent a significant leap toward extremely compact, lightweight, and quiet rotary compressors of all sizes. In mass production, these extremely compact and quiet miniature compressors will become fairly inexpensive due to their extremely small sizes (i.e., low materials cost and less finish machining and grinding needed!), to usher in their uses in many applications such as household refrigerators, countertop appliances, and many others such as distributed

superefficient cooling systems hitherto not feasible due to historically high noise levels of conventional rotary compressors.

Table 2. Comparison of 2 compact BLDC rotary compressors incorporating the present invention with a semi-compact rotary compressor and a large conventional BLDC reciprocating compressor

Comp. Designation / Parameteres	A	B	C	D	E
	Compact BLDC rotary compressor, without noise/vibration reduction measures	Semi-Compact Rotary BLDC compressor with large mass & other means to reduce noise/vibration	BLDC reciprocating compressor with large housing for conventional noise/vibration reduction measures	Compact BLDC rotary compressor, with noise/vibration reduction measures	Compact BLDC rotary compressor, with noise/vibration reduction measures
Manufacturer	Aspen Compressor, USA	Teco Compressor, Taiwan	Danfoss, Germany	Aspen Compressor, USA	Aspen Compressor, USA
Model number	14-12-1101	KSDC010LJC KXY	BD35F	Q-9-12-4100	Q-4-12-4100
Input Voltage, VDC	12				
Displacement, cc/rev.	1.4	1.0	2.0	1.9	1.4
Cooling Capacity, W	360	145	234	455	360
Comp. Weight, lbs	1.45	3.20	9.50	1.93	1.87
Comp. Volume, in^3	11	24	130	13	13
Height with tube, in.	3.5	5.4	8	4.0	4.0
Max. Diameter, in.	2.2	2.4	8	2.6	2.6
Gravimetric Cooling capacity Density, W/lb	249	45	23	236	193
Relative Ratio	11	2.0	1.0	10	8.4
Volumetric Cooling Capacity Density, W/in^3	33	6.1	1.8	35	28
Relative Ratio	18	3.4	1.0	19	15
Noise Level, dBA, 90cm	55 @60 Hz	42 @68 Hz	35 @60 Hz	41 @60 Hz	41 @60 Hz

Figure 2 shows the noise level data obtained from the several prototypes showing steady reduction of the noise levels starting from 55~56 dBA at 3600 RPM while gradually introducing each of new patent pending advanced noise reduction features over a few month period in early 2013 and ending up with the production compressor to be introduced to the market in January 2014 with 41 dBA rating at 90cm and 3600 RPM (60 Hz). It is notable that as of this writing, roughly half of the features that can be incorporated within the tight casing of a rotary compressor easily and inexpensively have been incorporated in the prototypes tested and the first generation quiet series (Q1-series) production compressors. It is expected that we will be able to achieve even lower levels of

noise than 41dBA and also much lower vibration levels as the remaining features are introduced in the future quiet models. Also notable is the fact through this concentrated compressor noise reduction effort that included complete redesign of the motor, the COP of the new Q-series compressors also improved by 5 to 35% over the evaporator temperature range shown, and the maximum available torque nearly doubled so that they can be used in more demanding applications

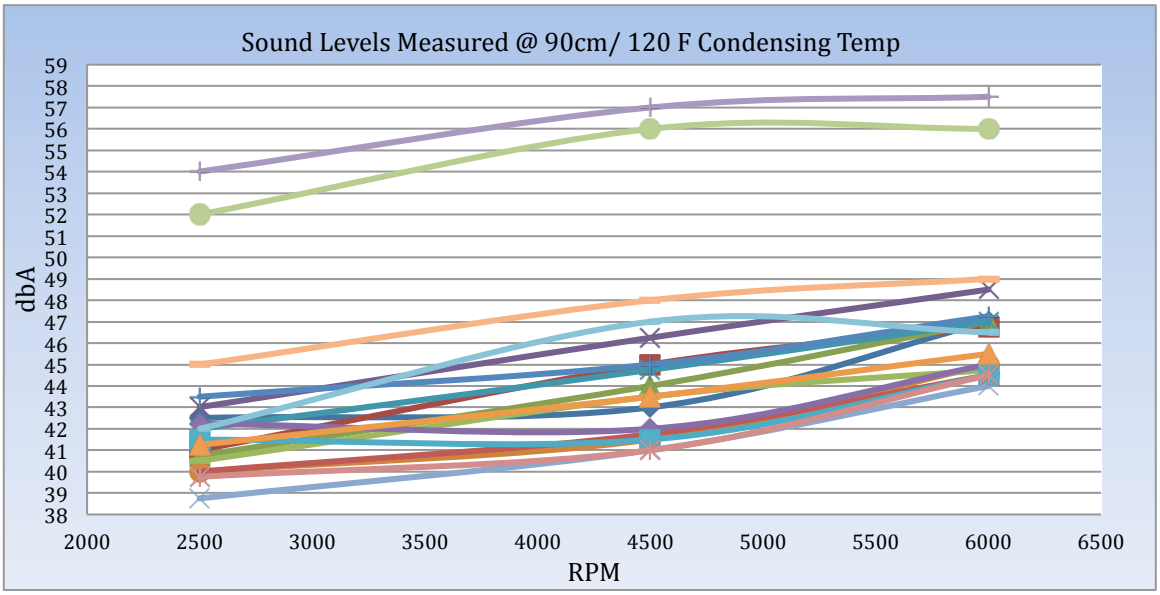

Figure 2. Noise level data showing progressive noise reduction

involving higher condensing conditions, lower evaporator temperatures, and with higher pressure refrigerant like R-410a or others in addition to R-134a and R-404a that were usable in the original miniature compressors.

CONCLUSIONS

A patent pending advanced noise/vibration reduction methods have been used to reduce the noise of miniature rotary compressors by as much as 14 dBA to 41 dBA at 90cm & 60H$_z$. The first generation quiet single-cylinder miniature rolling piston compressors will be introduced worldwide in January 2014 with the promise of further reduction of noise and vibration levels in future models. These quiet miniature rotary compressors are intended for compact countertop appliances, refrigerators, smart distributed cooling, heating and other HVAC devices, etc.

References: 1. "Experimental Evaluation of Aspen Miniature Rotary Compressor", Abhijit A Sathe, Eckhard A Groll and Suresh V Garimella, Cooling Technologies Research Center, 19th Annual Compressor Engineering Conference at Purdue University, West Lafayette, Indiana 47907, July 2008; 2. "Game-Changing" Miniature BLDC Rotary Refrigeration Compressors – What can you do with them?", White paper, International Appliance Manufacturing, December 2012

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ABSTRACT (50 WORD)

Presented are test data on successful noise reduction in new production model, single-cylinder, miniature rolling piston compressors from 55dBA to 41dBA without increasing compressor size, and with further reduction potential and applicability to other compressors. The new quiet rotary miniature compressors are intended for compact countertop appliances, refrigerators and others.

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