Variable Speed Oil-Free Magnetic Bearing Centrifugal Compressors

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Technology and product revolutions take time, especially in the HVAC market, which historically has relied on incremental improvements to tried-and-true solutions. But, you need to have a starting point for those incremental improvements and that starting point is frequently itself a revolution. For example, most HVAC industry compressor revolutions have come in the form of the new compression technology; however, only one has been a combination of the other component technologies beyond the compression method itself. This technology has created a revolution which has transformed the HVAC industry in terms of mid-capacity chiller efficiency, sound level, footprint and long-term performance maintenance expectations.

For nearly 100 years, centrifugal chillers have been popular in the HVAC industry because of their efficiency, reliability and scalability benefits in the large capacity water-cooled chiller segment. Over the years, this technology experienced incremental improvements with multiple stages and configurations. However, the main component technologies including the starter, motor/stator and bearings did not significantly change with the improvements.

The Beginnings

In the mid-1990s, a team of engineers in Australia recognized the opportunity for an HVAC compressor technology revolution. They saw the risk associated with the coming refrigerant changes under the Montreal Protocol and perceived that compressor manufacturers would not be ready. Because of this, they built on the experience from both successful businesses to create the 'the perfect compressor' specification. This specification included in the final product benefits, something that was fully integrated, significantly smaller/lighter, quieter, environmentally friendly and more efficient than what was available at the time. Plus, it had to operate without lubricant oil and result in no friction losses and resulting component wear.

Product revolutions enabled by multiple technologies generally come to fruition based on one key component technology which achieves "its time." In the

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case of oil-free centrifugal compressors, that technology was the magnetic bearing. This technology was the key, along with the associated positioning sensors and permanent magnet motor, because they enabled the high-speed, contact-free centrifugal compression, which in turn enabled small, quiet, efficient and oil-free. At that time magnetic bearings, which were being experimented with on applications such as large pumping systems, were extremely complicated and costly. The exponential computing power and cost reduction curve of the time gave them confidence that, even if it was not economically feasible then, it should be by the time they get to market.

FIGURE 1 Magnetic bearings/control.

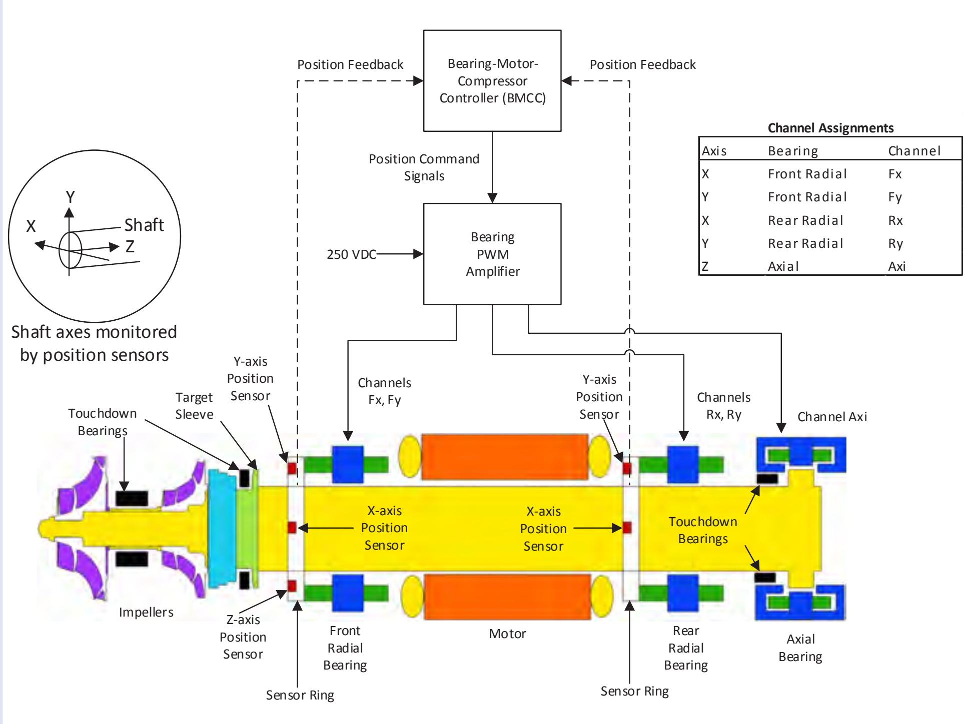


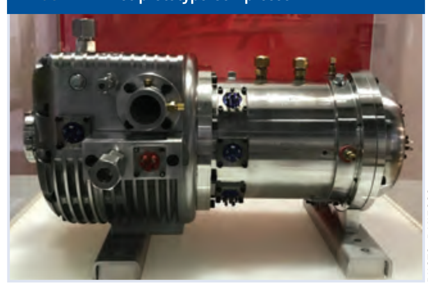
IMAGE: DANFOSS TURBOCOR APPLICATIONS MANUAL

The oil-free centrifugal magnetic bearings invented with this development consist of radial and axial components. The bearings control the radial position of the shaft within its orbit as well as counteracting the axial forces placed on the shaft by the thrust forces of the impeller. The axial force is based on the differential pressures across the impellers which push the shaft in the direction of the compressor suction. The magnetic bearing levitates the shaft and positions it axially using electromagnets. The bearings use a combination of permanent and electromagnets. The permanent magnets levitate the shaft and the electromagnets are used to fine tune the shaft position.

The electromagnetic field is controlled by a high-speed processing system and the location of the shaft is sensed by proximity sensors. They are placed radially around the shaft on both sides of the motor stator and the axial position is sensed by an additional proximity behind the second stage impeller. The shaft position is fed into a real-time digital processor which adjusts the electromagnetic field to perfectly center the shaft within its orbit and desired axial position.

The first compressor prototype was commissioned in 1995. The enabling technologies were not the only significant technology component barriers. Achieving the compressor prototype also involved inventing several other enabling component technologies, including the soft start, IGBT, DC-DC converter, high-speed motor, position sensors and digitally controlled magnetic bearings. Versions of these technologies existed previously but did not fit to the application or compressor goals.

FIGURE 2 First prototype compressor.



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From there, the first commercialization with compressors on chillers in the field occurred in early 2001. The compressors featured two-stage centrifugal, direct-drive, oil-free, magnetic bearing, permanent magnet motors, with fully integrated power electronics. The capacity was 300k W (~90 tons) and they achieved the goals of being a package which was more efficient, significantly smaller/lighter with lower sound, and oil/friction free.

Coincident Industry Change

Around the time that this compressor was first commercializing, the industry was also coming to the realization that part load efficiency was critical, with ASHRAE 90.1 equipment efficiency ratings changing to reflect the ~1% of the time that an average chiller operates fully loaded. The compressor technology choices and resulting oil-free operation enabled several benefits, most of which relate to part load efficiency and/or increased efficiency at higher differential temperatures (pressure ratios):

- Compressor turndown—Turndown with previous compression technologies was significantly limited by the differential temperature and resulting pressure required to move oil through the system.
- Variable/high-speed—Variable speed in combination with high-speed operation enable highly-efficient operation, specifically around the 75% and 50% load points, which the industry has determined to be most critical for minimizing operating costs.
- Two-stage centrifugal compression—Two stages of centrifugal compression enables more efficient operation, at higher pressure ratios and especially in combination with an economizer.
- Economizer—Two compression stages also enables the economizer cycle, where intermediate pressure gas is injected into the second stage suction, also increasing efficiency at the higher differential temperatures (pressure ratios)

FIGURE 3 Sound level and associated issue comparison.

IMAGE: DANFOSS

FIGURE 4 Regional variations in air-cooled chiller ambient rating conditions/weighting factor.

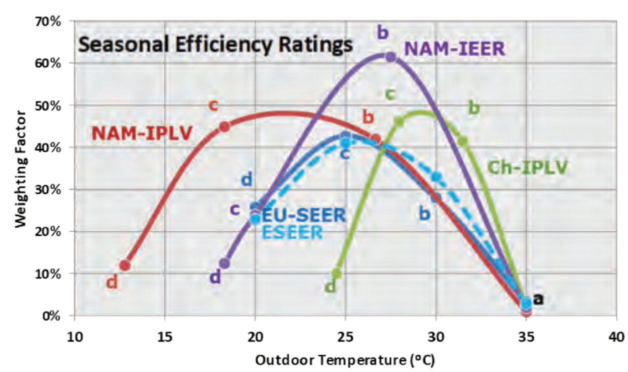

IMAGE: DANFOSS

The Bet

This was not a low-cost solution. That first ~90 ton/300 kW compressor was created on a bet that the mid-capacity HVAC market would pay a premium for a compressor that was:

- ~30% to 50% more efficient than it's constant-speed competitors
- ~25% of the physical footprint of the positive displacement competition
- ~8dBA lower sound than the positive displacement competition
- Simplified the system design and eliminated long-term performance degradation resulting from oil and its management.

The bet was that the market would value these benefits enough to pay the premium that the combination of technologies required. Historically, the HVAC market in this capacity range had been significantly driven by product price, with little consideration for efficiency or the other potential benefits of alternatives; if it met the code and/or customer requirements, then best price won. This is in contrast to the larger capacity segments, where customers were used to purchasing product based on life-cycle cost, including the efficiency and other benefits in the long-term operating cost-driven decision. The inventors of this technology were betting that there was an unserved 'latent" life-cycle cost focused market in this mid-capacity HVAC segment.

They knew that the first-cost focus was changing, albeit slowly/regionally, based on a combination of related regulatory and industry trend factors. The regulatory trend factors included increasing efficiency requirements along with the transition to non-ODP refrigerants. The pace of these regulatory changes was increasing, which along with rising energy costs and environmental concerns drove more focus on the efficiency and long-term performance maintenance benefits which this technology provides. They knew that the

FIGURE 5 Oil-free vs. oiled chiller system diagram comparison.

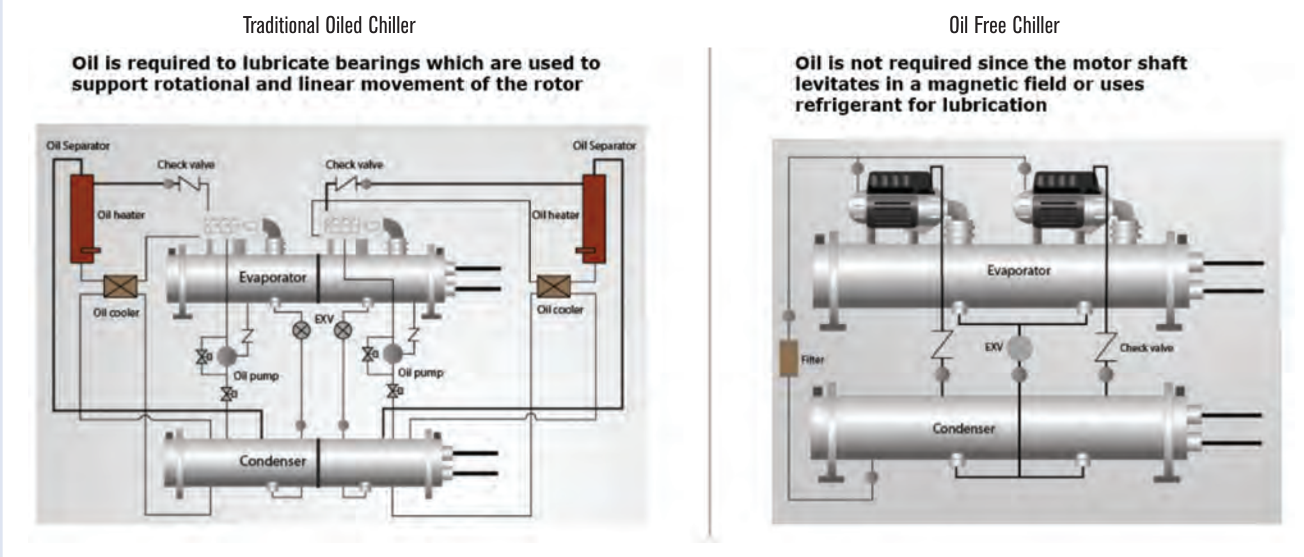

IMAGE: DANFOSS

30%-50% efficiency benefit which it enables relative to the positive displacement constant speed compressor technology it would replace would grow in importance to an increasing portion of the market.

The Long Road to Success

Fortunately, they were right. But success and industry transformation were not immediate. It took several years from that first compressor installation, before industry adoption and resulting volume drove a profitable business. Industry adoption ultimately required expansion to four different platforms and integration in the portfolio of several OEM chiller manufacturers, including a related chiller OEM startup investment. Success ultimately required working to develop product with several innovative early adopter OEMs, including small and large, from all regions.

These equipment manufacturers have learned that it's not a single technology benefit that any one end customer values for any specific application; it's not all about efficiency or low sound level or the small physical footprint or the ability to maintain the high performance over time. It's some combination of those and ultimately any of them can be critical.

For example, if the application is replacing an old chiller in a small/crowded equipment room which is adjacent to an auditorium or operating room, the technology footprint and sound level benefits are paramount. In cases such as this, efficiency may not even

FIGURE 6 Montreal Protocol High-GWP refrigerant phasedown chart, in terms of CO_2 equivalent emissions.

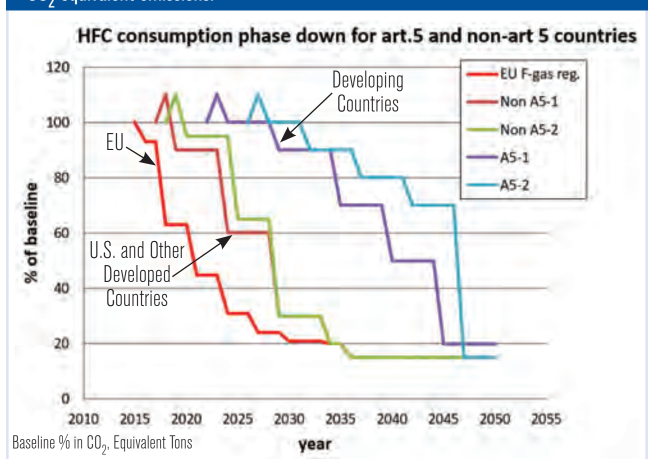

IMAGE: DANFOSS REFRIGERANTS WHITE PAPER–REFRIGERANT OPTIONS NOW AND IN THE FUTURE

be a consideration. They have in-turn recognized from this realization, the opportunity to optimize equipment designs and derivatives of them to take advantage of these benefits / combination of benefits.

Recent History

One of the main drivers for the original compressor development was the phaseout of ozone-depleting substances under the Montreal Protocol and the perception that a compliant solution was needed quickly to help customers meet the requirements. Now we are amid the industry phasing out high global warming potential substances. Europe is the first to move globally with this phaseout, implementing the F-Gas regulations with the

FIGURE 7 Compressor development timeline.

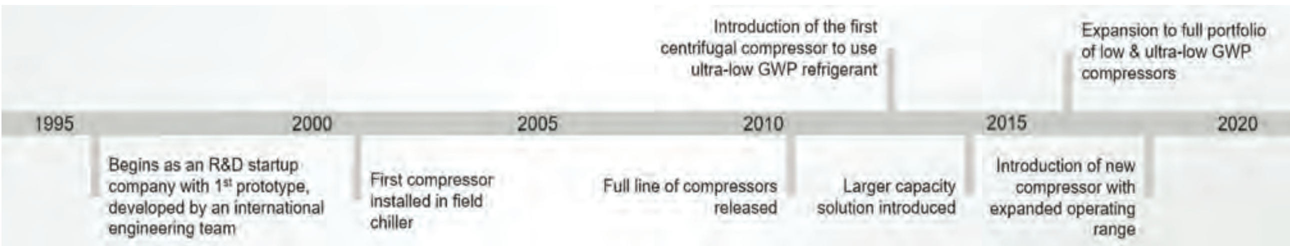

IMAGE: DANFOSS

first phaseout step in-place in 2016 and the second in 2018.

This has presented ongoing challenges to the industry as a whole—but also raises opportunities. With the combination of technologies also comes the flexibility to adjust the design to accommodate alternative refrigerants, including one of the HFO alternatives that meets the long-term ultra-low GWP goals, and allows an efficiency gain vs the current refrigerant baseline while trading off capacity. This long-term solution furthers a user's ability to meet current and future environmental goals, lower both direct and indirect CO_2 emissions, and also minimize the long-term risk associated with utilizing the refrigerant it replaced. Thus, oil-free magnetic bearing compressor technology has expanded from a single compressor with a single HFO, to four different platforms with an additional low-GWP option.

In the larger capacity segment, where customers were already making purchase decisions based on life-cycle cost analysis, the same technology concept could provide benefits vs the currently-available solutions.

On the oil-free long-term performance benefit and after extended period of operation, oil-free compressors have proven to maintain their original performance over time, validating the long-term performance maintenance benefit. Recent studies have shown that oil-free compressors do not incur any mechanical wear that can adversely affect performance over time. Independent studies have also shown that most chillers installed in the field have excess oil in the system which can also adversely affect performance (ASHRAE Research Project Report RP-751). This risk is eliminated with oil-free compressor technology.

In the last few years, the industry has recognized the value which oil-free centrifugal compression provides, including with the validation coming from several additional related technology developments. The result has been that, what was once the dream of a development team in Australia, has become the mainstream HVAC industry technology solution for mid-size air- and water-cooled chillers.

For the most recent developments, we determined the opportunity to bring those same technology benefits to an expanded application array. Expanding a compressor application array in our industry generally means higher differential temperatures and pressures (lift, in dynamic compression terms). The main constraint in expanding

FIGURE 8 Recent compressor developed for higher lift (differential temperature/pressure) conditions.

PHOTO: DANFOSS

to higher lift applications with an oil-free magnetic bearing-based centrifugal compressor design is in managing forces. Managing these forces becomes significantly easier with a mechanical design that separates the two compression stages, balancing the axial (back-and-forth) form of those forces. This new design expands the technology application potential from traditional water-cooled and temperate climate air-cooled to higher ambient air-cooled, heat pump (water-to-water and air-to-water), thermal storage and medium temperature process applications.

What The Future Holds

With over 70,000 compressors installed mostly in water-cooled and air-cooled chiller applications, additional improvements to reliability and performance, it is now time to determine the next opportunity. Luckily, the constantly-evolving refrigerant and efficiency regulatory standards are helping to change the game ahead of technology developments. The evolving standards are pushing up the efficiency requirements and driving refrigerants to new low-GWP alternatives, which are optimally lower-pressure to maximize efficiency and capacity while minimizing flammability and GWP. This in turn helps enable the opportunity for alternative technologies which are optimized to move a high volume of low-pressure fluids, such as multistage, direct-drive, high-speed, magnetic bearing, oil-free centrifugals.

In other words and keeping in mind the industry lesson to not forget the customer problems you were solving in the first place, the efficiency, refrigerant and long-term performance maintenance factors are only becoming more important for all potential applications, in-turn helping more customers meet their operating cost reduction and environmental goals. There is a latent market need wherever this technology is not already available. And, the sound level and footprint benefits are also becoming more critical, as the markets develop and transition away from new construction and building space becomes tighter.

Any time there is a refrigerant change there is optimization of the designs to the new fluid. Optimization is more critical when there is a significant pressure change. It is not only critical for the compressors but all components in the system which govern the flow and heat transfer of that fluid. Component development and optimization is more critical when the fluid pressure change is higher and for applications which are significantly vested in the existing solutions. This is of course true in general for the HVAC industry. But, as our history and the history of the industry shows, we are always capable of change, especially when there are a combination of external drivers and inherent technology benefits with the change. It's even better when you can incrementally build on the last few compressor developments to achieve the future goals, not requiring the bravery of those who 'changed the game'.

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