Small Oil-Less Centrifugal Compressors: Bringing Energy Efficiency and Reduced Costs to Chiller Plants

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ABSTRACT

According the U.S. Department of Energy, small oil-less centrifugal compressors (defined as 25 to 80 tons) have an energy savings potential of 0.15 Quads (Energy). Until recently, there were no commercially available, centrifugal compressors in the 60-90 ton range. In 2002, the Turbocor compressors went to market as "reliable, quiet, energy-efficient, and low maintenance alternatives to conventional oil-lubricated compressors for mid-range HVAC applications." With thousands of reciprocating and screw compressor based chillers (both air-cooled and water cooled) operating with environmentally unfriendly refrigerants at unacceptably low efficiencies, the retrofit market is huge.

During the past summer and over the next year, the San Diego Regional Energy Office is monitoring four applications of the Turbocor oil-less centrifugal compressor: (1) water cooled screw machine retrofit, (2) water cooled reciprocating compressor replacement, (3) air-cooled reciprocating compressor retrofit, and (4) the new McQuay / Turbocor Model WMC installation (replacing old air-cooled chillers). From this measurement and verification data and discussions with the HVAC installers, unbiased conclusions on the benefits and difficulties with this new technology will be determined.

Small oil-less centrifugal compressors have the potential to replace thousands of reciprocating compressors – "energy hogs" – and achieve significant energy savings. Turbocor claims an Internal Part Load Value (IPLV) of 0.41 kW per ton. This offers a 0.22 kW per ton energy savings over the equivalent screw compressor and much more over a 15-year-old reciprocating compressor. McQuay's Model WMC frictionless, oil-less chiller (using two Turbocor compressors) advertises an IPLV of 0.375 kW per ton.

This paper will provide a brief overview of the current markets and applications of this emerging technology and will identify (based on the data results) how the oil-less centrifugal compressor reduces energy usage and costs in multiple applications. In addition, this paper will assess the "before and after" energy usage of each system, installation costs, installation issues ("learning curve"), maintenance issues, and site specific energy savings.

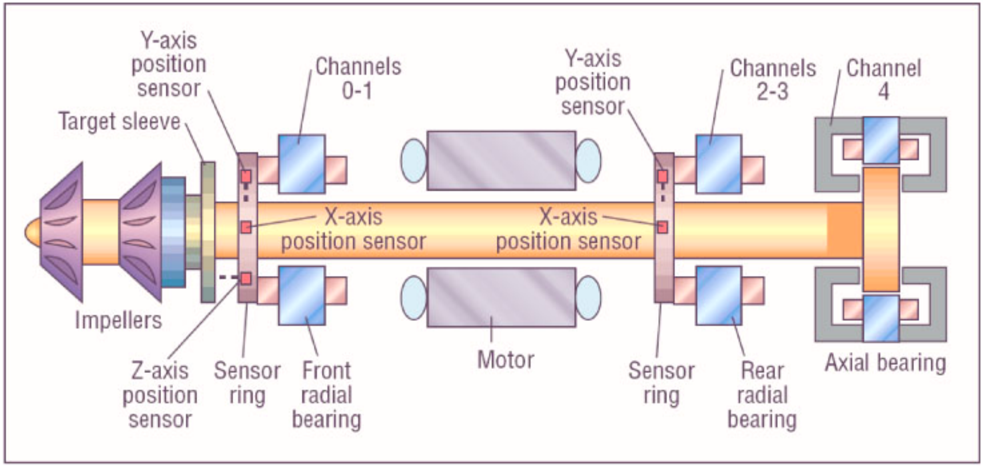
Background of the Turbocor

Turbocor began research and development on a new compressor in 1993. The design goals for developing a small centrifugal compressor included lubricant free operation and a direct drive system. The result of their efforts is a compressor that has a capacity of 60-90 tons, uses refrigerant R-134a, uses magnetic bearings (no oil), and a direct drive system (no gears). Additional benefits include a light weight design (80% less than traditional compressors) and reduced noise and vibration. By 2001, beta test sites proved the compressor design was viable for market introduction.

Operation

The compressor's rotor shaft and impellers levitate during compression and float on a magnetic cushion. Two radial and one axial magnetic bearing are employed. The compressor has an integrated variable frequency drive (VFD). VFDs provide the best part load efficiency and operate most effectively with centrifugal compression. The speed of the compressor adjusts to changes in load and/or condenser water temperature. Figure 1 shows a diagram of the compressor.

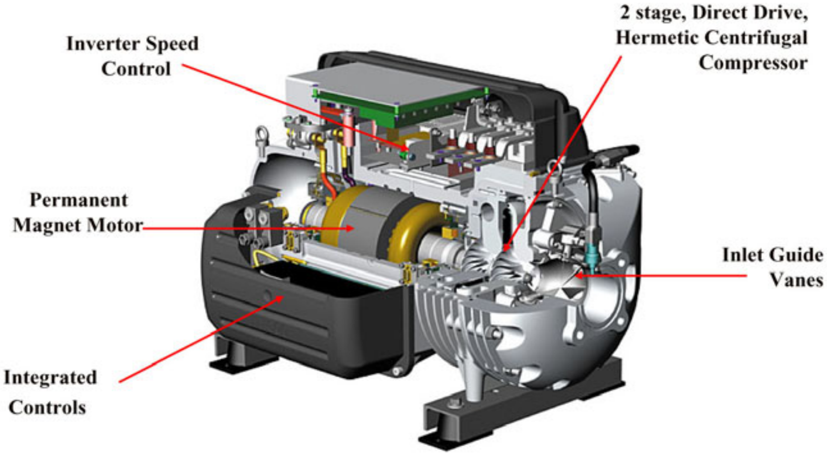
Figure 1. Diagram of Turbocor Compressor (Crowther)



The minimum load on the compressor is 15%. The auto balance feature repositions the magnetic bearing six million times a minute to maintain centered rotation at all times (Crowther). It uses 1.6 amps to start up (elevate the shaft) and operates at 16,000 to 40,000 RPMs. The motor is a permanent magnet brushless DC motor and the motor, electronics, and VFD are refrigerant cooled. The compressor is designed to handle a power outage. The motor becomes a generator; after the compressor comes to a complete stop the rotor de-levitates normally onto touchdown bearings. Should the computer fail, the compressor is designed to handle eight "crashes".

The oil less design eliminates some typical operating problems associated with oil flooded compressors. Most air cooled chillers and roof top units that use direct expansion (DX) evaporators allow some oil to travel through the refrigeration loop and back to the compressor; this can be a problem particularly at part load. Water cooled units often use flooded evaporators and any oil in the evaporator tubes can cause a decrease in heat transfer (Crowther). On the following page, Figure 2 displays the oil-less Turbocor compressor in three dimensions.

Figure 2. 3-D Diagram of the Turbocor Compressor (Crowther)



Energy Savings and Cost

The Turbocor manufacturer claims 30% energy savings versus standard centrifugal compressors, 33% versus screw compressors, and 40% versus reciprocating compressors. According to the manufacturer, the incremental cost is 1.33 compared to a centrifugal machine, 1.45 compared to a screw machine, and 1.15 compared to a reciprocating machine (Crowther). The following four case studies in the next section will demonstrate the actual savings achievable and the associated implementation costs.

The San Diego Regional Energy Office is monitoring four applications of the oil-less compressors: (1) water cooled screw machine retrofit, (2) water cooled reciprocating compressor replacement, (3) air-cooled reciprocating compressor retrofit, and (4) the new McQuay Model WMC installation (replacing old air-cooled chillers).

Water Cooled Screw Machine Retrofit

A 250-ton Carrier 23XL screw chiller in San Diego was retrofitted with two 90-ton oil-less centrifugal compressors. The retrofit was a test site for the technology and has been operating since March 2004. An additional benefit of the retrofit was significant noise and vibration reduction in the space above the chiller. At times the facility was not able to use the screw chiller due to the excessive noise in the offices and was forced to run a backup chiller. The pre-retrofit picture, Figure 3, shows the blanket placed over the screw compressor to try and reduce some of the noise. The retrofit, shown in Figure 4, took 10 days to complete: 3 men 10 days or about 240 hours. Challenges and recommendations during the retrofit include:

- One compressor D.O.A. (dead on arrival) after 30 minutes of run time
- Attempt to repair at job site caused exposure and loss of confidence of customer
- Recommend all repairs done off-site to reduce customer concerns
- Two failures of the DC to DC converter board
- After final completion of the project, the oil-less chiller has operated for over 6,000 hours without any maintenance issues, owner complaints, or chiller “trips”.

The retrofit cost was $106,000; with an SDG&E utility incentive payment of $60,000, the payback was estimated at less than two years ($30,000 per year savings).

Figure 3. Pre-Retrofit Screw Compressor

Figure 4. Post-Retrofit of Oil-less Compressors

At light loads the retrofitted chiller is able to operate at 25 kW; the Carrier minimum operating point with the screw compressor was 50 kW. Table 1 below compares the Carrier screw chiller to the retrofitted oil-less chiller. Measurements were taken over a 1 hour period from 6 pm to 7 pm in July 2004. As one can see from the chart, there was a 32.5% reduction in energy usage during this time period. A similar test was conducted during the afternoon (2 pm). During this test period there was a 13% reduction in energy usage.

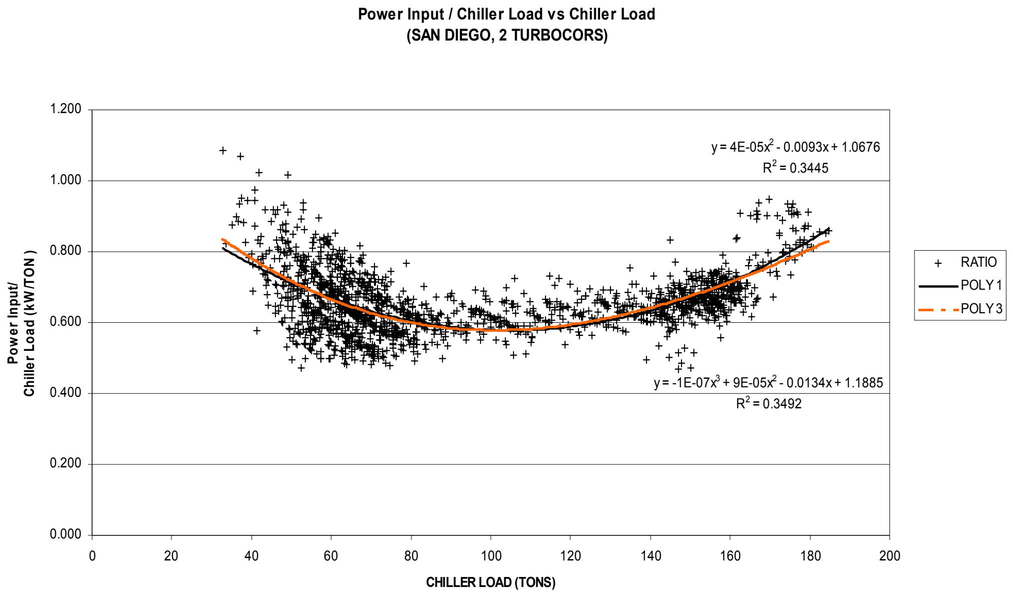
Table 1. Screw Compressor (Before) Versus Turbocor Compressor (After)

Measurement	Before	After	Units	Change	%Change
Current, A Phase	88	57.5	amps	30.5	-34.7 %
Current, B Phase	82.3	55.2	amps	27.1	-32.9 %
Current, C Phase	82.2	54.6	amps	27.6	-33.6 %
Power Factor, B Phase	0.87	0.90		-0.03	3.4 %
Power Factor, C Phase	0.89	0.92		-0.03	3.4 %
Energy, A Phase	22.188	14.598	kWh	7.590	-34.2 %
Energy, B Phase	19.932	13.781	kWh	6.151	-30.9 %
Energy, C Phase	20.510	13.892	kWh	6.618	-32.3 %
Energy, Total Elapsed	62.630	42.271	kWh	20.359	-32.5 %
Energy, estimated per month	45751.5	30878.9	kWh	14872.6	-32.5%

Data collected by Thomas Shaw of Alpha Mechanical Service and Engineering.

Following the retrofit, monitoring equipment was installed to log the energy usage and operating parameters of the retrofitted chiller. Condenser water temperature was held at 80°F and the following kW/ton data in Figure 5 was acquired. Figure 5 shows that the average efficiency of the retrofitted chiller ranged between 0.50 kW/ton and 0.80 kW/ton. The second phase of the retrofit (starting in May 2005) will be to add a third 90-ton oil-less compressor to the chiller, program a condenser reset program into the existing direct digital control (DDC) system and install variable frequency drives on the cooling tower fans. With reduced entering condenser water temperatures, the Turbocor compressors will increase their operating efficiencies by about 35%.

Figure 5. Two 90-Ton Oil-Less Compressor Retrofit

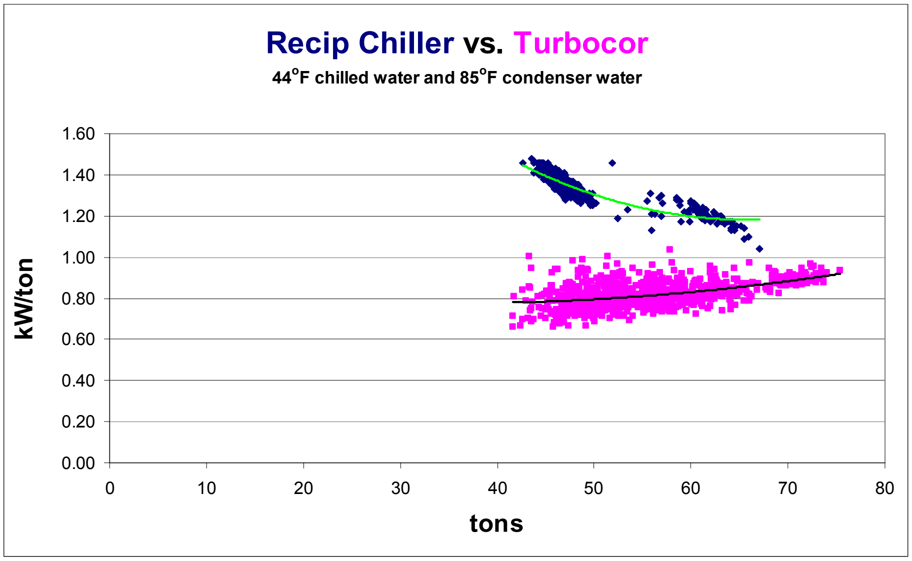


Water Cooled Reciprocating Compressor Retrofit

One 100-ton Trane reciprocating chiller was compared to a Turbocor Multistack unit. The oil-less Multistack unit is shown in Figure 6 below. In Figure 7 below, chiller parameters were logged and the kW/ton was plotted. In this analysis, the chilled water set point was held at 44°F and the entering condenser water temperature was maintained at 85°F. At this facility, the oil-less centrifugal compressor provides 40% energy savings over a reciprocating compressor, or 0.5 kW/ton average savings.

Figure 6. Multistack Turbocor Unit

Figure 7. Reciprocating Compressor Versus Turbocor Compressor



Air-Cooled Reciprocating Compressor Retrofit

A County of San Diego East County Family Services facility was served by one 84-ton York air cooled chiller (230 Volt, R-22) with two reciprocating compressors (Figure 8). The building, located in El Cajon, CA, is a 22,080 sq ft office facility that operates from 6 am to 6 pm 5 days per week. The chiller has been riddled with problems since installation – compressor failures, noise and significant oil in the refrigerant. The chiller was very inefficient and operated at 1.4 kW/ton. In April 2005, the chiller was retrofitted with one R-134a 90-ton oil-less centrifugal compressor, a transformer to step the voltage from 230V to 480V, one electronic expansion valve (EXV), and a variable frequency drive to control the two condenser fans (Figure 9). Based on measurement and verification data from May 2005, the chiller now operates at 0.61-0.7 kW/ton. Data collected on May 5, 2005 indicated the entire chiller was operating between 19-tons and 27-tons and 13 kW-19 kW with a 47^{o}F chilled water setpoint. The savings are estimated at $10,000 per year.

Figure 8. Air Cooled Reciprocating Chiller Pre-Retrofit

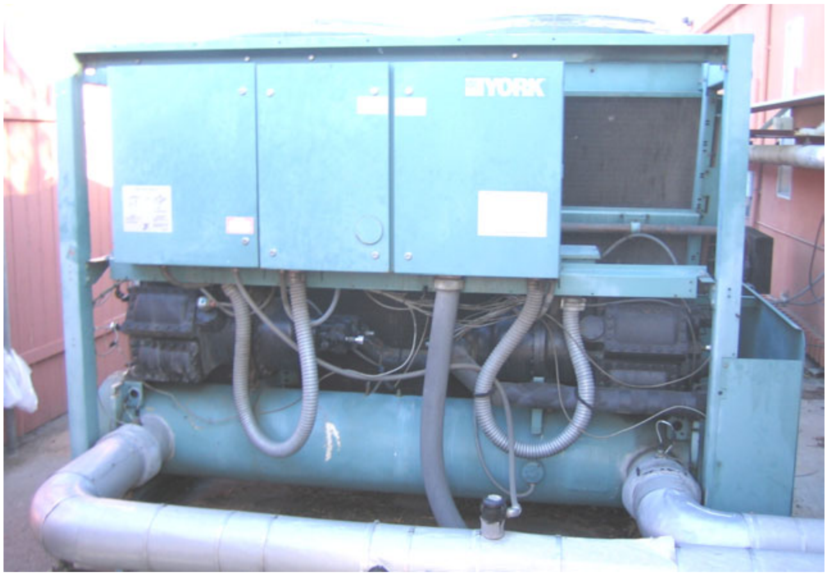


Figure 9. Air Cooled Reciprocating Chiller Post Retrofit

McQuay Model WMC Installation

In 2003-2004, a laboratory in San Diego was planning a remodel and HVAC upgrade. The old HVAC system consisted of seven variable air volume air-handlers served by two 130 ton York reciprocating chillers (two compressors and four condenser fans in each), circulating pumps (3 x 10 hp pumps), distribution piping and two-way valves at each air handling unit cooling and heating coil. There was also a small 40-ton backup reciprocating chiller (York) that was seldom used. Figure 10 below shows the two old chillers and associated HVAC ductwork.

Figure 10. Air Cooled Chillers and Facility Roof

The owners were convinced that a "band aid" approach was not the way to go. The HVAC system was gutted and a new ultra efficient central plant was built. Installation included two 150 ton WMC McQuay / Turbocor chillers, new high efficiency chilled water and condenser water pumps, two 200-ton cooling towers, and variable frequency drives on all pumps and motors. Also, installation included a Direct Digital Control (DDC) system and Hartman LOOP[1] control sequence for the chiller plant. Installation was completed in January 2005. Figure 11 on the following page shows one of the new chillers.

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[1] Hartman LOOP™ network-based control optimizes all-variable speed plants by taking advantage of the exclusive characteristics of variable-speed pumps, chillers and fans. For more information see www.hartmanco.com

Figure 11. McQuay WMC150 Chiller

Once the plant was converted to a water-cooled, all-variable speed system, the speed of the operating equipment is now controlled by the DDC system to provide cooling at optimum efficiency under all operating conditions. Simple direct control algorithms coordinate the operation of chillers, pumps and tower fans based on demand for cooling from the air systems that is determined by cooling coil valve position. Chilled water temperature and leaving tower water temperature float (within preset limits) to allow components to operate at highest efficiency at all times. Hartman LOOP control coordinates the operation of the condenser pumps and tower fan speed based on chiller loading. Electric chillers are sequenced on and off line according to the "natural curve principle"[2], which sets a chiller kW threshold for sequencing, based on current operating condenser and evaporator temperature conditions. Speed of the distribution pumps is controlled according to the "valve orifice area"[3] method. An analysis was performed to estimate the energy savings from installing two different central plants: (1) a new Title 24[4] compliant air-cooled chiller plant or (2) water cooled McQuay WMC150 all variable speed central plant. The results are shown below in Table 2 on the following page.

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[2] Chiller performance (kW/ton) versus cooling capacity with a variable speed drive is plotted for various condenser water temperatures. The loci of the curves are connected producing the chiller's "natural curve."

[3] The "valve orifice method" controls pump speed by using the percentage of total valve orifice area open to determine the required flowrate. This control method allows the head to go to zero as flowrate goes to zero.

[4] Title 24 is the California energy efficiency standards.

Table 2. Estimated Energy Savings from Retrofit

ECO	Tonnage (tons)	Est. Annual Electrical Savings (kWh)	Peak Demand Reduction (kW)	Est. Annual Cost Savings	Est. Implementation Cost	SDG&E Rebates	Final cost after rebate	Simple Payback (Years)
Standard Practice - New air cooled chiller plant								
1	300	138,870	15.85	$16,491	$400,000	$0	$400,000	24.3
Newly installed plant - water cooled McQuay WMC150 chillers, all variable speed controlled by the Hartman LOOP								
2	300	509,190	58.13	$60,468	$600,000	$164,000	$436,000	7.2

Spot measurements were taken on March 7, 2005 at the chiller. The entering condenser water was read at 69.2^{o}F and the chilled water set point was 46^{o}F. The lead compressor was putting out 70 tons and only consuming 25 kW (0.36 kW/ton). Table 3 below shows the operating conditions of the McQuay WMC150 chiller with system settings of 44°F leaving chilled water temperature and 80°F entering condenser water.

Table 3. Operating Conditions of 150-Ton McQuay WMC Chiller

Size	**Input**	**Efficiency**	**RLA**	**NPLV**	**75% Load**	**50% Load**	**25% Load**	**Evaporator**		**Condenser**	
Tons	kW	kW/ton	Amps	kW/ton	kW/ton	kW/ton	kW/ton	Ft PD	Temp in	Ft PD	Temp out
150	85.6	0.571	122	0.355	0.434	0.315	0.294	8.5	56	6.6	89.3

With the installation of an all variable speed primary only central plant, the minimum flow in the evaporator (175 GPM) and condenser (340 GPM) must be considered. To obtain the high efficiency of the WMC chiller, McQuay uses large heat exchangers. That is the obvious reason for the physical size of the chillers for only 150 tons of capacity. Using large vessels with a lot of tubes, the water velocity even at full load is fairly low. Although this design philosophy is great for efficiency, it does hinder the amount of flow reduction that can take place. According to McQuay, for reduced flows, it was important to keep the water velocity at a minimum of 2.8 feet per second to prevent laminar flow in the vessels. When laminar flow begins, which is a condition where water "hugs" the walls of the tubes loosing its turbulence, heat transfer begins to suffer. But, for the evaporator, reduced flow increases the temperature drop across the vessel which improves heat transfer at low loads. These two phenomena cancel each other out and the chiller does not significantly suffer from any decrease in efficiency. Thus the evaporator flow rate can be allowed to change from the design of 300 GPM down to 175 GPM. The condenser flow rate can be allowed to change from the design of 450 GPM down to 340 GPM. One last item to consider in variable flow applications - it is important that the flow rate change slowly because any manufacturer's chiller needs to sense a change in load, react to it, and stabilize. For this project, it was recommended that the rate of change not exceed 2% every 30 seconds.

Conclusion

In each of the four case studies above, the facility saw energy savings (especially during low load hours) of 30-50% when compared to existing screw and reciprocating technologies. In nearly all the cases, the compressor efficiencies (for all technologies) do not match the advertised kW/ton. Compressor efficiency is highly dependent on the operating parameters such as entering condenser water temperature, chilled water temperature, the amount of oil leaked into the refrigerant and size of the vessels (condenser and evaporator heat exchangers). The total installed cost for Turbocor retrofits has been on average about $45,000 per compressor. Simple paybacks range from 1.6 years to 9.9 years depending on the individual application, ton-hours, hours of operation, utility incentive and size of the central plant.

The authors are convinced that the oil-less centrifugal compressor is the future of HVAC. Below (in Figures 12-15) are before and after pictures of additional retrofits in San Diego County. We believe that as local HVAC contractors get over “the learning curve” of the retrofits, as the compressors come down in price (currently the Turbocor unit is about $23,000), and as the technology continues to improve and gain familiarity, many retrofits will be “slam dunks”.

Figure 12. **Before – 250 Ton Centrifugal Chiller**

Figure 13. **After – 250 Ton Retrofitted Chiller**

Figure 14. **Before – 120 Ton Recip Chiller**

Figure 15. **After – 120 Ton Retrofitted Chiller**

References

Energy Consumption Characteristics of Commercial Building HVAC Systems Volume III: Energy Savings Potential – DOE's Building Technologies Program.

Crowther, H and Smithart, E. 2004. "Frictionless Compressor Technology." *HPAC Engineering* (January).