2021

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Li, Song; Carow, James; Bacellar, Daniel; and Martin, Cara, "Comparative Studies of Scroll and Rotary Compressors for US Market Heat Pumps and Air Conditioners" (2021). *International Compressor Engineering Conference.* Paper 2664.
https://docs.lib.purdue.edu/icec/2664

Comparative Studies of Scroll and Rotary Compressors for US Market Heat Pumps and Air Conditioners

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ABSTRACT

Rotary compressors have long been developed and adopted for heating, ventilation, and air-conditioning (HVAC) applications across Asia, primarily due to their simpler mechanism and fewer parts as compared to their counterparts such as scroll compressors. However, rotary compressors in heat pumps (HPs) and air conditioners (ACs) in the US have limited market share and are often confined to systems smaller than 3.0 tons (10.6 kW). This paper consists of two parts; the first is on rotary compressor technology and its advantages and disadvantages from both technical and market standpoints. The review consists of a survey of the literature, as well as a survey from field experts through anonymous interviews. Conventionally, rotary compressors are regarded as having lower efficiency in systems larger than 3.0 tons (10.6 kW), which limits their current application to small packaged systems and automotive ACs. The second part includes an experimental investigation of compressor and system efficiencies using scroll and rotary compressors. The compressors compared were drop-in replaced in typical 2.5 (8.8-kW) and 5.0-ton (17.6-kW) R410A split HP systems. Experimental tests, both in cooling and heating modes, were conducted under AHRI 210/240 Standard operating conditions. The test units were extensively instrumented on both the refrigerant and air-side to measure temperature, humidity, pressure, flow rate, and power consumption, according to ASHRAE Standard 41.2. Indoor and outdoor units were placed in a wind tunnel and in an environmental chamber, respectively. The results showed the 2.5-ton (8.8-kW) unit rotary compressor's isentropic efficiency was 2.6% and 14% higher than the scroll compressor in cooling and heating, respectively. At 5.0 tons (17.6 kW), the isentropic efficiency of the rotary compressor was 5.4% lower in cooling and 6.3% higher in heating. In terms of volumetric efficiency, at 2.5 tons (8.8 kW) the rotary compressor was 1.7% lower in cooling than scroll compressor, and comparable to the scroll compressor at two of three heating mode test points. At 5.0 tons (17.6 kW), the rotary compressor volumetric efficiency was 0.7% and 2.8% higher than the scroll compressor in cooling and heating mode, respectively. The overall system with the rotary compressor had 5.7% higher seasonal energy efficiency ratio (SEER) and 3.0% higher heating seasonal performance factor (HSPF) than the scroll compressor at 2.5 tons (8.8 kW). At 5.0 tons (17.6 kW), the system with the rotary compressor was 2.6% higher in SEER and 0.6% higher in HSPF compared to the system with the scroll compressor.

Keywords: rotary compressor, scroll compressor, split heat pump, experimental test, comparison

1. PART I: REVIEW ON ROTARY COMPRESSORS

Compressors plays a vital role in the HVAC and refrigeration (HVAC&R) industry, and they are the most energy demanding component within a vapor compression cycle (VCC). Their characteristics are important in defining their operation and, as such, they are usually selected for specific applications within a given market. For example, rotary compressors have been widely adopted for HVAC applications throughout Asia, due to their simple mechanisms and fewer moving parts. However, in the US the rotary compressor is limited to small (less than 3 tons or 10.6 kW) packaged systems and other small VCCs such as automotive ACs. To better understand the reason behind the limited application of rotary compressors in the US market, a total of twelve direct interviews were conducted, which were compiled, along with feedback received from a diverse set of representatives from the industry in private conversations: 45% were from compressor manufacturers, 44% from HVAC&R system manufacturers, and 11% from academia (Figure 1a). All feedback and comments received were categorized into different groups, and their frequencies were calculated based on the total number of comments, as shown in Figure 1b. The most frequent comment (almost 14%) is that from a performance or efficiency standpoint; rotary compressors are suitable for small systems (less than 3 tons or 10.6 kW), but do not have a comparative performance in larger capacity systems (threshold around 2-4 tons or 7.0-14.1 kW) versus other technologies such as scroll compressors.

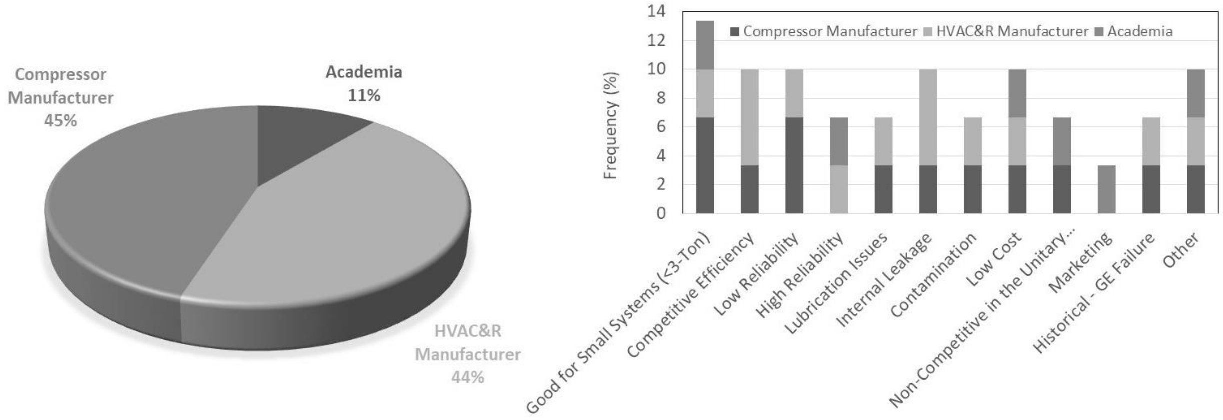

Figure 1: Interview Statistics: a) Source Types; b) Grouped Responses.

Another common response for rotary compressor utilization within the US was the impact of one particular event, namely General Electric’s (GE) challenge to introduce rotary compressors in their refrigeration systems during the 1980’s (Magaziner and Patinkin, 1989). By 1986, GE built a plant and started producing rotary compressors for their refrigeration products. But in 1988, some compressors from their product portfolio started failing. After investigation, GE discovered improper lubrication led to failing of small parts, and a major recall was announced. Not long after GE’s rotary compressor recall, GE sold its rotary compressor manufacturing plant in São Carlos - Brazil to another manufacturer Tecumseh (Form 10-K Tecumseh Products Co. Annual Report, 1994), and then focused its rotary compressor market on recreation vehicle (RV) products instead. Another crucial historical event was Copeland’s introduction of their scroll compressor, which has less internal leakage and better performance above 2.5 tons (8.8 kW). From 2014-2018, almost 70% of all US manufacturers’ shipments (transfer of ownership) of central ACs and air-source HPs were larger than 2.2 tons (7.7 kW) (Figure **2**) and scroll compressors have been widely used across all brands in AC/HP systems in the US. Both events are better depicted in Figure 3, and seem to have driven the opinion about rotary compressors in the US that, in general, they are not worth the cost of technology development and replacement.

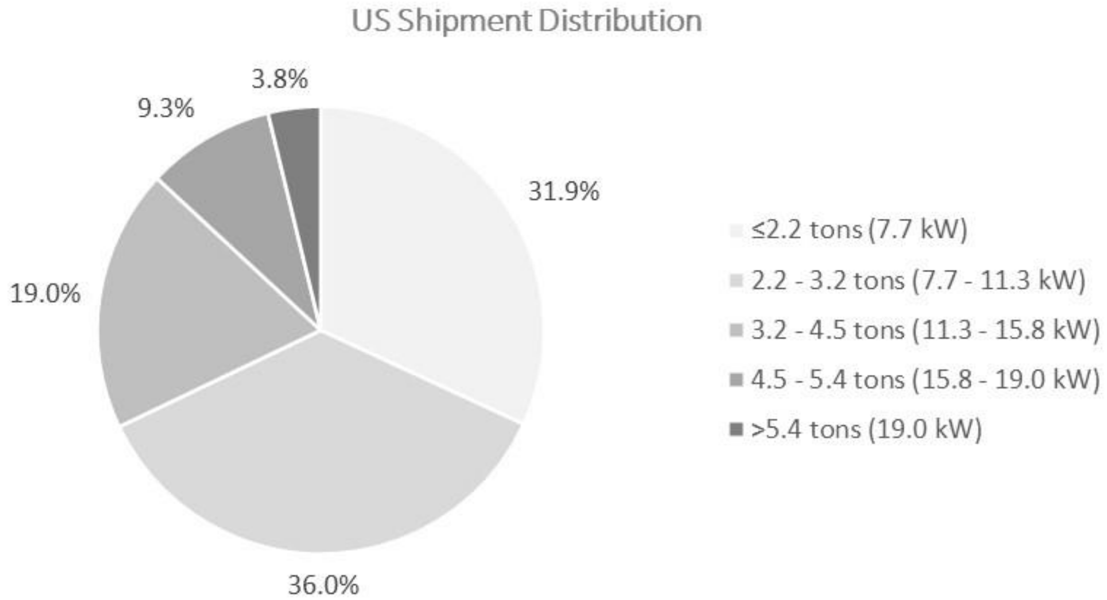

Figure 2**:** 2014-2018 US Manufacturers’ Shipments of Central ACs and Air-source HPs Distribution ("AHRI Statistics.")

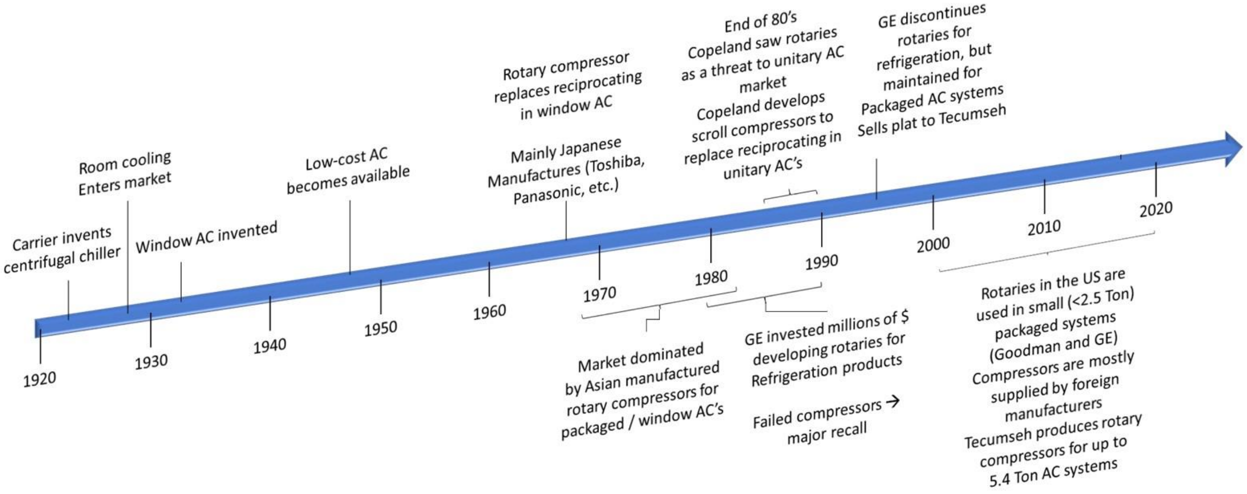

Figure 3: Timeline of Compressors in the US HVAC&R Industry

To better evaluate rotary compressor's potential in the HVAC&R applications, a large amount of research work accomplished. Shi (Shi et al., 2016) replaced the aluminum scroll compressor used in electric vehicle heat pump systems with a steel rotary compressor, which is better at enduring long-term high-pressure application, and studied the impact of different refrigerants on system capacity and COP. An investigation was attempted by another research group, in which several compressor geometric parameters were optimized, and a new rotary compressor model was developed to improve COP and capacity, reaching maximum cooling capacity of 70 HP (52 kW) (Monasry et al. 2018). In contrast, Sathe et al. (2008) developed a prototype miniature rotary compressor with an estimated cooling capacity ranging from 0.046 ton (0.163 kW) to 0.139 ton (0.489 kW), making it ideal for electronic cooling applications.

There are no fundamental aspects of the different compressor technologies, or clear consensus, that suggest which compressor type is better suited for each application. The technical simplicity and low cost of rotary compressors are the main drivers for pursuing a robust technology that can be deployed in any system. In particular, the literature lacks comprehensive compressor investigations for mid-size heat pumps (2-5 tons). The second part of this study consists of a comparative experimental investigation of such systems while using typical scroll compressors and equivalent rotary compressors.

2. PART II: EXPERIMENTAL INVESTIGATION

Instead of only testing rotary compressor performance, the present study conducted a direct comparison between rotary compressor and a baseline scroll compressor and compare how they performed in two split HP systems, one rated at 2.5 tons (8.8 kW) nominal cooling capacity, and the other at 5.0 tons (17.6 kW). Both systems were equipped with a fixed-speed scroll compressor and served as the baseline. With regards to system selection, fixed speed compressors were chosen instead of variable speed compressors; while variable speed systems have their advantages, they currently only account for approximately 20% of the US market (BPA, 2016).

Comprehensive instrumentation was installed on both refrigerant and air-side, and both systems were operated under a series of test conditions. Scroll compressors were then replaced with comparable rotary compressors and test conditions were repeated. Based on the test data, system performance with each of the compressors was compared in both cooling and heating modes.

The two units under test (UUT) were selected to represent a typical split HP. Both UUTs are equipped with a fixed thermal expansion valve (TXV) and run on a single speed scroll compressor that used R410A as the refrigerant. A total of six operating conditions (Table 1) were defined according to AHRI Standard 210/240 (2017), specifically for a single stage air-cooled system.

Before testing, the outdoor unit was placed inside a temperature and humidity-controlled chamber, and the indoor unit was connected to a wind tunnel, in which temperature and humidity were both set to the test conditions. Both UUTs were extensively instrumented on both the refrigerant and air-side to measure temperature, humidity, pressure, flow rate, and power consumption, according to ASHRAE Standard 41.2 (1987). A detailed test schematic is shown in Figure 4. During testing of the 2.5-ton (8.8-kW) unit, refrigerant-side mass flow rate was not recorded continuously and was recorded manually once steady state operation was achieved. For the 5.0-ton (17.6-kW) unit tests, refrigerant flow rate was recorded continuously. The six tests listed in Table 1 were first conducted on both UUTs with their original scroll compressors. Refrigerant charge was tuned to achieve the highest possible energy efficiency ratio (EER), and the test results served as baseline. Then each compressor was replaced by a comparative rotary compressor, and refrigerant charge was again tuned to achieve the highest possible EER. Displacement volumes and refrigerant charges are summarized in Table 2 for all compressors. The series of six tests were then repeated with replacement rotary compressors. For the 5.0-ton (17.6-kW) UUT, a series of indoor units are compatible with the outdoor unit, but only the lowest efficiency indoor unit was available for testing, hence the unit's overall capacity was lower than nominal capacity for both compressors.

Table 1: Test Conditions

Test name	Test mode	Air entering outdoor unit, dry bulb/wet bulb °F (°C)	Air entering indoor unit, dry bulb/wet bulb °F (°C)	Compressor speed	Indoor airflow
A_{Full}	Cooling	95/75 (35/24)	80/67 (27/19)	Full	Full^{1}
B_{Full}	Cooling	82/65 (28/18)	80/67 (27/19)	Full	Full^{1}
Maximum Operation	Cooling	115/- (46/-)	80/67 (27/19)	Full	Full^{1}
$H1_{Full}$	Heating	47/43 (8/6)	70/60 (21/16)	Full	Full^{1}
$H2_{Full}$	Heating	35/33 (2/1)	70/60 (21/16)	Full	Full^{1,}
$H3_{Full}$	Heating	17/15 (-8/-9)	70/50 (21/10)	Full	Full^{1}

1: Manufacturer provided volume flow rate at full speed setting for cooling and heating, respectively.

Table 2: Compressor Specification

Compressor Type	Nominal Capacity ton (kW)	Displacement Volume (cc)	System Charge lb (kg)	Factory Charge lb (kg)	A_{Full} Capacity ton (kW)
Scroll	2.50 (8.8)	22.45	7.72 (3.50)	7.13 (3.23)	2.32 (8.16)
Rotary		23.20	8.16 (3.70)	7.13 (3.23)	2.36 (8.30)
Scroll	5.00 (17.6)	45.43	7.40 (3.36)	10.56 (4.78)	4.37 (15.37)
Rotary		45.50	7.40 (3.36)	10.56 (4.78)	4.43 (15.58)

2.1 TEST RESULTS

All six tests were conducted for rotary and scroll compressors, at both 2.5 (8.8) and 5.0 tons (17.6 kW) capacities, and their performance were compared at both the component (compressor) and system levels. The compressor isentropic efficiencies for each test were calculated based on compressor suction and discharge conditions for both cooling and heating modes (Figure 5), according to Equation (1). At 2.5 tons (8.8 kW), the isentropic efficiency for the rotary compressor was 2.6% higher in cooling and 14% higher in heating than the scroll compressor. Additionally, based on the three test points in cooling mode, the rotary compressor displayed less sensitivity (curvature) than the scroll compressor across a range of condensing temperatures. Similar sensitivity to condensing temperature in cooling mode is observed by Diniz & Deschamps (2016), in which both compressor types were studied under a wider range of condensing temperatures and larger number of test points. In their studies on R22 rotary and scroll compressors at 1.5 tons (5.3 kW), the rotary compressor also displayed less sensitivity/variation to condensing temperatures (Figure 6).

At 5.0 tons (17.6 kW), the isentropic efficiency for the rotary compressor was 5.4% lower in cooling and about 6.3% higher in heating mode (Figure 5). For both the 2.5-ton (8.8-kW) and 5-ton (17.6-kW) UUT, in heating mode, the rotary compressor displayed the highest isentropic efficiency at the lowest condensing temperature, while the scroll compressor showed the lowest isentropic efficiency at the lowest condensing temperature. The rotary compressor had higher isentropic efficiency at 2.5 tons (8.8 kW), but lower isentropic efficiency than the scroll compressor at 5.0 tons

(17.6 kW), which corresponds to the feedback from interviews that rotary compressors are more suitable for small systems.

$$\boldsymbol{\eta_i} = \frac{h_{Di} - h_S}{h_D - h_S} \tag{1}$$

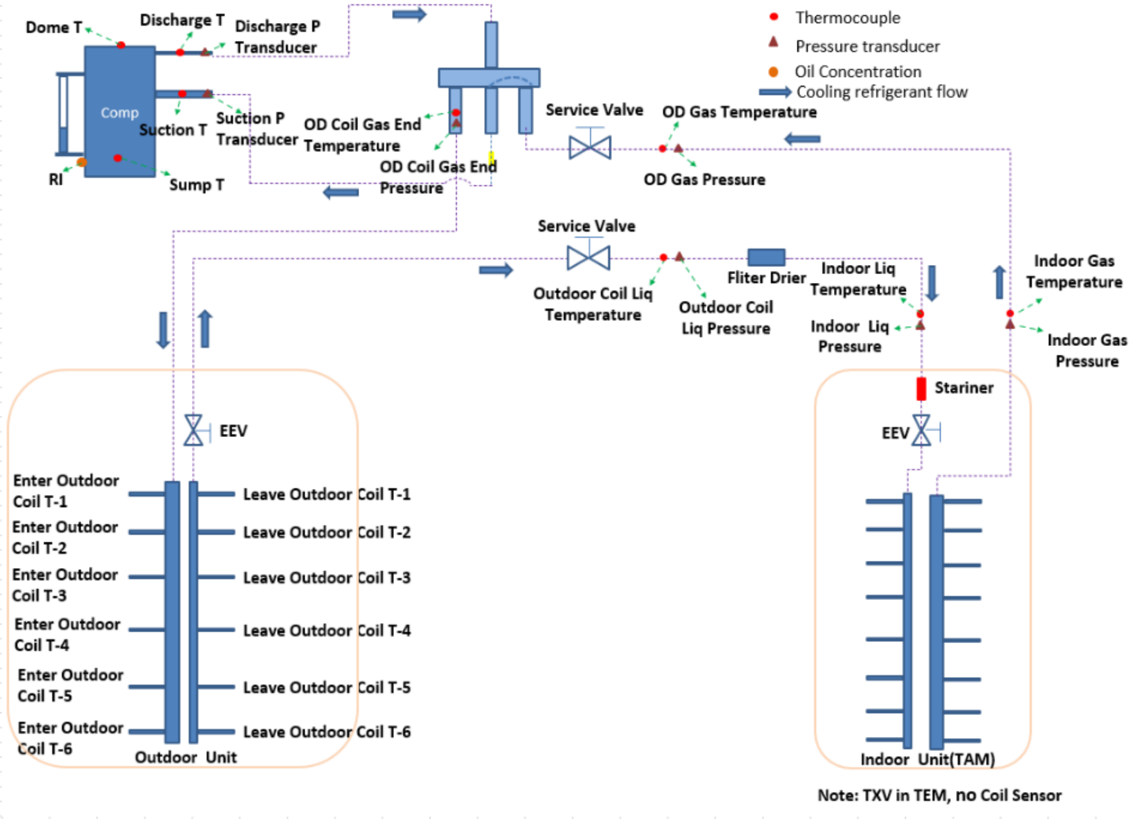

Figure 4: Test Schematic & Instrumentation

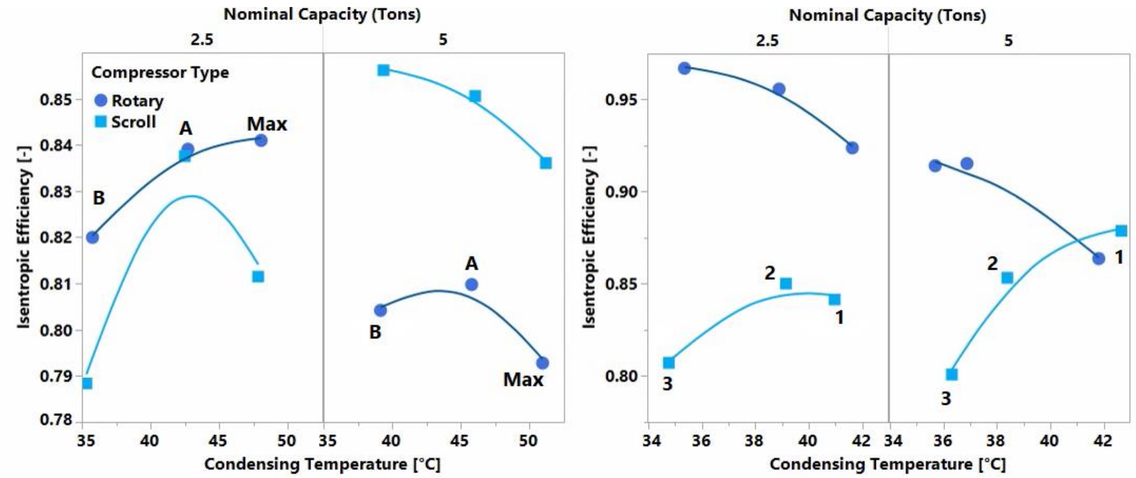

Figure 5: Isentropic Efficiency vs. Condensing Temperature: a) Cooling, b) Heating

Volumetric efficiency (Figure 7), was estimated based on the measured refrigerant flow rate, compressor displacement volume and suction conditions, according to Equation (2). At 2.5 tons (8.8 kW), the volumetric efficiency for the rotary compressor was lower than the scroll compressor by 1.7% in cooling mode (point B, A and Max), and comparable to the scroll compressor at heating mode points 1 and 2. At point 3 (the most extreme heating mode test point), refrigerant flow was unstable during frost accumulation. As mentioned in the previous section, refrigerant flow rate was recorded manually for the 2.5-ton (8.8-kW) UUT, and it may have been recorded outside of steady state, particularly for heating test point 3 for rotary compressor. As a result, volumetric efficiency of the rotary compressor was significantly lower due to lower refrigerant mass flow rate recorded. At 5.0 tons (17.6 kW), volumetric efficiencies for the rotary compressor were higher than the scroll compressor in both cooling and heating mode: 0.7% and 2.8%, respectively. In some cases, the actual volumetric efficiency may differ from what is calculated. As discussed in Jähnig (1999), the true compressor inlet conditions differ from the measured suction conditions due to pressure drop entering the compressor, as well as heat transfer to the refrigerant from the compressor motor and shell. Also, motor slip does occur, and the actual rotational frequency is expected to be less than the supply power's frequency. Moreover, experimental variation and measurement uncertainty can also influence the calculations. When compared with studies by Diniz & Deschamps (2016), both compressors display volumetric efficiency sensitivity to condensing temperatures across a range of capacities, and volumetric efficiencies were observed to decrease at higher condensing temperatures (Figure 8).

$$\eta_v = \frac{\dot{m}_{ref}}{\omega * V * \rho_S} \tag{2}$$

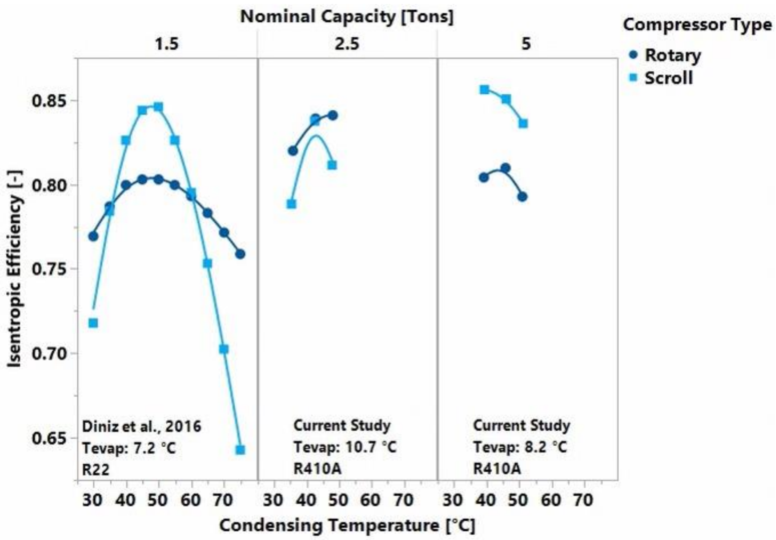

Figure 6: Isentropic Efficiency Comparison in Cooling Mode (Diniz & Deschamps , 2016)

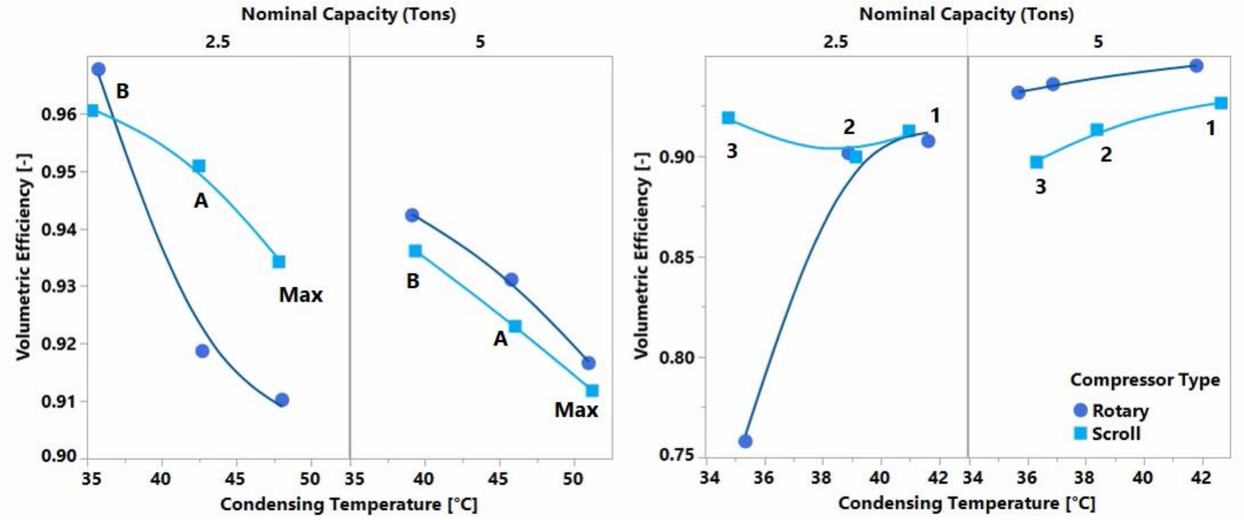

Figure 7: Volumetric Efficiency vs. Condensing Temperature: a) Cooling, b) Heating

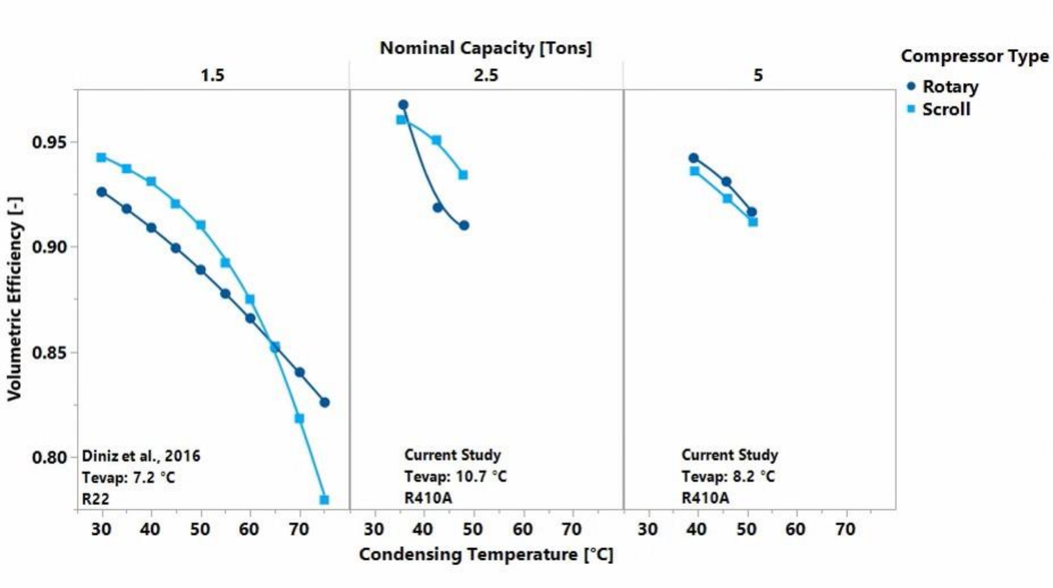

Figure 8: Volumetric Efficiency Comparison in Cooling Mode (Diniz & Deschamps, 2016)

In terms of the overall unit performance, the seasonal energy efficiency ratio (SEER) and heating seasonal performance factor (HSPF) were calculated for cooling and heating modes, respectively. At 2.5 tons (8.8 kW), the rotary compressor had 5.7% higher SEER than the scroll compressor, and 2.6% higher SEER when capacity increased to 5.0 tons (17.6 kW), as shown in Figure 9. Both compressors displayed a higher SEER value at lower capacity. On the other hand, HSPF was calculated for both compressors at the two capacities, across six climatic regions (Region I to VI) defined in AHRI Standard 210/240 (2017). On a regional basis, the 2.5-ton (8.8-kW) unit always had higher HSPF values than the 5.0-ton (17.6-kW). At 2.5 tons (8.8 kW), the UUT with the rotary compressor had, on average, 3% higher HSPF than the UUT with the scroll compressor across six regions, and HSPF was 0.6% higher at 5.0 tons (17.6 kW) (Figure 10). For both capacities, Region I yielded the highest HSPF value, while the lowest HSPF occurred at Region V.

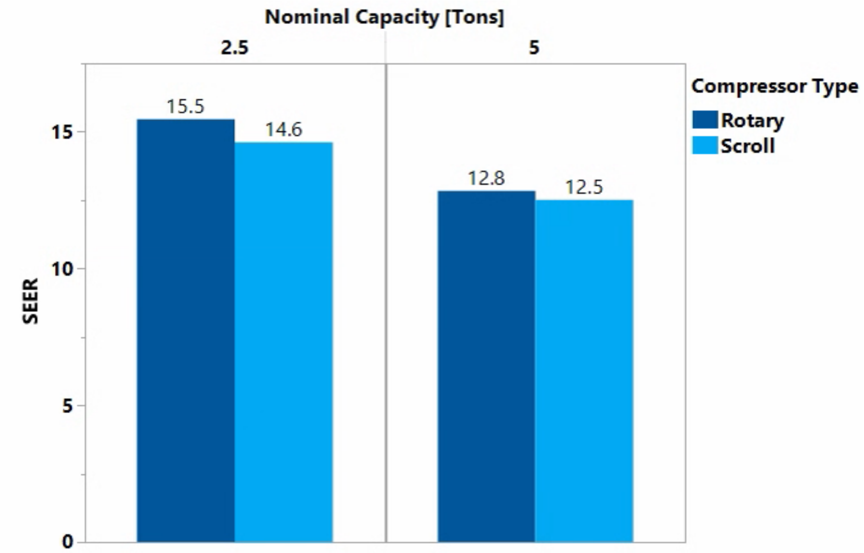

Figure 9: SEER and Nominal Capacity

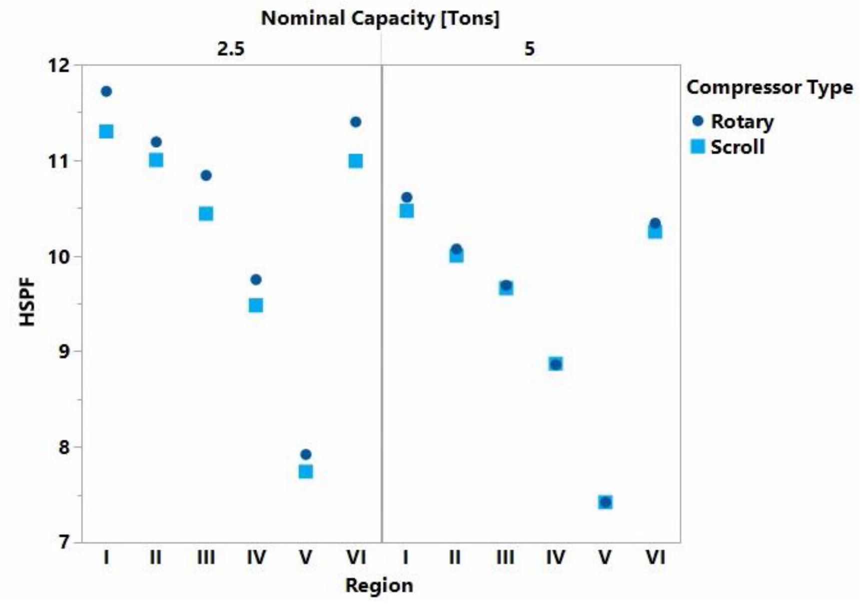

Figure 10: HSPF by Region and Capacity

3. CONCLUSIONS

This work presented: a) a review on rotary compressors; and b) a comparative experimental study between rotary and scroll compressors. The first part included a series of interviews from the industry regarding rotary compressor application as well as supplemental review of the literature. The two most frequent comments received were: limited application of rotary compressors in small capacity systems and the GE failure in using rotary in their refrigeration systems in the 1980's. To evaluate the limitation of rotary compressors in larger capacity systems, a series of cooling and heating tests (AHRI210/240 Standard specified operating conditions) were conducted for two typical US split HPs of 2.5 (8.8) and 5.0-ton (17.6-kW) capacities, using both scroll and rotary compressors. The results showed that at 2.5 tons (8.8 kW), the rotary compressor's isentropic efficiency was 2.6% and 14.0% higher than the scroll compressor, in cooling and heating modes, respectively. For the 5.0 tons (17.6 kW) system, the efficiency of the rotary compressor was 5.4% lower during cooling and 6.3% higher during heating. In terms of volumetric efficiency, at 2.5 tons (8.8 kW) the rotary compressor was lower than the scroll compressor by 1.7% in cooling, and comparable to the scroll compressor at two of the three heating mode test points. At a higher capacity of 5.0 tons (17.6 kW), the rotary compressor was higher than scroll compressor by 0.7% and 2.8% in cooling and heating modes, respectively. When considering system-level efficiency, the 2.5-ton (8.8-kW) system installed with the rotary compressor had 5.7% higher SEER and 3% higher HSPF than with the scroll compressor. For a higher capacity of 5.0 tons (17.6 kW), the unit with the rotary compressor had 2.6% higher SEER and 0.6% higher HSPF as compared to the unit with the scroll compressor.

NOMENCLATURE

AC	Air-conditioner	(-)
AHRI	Air-conditioning, Heating, and Refrigeration Institute	(-)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	(-)
BPA	Bonneville Power Administration	(-)
EER	Energy efficiency ratio	(Btu/W.h)
GE	General Electric	(-)
h_D	Discharge enthalpy	kJ/kg
h_{Di}	Discharge isentropic enthalpy	kJ/kg
h_S	Suction enthalpy	kJ/kg

HP	Heat pump	(-)
HSPF	Heating Seasonal Performance Factor	(Btu/W.h)
HVAC	Heating, ventilation, and air-conditioning	(-)
HVAC&R	Heating, ventilation, air-conditioning, and refrigeration	(-)
$\dot{m}_{ref}$	Refrigerant mass flow rate	kg/s
η_i	Isentropic efficiency	(-)
η_v	Volumetric efficiency	(-)
ω	Rotational speed	revolution/s
R	Refrigeration	(-)
ρ_S	Suction density	kg/m^3
RV	Recreation vehicle	(-)
SEER	Seasonal Energy Efficiency Ratio	(Btu/W.h)
TXV	Thermal expansion valve	(-)
UUT	Unit under test	(-)
V	Compressor displacement volume	m^3
VCC	Vapor compression cycle	(-)

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ACKNOWLEDGEMENT

Test data was provided by Shanghai Highly Electric Appliances Corporation (SHEC).