2018

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ABSTRACT

Homeowners in the United States can generally choose among three types of air conditioning systems: fixed-speed compressor systems that cycle on and off to deliver an average cooling capacity; fixed-speed / multi-capacity compressor systems with reduced cycling; and variable speed compressor systems that match the cooling load of the household, thereby delivering better temperature and humidity control with higher efficiency and comfort levels. While HVAC systems account for about 45% of the energy consumption in U.S. homes and variable speed compressor systems can achieve significantly higher efficiency, they only account for 10% of the market and systems installed in new buildings mostly remain single speed. This could be explained in part by the initial system cost and the complex electronic circuitry used to vary compressor speed. This paper presents a system solution to improve the Seasonal Energy Efficiency Rating (SEER) of Permanent Split Capacitor (PSC) compressor systems by introducing a low power inverter used only for operation at low capacities. SEER results for 3 tons and 5 tons systems with scroll and rotary compressors are presented. The impact of varying the speed of the PSC outdoor fan on SEER is also discussed.

1. INTRODUCTION

Vapor compression air conditioning systems installed in residential housing in the United States typically include the following subsystems: a compressor, and expansion apparatus, an evaporator coil and its associated fan, and a condensing coil and its associated fan. The technologies used for these various elements have significant impact on the efficiency achievable by HVAC units. Low SEER systems traditionally use fixed speed Permanent Split Capacitor (PSC) compressor and fans, whereas high SEER units tend to implement variable speed control.

The following sections will first present the key characteristics of both single speed and variable speed systems and then outline the SEER gains achieved by introducing a novel power electronic control and vary the compressor and outdoor fan speeds of a single speed system using PSC motors. Finally, the paper will discuss the technique used for SEER optimization when varying the speed of all three motors and present the results of a study of oil circulation when operating the compressor at low speeds.

2. SINGLE-SPEED SYSTEM OVERVIEW AND CHARACTERISTICS

Fixed speed compressors are used in single speed systems. In US residential installations, HVAC units typically deliver two tons (6.7 kW) of cooling capacity for small systems up to five tons (17 kW) of cooling depending on the climate and size of the dwelling.

2.1 PSC Motors Performance

A PSC is an induction motor that comprises two sets of windings and that is capable of running directly from single phase power, without the need for a power electronics converter to accelerate from standstill to the rated operating point. A capacitor connected in series with one of the windings is used to operate the two phase motor from a single phase supply. Figure 1 presents normalized torque and current profiles of a PSC motor from standstill to no load.

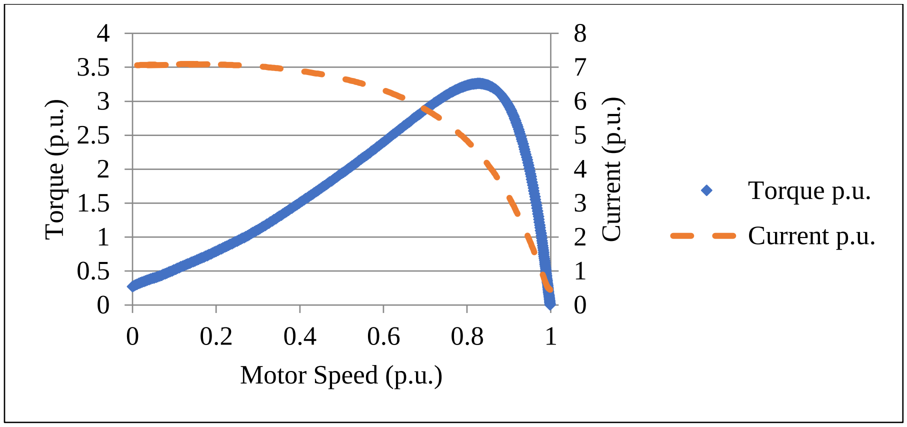

Figure 1. PSC torque and current versus speed.

As depicted in Figure 1, a PSC may only develop a fraction of its full load torque when starting from a standstill condition, and draws several times its rated current until the speed approaches rated speed. These characteristics of PSC motors impose several limitations on the operation of single speed systems.

Finally, the typical efficiency curve of a PSC motor dictates that the operating point should be maintained as close as possible to the motor rated point in order to maximize efficiency. Indeed, either an increase or a decrease from the optimal operating speed result in a decrease in motor efficiency.

2.2 Single Speed System Operation and Efficiency Calculation

As PSC compressors are designed to work at single speed, they always provide maximum cooling capacity. Therefore, single speed systems are cycled on and off by the thermostat to achieve the desired temperature setting for the air conditioned space. However, the operating characteristics of PSC motors impose limitations on the functioning of single speed systems in terms of cycling capabilities. Indeed, during normal operation, a pressure differential appears between the suction and discharge ports of the compressor, and this pressure differential remains for some time after the power is removed from the compressor. Under such circumstances, because a PSC has limited starting torque, the thermostat is unable to cycle rapidly and a lock-out time up to several minutes is implemented to prevent short cycling and high current consumption in a locked rotor compressor. Cyclical operation of the HVAC unit precludes tight regulation of the temperature in homes and may also negatively affect the dehumidification of indoor air.

In the United States, the efficiency of an HVAC system is evaluated through its Energy Efficiency Ratio (EER) and Seasonal Energy Efficiency Ratio (SEER). The EER is the ratio of the system cooling capacity (in Btu/hr) with the power consumed by the HVAC system, including the compressor, the indoor fan, and the outdoor fan input power. The SEER for a single-speed system is calculated according to the ANSI/AHRI Standard 210/240 for the Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment. The standard calls for several tests, some in continuous operation, some under cyclical operation in order to establish the cyclic coefficient of degradation C_d. Table 1 summarizes the tests to assess single speed rating.

Table 1. Single-speed system test points. 80.0ºF / 67.0ºF indoor air.

Test condition	Outdoor air temperature ºF	Compressor speed	Cooling air volume rate
A (steady)	95.0/75.0	Max.	Max.
B (steady)	82.0/65.0	Max.	Max.
C (steady)	82.0/-	Max.	Max.
D (cyclic)	82.0/-	Max.	Max

Once the tests in Table 1 are completed, the SEER rating is calculated according to Equation (1) below.

$$\mathrm{SEER}_{\mathrm{single\ speed}} = \mathrm{EER}_{\mathrm{B}} \times (1 - 0.5 \times \mathrm{C}_{\mathrm{d}}) \qquad (1)$$

3. VARIABLE-SPEED SYSTEM OVERVIEW AND CHARACTERISTICS

Variable speed HVAC systems typically use high efficiency permanent magnet motors for the compressor, the indoor fan, and the outdoor fan that allow to reach substantially higher SEER when compared to single speed systems. Furthermore, the speeds of these high efficiency motors can be adjusted independently to reach optimal system performance for a wide range of environmental conditions.

3.1 Variable Speed Units Motors Performance

Motors with permanent magnets are typically used in variable speed systems in order to achieve higher efficiency. Indeed, when compared with PSC motors, Permanent Magnet motors (PM) have inherently higher efficiency as the rotor losses present in the case of PSC motors are eliminated. However, permanent magnet motors must be coupled to variable speed electronic controllers in order to operate from utility power. Figure 2 below displays the typical efficiency difference that can be measured between PSC and PM or Brushless Direct Current (BLDC) motors.

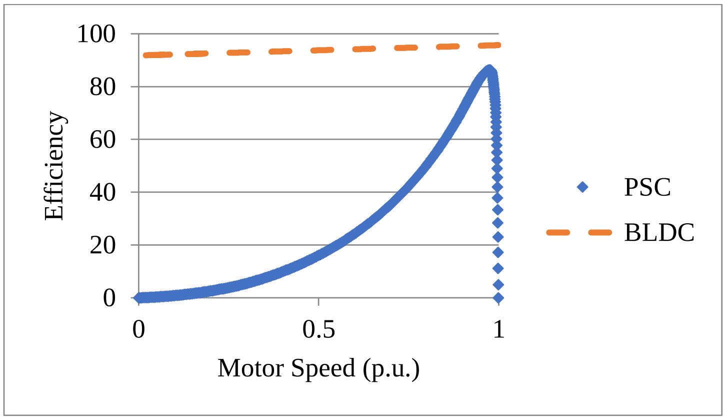

Figure 2. PSC and BLDC efficiency versus speed.

As can be seen in Figure 2, BLDC motors can achieve very high efficiency over a wide speed range when compared with PSC motors. However, when evaluating the impact of variable speed technology on HVAC system, it is necessary to include the losses from the electronic controller over the complete speed range.

3.2 Variable Speed Controller Electronics

Variable speed controllers are used to provide a source of variable voltage and variable frequency to motors from the fixed frequency, fixed voltage of the utility power source. Figure 3 below describes the elements of a typical variable speed drive.

Figure 3. Block diagram of a variable speed drive.

The power conversion in the electronic drive comprises two steps. First, the AC mains voltage from utility power is transformed into a DC voltage stored on a DC bus capacitor by a power factor correction unit. A power factor correction unit is typically included with variable speed compressor systems to ensure that the maximum power can be extracted from the main supply. As an example, a 4kW residential unit with power factor correction unit would draw about 18 Amps from the power source. The same unit without power factor correction could draw close to 28 Amps. Depending on the service available in residential housing and the protection used on the circuit, it is possible that running a 4kW without power factor correction would result in nuisance tripping of the line breaker.

The second step in the power conversion is realized by the inverter. The inverter transforms the DC bus voltage into a source of variable voltage and variable frequency to adjust the operating speed of the motor.

The switching of the power electronics components of the variable speed drive produces losses and for a typical converter used in residential applications, the efficiency will range from 92% to 94%. These losses generate heat and often result in thermal challenges for operating the electronic drive at high ambient conditions.

3.3 Variable Speed System Operation and Efficiency Calculation

In a variable speed system, the system controller of the air conditioning unit receives information regarding ambient temperature as well as user set point from the thermostat and commands specific operating speeds for the compressor, indoor fan and outdoor fan motors. By varying the speeds of all three motors, the system controller is able to adjust the cooling capacity to match the cooling load, and can therefore improve comfort through tighter temperature and humidity control, and through reduced operating noise by reducing or eliminating cycling and airflow noise.

Similar to single speed systems, the ANSI/AHRI Standard 210/240 provides the testing procedures and calculations to compute the SEER for variable speed systems. These tests are presented in Table 2 below.

Table 2. Variable-speed system test points. 80.0ºF / 67.0ºF indoor air.

Test condition	Outdoor air temperature ºF	Compressor speed	Cooling air volume rate
A_2 (steady)	95.0/75.0	Max.	Max.
B_2 (steady)	82.0/65.0	Max.	Max.
E_v (steady)	87.0/69.0	Intermediate	Intermediate
B_1 (steady)	82.0/65.0	Min.	Min.
F_1 (steady)	67.0/53.5	Min.	Min.
G_1 (steady)	67.0/-	Min.	Min.
I_1 (cyclic)	67.0/-	Min.	-

For variable-speed systems, tests are conducted at three distinct compressor speeds. The relationship between compressor speeds follows Equation (2).

$$\mathrm{Speed}_{\mathrm{intermediate}} = \mathrm{Speed}_{\mathrm{min}} + \frac{\mathrm{Speed}_{\mathrm{max}} - \mathrm{Speed}_{\mathrm{min}}}{3} \tag{2}$$

Indoor and outdoor fan speeds may also be varied to further adjust the cooling capacity delivered by the system.

4. PROPOSED SOLUTION: VARIABLE SPEED OPERATION OF SINGLE SPEED SYSTEMS

HVAC systems using variable speed compressors can achieve significantly higher SEER rating compared to their single speed counterparts. However, variable speed compressors have to be used in conjunction with electronic controllers that reduce to overall system efficiency and pose significant thermal management challenges at maximum load. A system solution combining a single speed compressor for full load operation with a low power electronic drive for low power operation is proposed to address some of these shortcomings.

4.1 System Overview

The proposed system approach associates a single speed compressor able to run at full load directly from utility power with a low power electronic drive enabling the possibility to run the compressor at lower speeds in order to adjust the cooling capacity to match the cooling load. Figure 4 below depicts a block diagram for the proposed solution, and Figure 5 shows an air cooled electronic drive for 5 tons HVAC systems.

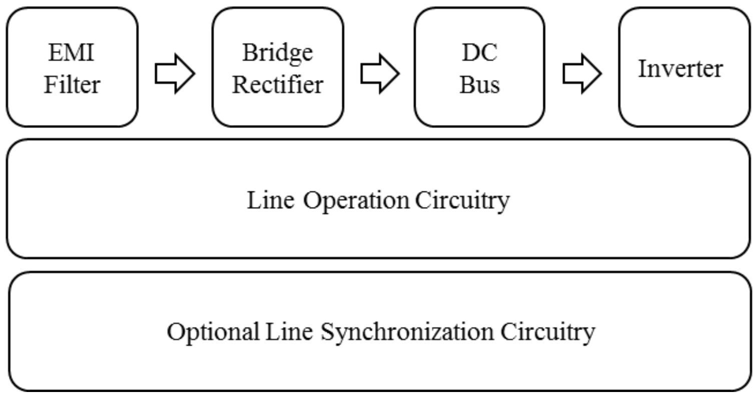

Figure 4. System solution to convert fixed-speed system into variable speed.

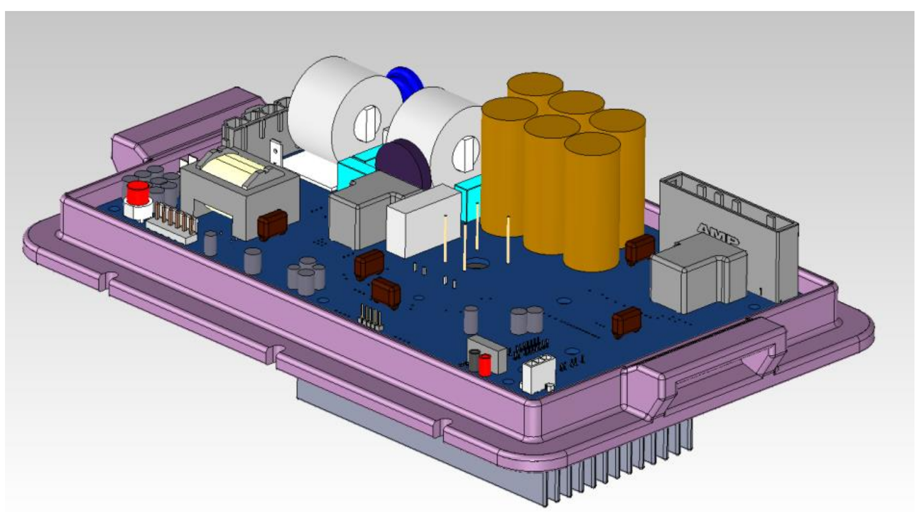

Figure 5. Air cooled electronic drive for 5T system.

Contrasting the systems detailed in Figures 3 and 4, it can be seen that the proposed solution comports the components necessary for line operation as well as some elements common with traditional variable speed drives. However, because the electronic drive is not used at full load operation, the power factor correction unit can be eliminated, thereby improving the efficiency of the electronic drive. Finally, an optional line synchronization circuitry can be implemented in the proposed solution. With this circuitry, it is possible to implement soft starting and develop maximum starting torque on the compressor under pressure differential between the discharge and suction ports.

4.2 System Operation and Benefits

With the proposed solution, the operation of the compressor at full load is not affected by the electronic drive. Therefore, the performance measured at the A2 and B2 conditions remains unchanged. The electronic drive is connected between the compressor and utility power only during variable speed operation. The drive varies the compressor speed between standstill and 75% of full speed to meet reduced cooling loads. When the cooling load increases beyond this operating range, the electronics transitions the compressor to utility power to operate at full load. Figure 6 below illustrates this concept.

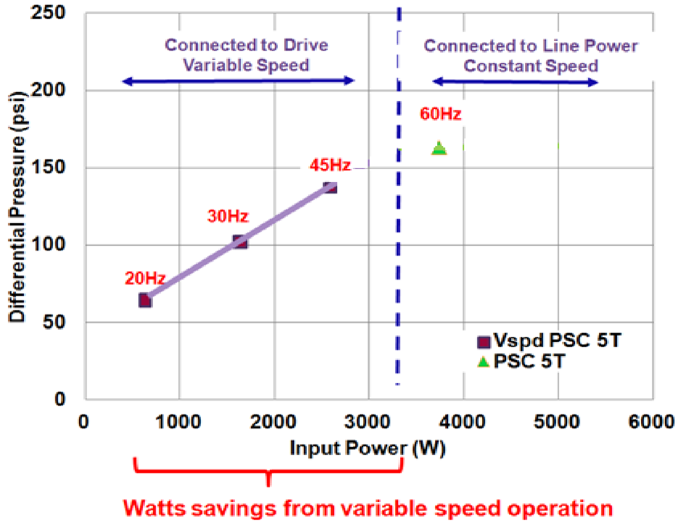

Figure 6. Operating modes enabling variable speed operation of a PSC compressor.

The proposed modes of operation present significant improvements when compared to single speed systems. Indeed, besides the improvement in SEER, this solution allows for smooth and controlled starting of the compressor under large pressure differential, eliminating large inrush currents of the typical line started PSC compressors. Furthermore, lower operating speeds allow for reduced cycling of the HVAC system and increased comfort. Finally, the addition of the electronics drive allows for monitoring of the compressor operation even when on utility power, thereby reducing system stress under locked rotor conditions.

While the proposed system offers substantial advantages when compared to single speed systems, it also offers benefits over traditional variable speed systems. Indeed, as the electronic converter is bypassed during operation on the line, its power rating, and therefore overall size, can be reduced. Furthermore, thermal management for the electronics and heatsinking is simplified as full load high ambient operation occurs on utility power.

5. PROPOSED SOLUTION: PSYCHROMETRIC TESTING RESULTS

The system solution was evaluated by determining the SEER improvement that could be achieved by using the electronic drive to operate the single-speed heat pump as a variable-speed heat pump. An experimental approach was implemented to determine the maximum SEER improvement that could be achieved and to identify the optimum component speeds that would lead to such an improvement. The experimental approach used here was first reported by Salts and Groll (2017) and is further developed in this paper to include the VSHP 3 test phase.

5.1 Experimental Setup

The electronic drive was tested in combination with two different single-speed heat pumps and five different compressors. Both heat pumps were originally equipped with fixed speed scroll compressors having a nominal frequency of 60 Hz. Both heat pumps were residential unitary split-system heat pumps consisting of an indoor and outdoor unit. The indoor units contained an evaporator, thermostatic expansion valve (TXV), and indoor fan. The outdoor units contained a compressor, condenser, outdoor fan, four-way reversing valve, and accumulator. Table 3 lists the compressors that were tested in each system. All compressors and outdoor fans tested were equipped with PSC motors while the indoor fans used ECM motors. Control of the motor speeds during the laboratory experiments was performed manually and the motor speeds were able to be adjusted independently of one another.

The heat pumps were tested in cooling mode, and the cooling capacities were determined using the refrigerant enthalpy method. The power consumptions of the indoor and outdoor unit are measured separately using Watt transducers. Data is collected through a National Instruments cRIO-9074 using a VI written in LabVIEW. All refrigerant and air properties have been determined using the software Engineering Equation Solver (EES.)

Table 3: List of Compressors Tested in each Heat Pump System

Heat Pump Nominal Capacity	Compressor Type	Manufacturer	Size
5 ton	Scroll	Manufacturer 1	5 ton
	Rotary	Manufacturer 2	4 ton
2.5 ton	Scroll	Manufacturer 1	2.5 ton
	Rotary	Manufacturer 2	3 ton
	Rotary	Manufacturer 3	2.5 ton

5.2 SEER Tests

The general approach used for evaluating the impact of the system solution is outlined in steps 1-4. Both the fixed-speed and variable-speed SEERs were determined according to ANSI/AHRI Standard 210/240-2008.

1. Select an off-the-shelf single-speed heat pump (SSHP)
2. Experimentally evaluate the baseline SEER of the SSHP
3. Modify the SSHP with the electronic drive to enable the variable speed operation of fixed speed motors
4. Experimentally evaluate the variable speed SEER of the newly modified heat pump.

The experimental determination of the variable speed SEER was done in three phases as shown in Table 4. Each phase isolated one of the three speed controlled components to be tested as the independent variable. As testing moved from one phase to another, the ideal variable speed conditions from the previous phase were carried over and applied to the next phase. For example, if it is determined that the largest SEER in VSHP 1 mode is achieved at a minimum compressor speed of 30 Hz, this will be the minimum compressor speed applied in every test case for the VSHP 2 phase.

Table 4: Phases of Testing for Evaluating the Proposed System Solution

Test Phase	Independent Variable	Variable Speed Components	Fixed Speed Components
VSHP 1	Compressor Speed	Compressor	Indoor Fan and Outdoor Fan
VSHP 2	Indoor Air Volume Flow Rate	Compressor and Indoor Fan	Outdoor Fan
VSHP 3	Outdoor Fan Speed	Compressor, Indoor Fan, and Outdoor Fan	None (Fully Variable Speed)

5.3 SEER Tests Results

Following the methodology outlined in Table 4, the results measured in a 2.5 ton and in a 5 ton systems are summarized in Table 5 below. The proposed solution varying the speed of a fixed speed compressor achieved SEER improvements with various magnitudes depending on the compressor technology used as well as the number of elements in the system controlled in variable speed mode. It is anticipated that the performance of the proposed solution will heavily depend on the ability of a fixed speed compressor to operate effectively at lower rotational speeds. While it is understood that all compressor types can be specifically designed to accommodate variable speed operation, the table above present results with unmodified and non-optimized single speed compressors. Under such conditions, it can be seen that the technology provided improvements of 1.67 SEER on scroll setup and over 5 SEER on rotary setups.

Table 5: SEER test results

Test Phase	5 Ton Scroll SEER	4 Ton Rotary SEER	3 Ton Rotary SEER	2.5 Ton Rotary SEER
Baseline	14	13.08	11.38	12.84
VSHP 1	14.94	16.46	14.33	17.95
VSHP 2	15.67	18.10	14.43	(*1)
VSHP 3	(*1)	(*1)	15.42	(*1)

(*1) Detailed testing not performed as preliminary testing showed little improvement testing in this mode of operation

Details about SEER testing of the 5 ton and 4 ton compressors in VSHP 1 mode with information related to operating speeds have been previously reported by Chretien et al. (2017).

6. COMPRESSOR ANALYSIS

The analysis below is provided to better understand the impact of the electronic drive on compressor performance, including an overall isentropic efficiency analysis and measurements of the oil concentration ratio in the liquid line.

6.1 Methodology

Scroll and rotary compressors used in residential heat pumps are often designed to use the speed of the rotating shaft to circulate oil to critical components within the compressor shell. Lubricant oil is used in the compressor to lubricate bearings and to seal gaps between high pressure and low pressure compression pockets. Significant efforts have been made to understand lubricant circulation within the compressor as well as lubricant migration from the compressor to the refrigeration system. Measurement and simulation results by Cho et. al. (2002) showed that oil flow to the journal bearing of a scroll compressor varied directly with shaft speed. These results demonstrate the potential for insufficient lubricant circulation within the compressor at low compressor speeds. Min and Hwang (2000) describe the mechanisms by which oil is discharged from a rotary compressor as well as methods to reduce the OCR. Reduction in OCR is typically desired to avoid running the compressor dry. Excess of oil in the refrigeration system has also been shown to have negative effects on system performance. Cuevas and Lebrun (2009) tested a variable speed scroll compressor and found that the OCR varied directly with shaft speed. The authors also observed a significant decrease in scroll compressor efficiency at low compressor speeds which they attributed to a lack of sufficient lubrication within the compressor. These studies highlight the desire to ensure sufficient lubrication in the compressor while also minimizing the amount of oil discharged to the compressor. This effort is made challenging by the fact that both of these phenomena have been observed to be directly related to shaft speed.

Because the compressors tested in this effort were designed to operate at a fixed speed, there was some concern about a lack of sufficient lubricant circulation inside the compressor when operated at low speeds. Based on the literature review, the OCR was identified as a metric that could be used as an indicator for internal oil circulation; it is assumed for example that a reduction in the amount of discharged oil measured in the liquid line is an indicator that lubricant circulation within the compressor is also reduced. The OCR was also a metric that could be measured without requiring any major modifications to the system or modifications that would impact system performance. The OCR was measured for the heat pump having the 3 ton rotary compressor from manufacturer 2 installed and is reported as the percentage weight of oil in the oil-refrigerant mixture.

To design the OCR measurement system and method for collecting the lubricant sample in the liquid line, ASHRAE Standard 41.4 was followed with one minor modification based on a literature review. Peuker (2010) describes that the method of evacuating the sample cylinder according to ASHRAE Standard 41.4 is not sufficient in removing all of the refrigerant which may be solved in the oil. The author suggests immersing the cylinder in a hot water bath during the evacuation process to ensure all of the refrigerant is removed from the cylinder, and provides data to support the efficacy of this method. Because the method was simple to implement and had been proven to work, it was adopted in this procedure. The OCR measurement method used in this study is also referred to as the weight measurement method and was used in the studies by both Min and Hwang (2000) and Cuevas and Lebrun (2009).

Compressor overall isentropic efficiency has also been determined. Overall isentropic efficiency is a function of the refrigerant mass flow rate, the compressor power, the enthalpy at the compressor inlet, and the enthalpy at the compressor discharge for an assumed isentropic compression as shown in Equation 3.

$$\eta_{Compressor} = \dot{m}_{ref} \frac{h_{2s} - h1}{P_{compressor}} \tag{3}$$

6.2 Results

Table 6 lists the results of the OCR testing and shows the influence of compressor speed on the oil circulation rate. The amount of oil discharged is reduced as compressor speed is reduced. As previously mentioned, the reduction in oil discharged from the compressor could be an indicator of a lack of lubricant flow in the compressor. This could lead to an increase in frictional losses in the bearings as well as an increase in leakage due to a lack of lubricant sealing. This however is only one explanation; the reduction in discharged oil could also be a result of the oil separation mechanisms operating more efficiently at lower compressor speeds.

Table 6: Oil Circulation Rate Results as a Function of Compressor Speed

Parameter	100 % Comp. Speed	57 % Comp. Speed	35 % Comp. Speed
Measured Cylinder Assembly Mass (g)	M1 987.2 M2 1156.2 M3 988.2	M1 987.2 M2 1156.2 M3 987.3	M1 987.2 M2 1156.2 M3 987.2
Mass of refrigerant (g)	168	168.9	169
Mass of oil (g)	1	0.1	0
Oil circulation rate	0.592%	0.059%	0.000%

The overall isentropic efficiency for the 3 ton compressor from manufacturer 2 is plotted in Figure 7. Both plots in the figure show the same results but in different ways. In general, isentropic efficiency decreases with decreasing compressor speed at a given rating condition. One possible reason for this is insufficient lubrication within the compressor. The higher efficiencies at full load test conditions A_2 and B_2 can be partly attributed to the fact that the electronic drive is not engaged at full speed operation and therefore no drive losses are incurred.

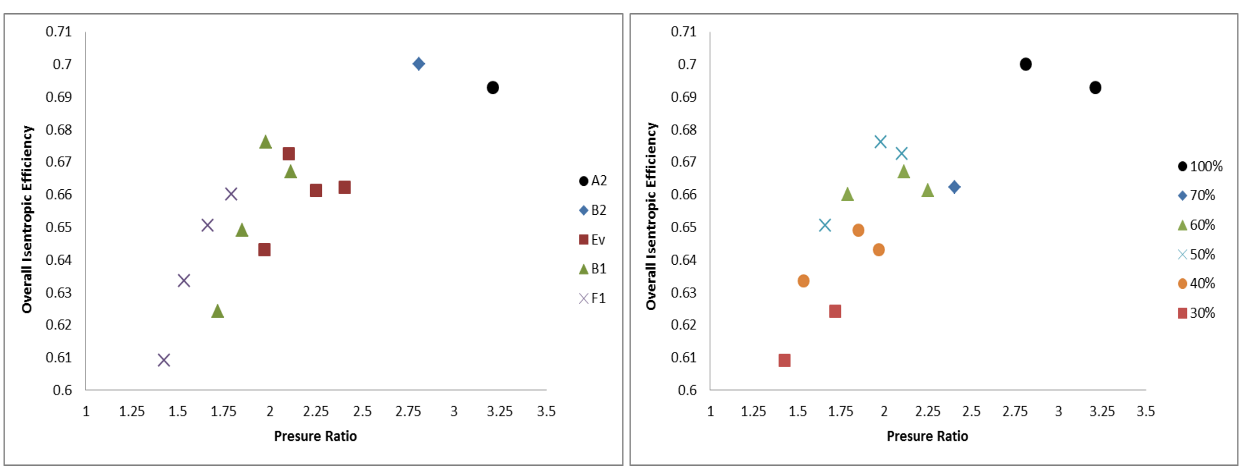

Figure 7: Overall Isentropic Efficiency vs Pressure Ratio at Different Compressor Speeds and Different Ratings Test Conditions

7. CONCLUSIONS

The addition of a variable speed drive to a single speed PSC compressor to enable variable speed operation under light cooling loads, when combined with variable speed indoor and outdoor fans, allows for over 33% improvement over baseline. Future work to benchmark the technology will include testing of fixed speed compressors with internals specifically designed to accommodate lower speeds of operation. Furthermore, for setups that have provided significant SEER improvements without requiring any modifications to the compressors, the study of oil circulation when operating at low speeds can be expanded to better understand the lubricant flow within the compressor shell. This study could be achieved through modelling or experimental work.

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