Assessment of Variable Capacity Rooftop Heat Pump

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Abstract: Recently, variable capacity rooftop heat pumps have been introduced into the commercial space conditioning market. Variable capacity technology enables heat pumps to operate more efficiently and with greater flexibility. The performance of a variable capacity rooftop heat pump was examined as a dedicated outdoor air system (DOAS) within a laboratory setting. The variable capacity DOAS was outfitted with an enthalpy wheel and modulating hot gas reheat. The variable capacity DOAS was setup to supply a constant volume of relatively neutral air and was examined in both low temperature and high humidity conditions. The results of laboratory testing provide power consumption characteristics for system operation and demonstrate the ability of the variable capacity rooftop heat pump to adjust capacity output in both heating and cooling-reheating mode. The laboratory tested DOAS was evaluated for two climates in the Southeast United States, which commonly house commercial packaged equipment using electric resistance heating. Analysis was conducted to compare the power consumption between the laboratory tested DOAS and alternative systems using electric resistance heat.

Key Words: variable capacity heat pump, dedicated outdoor air system

1 INTRODUCTION

Building codes require that fresh outdoor air be distributed into the occupied space of commercial buildings. ASHRAE Standard 62.1, “Ventilation for Acceptable Indoor Air Quality” specifies ventilation rates for various building types and occupancy levels. Heating, ventilation, and air-conditioning (HVAC) systems can be configured in numerous manners to provide sufficient fresh air ventilation. This paper will consider a packaged rooftop unit which supplies 100% outdoor air, which is termed dedicated outdoor air system (DOAS). A DOAS is primary responsible for providing fresh air ventilation and may contribute to space heating or cooling. A primary space conditioning system is always used in parallel with a DOAS to satisfy the thermal loads of the space. Dedicated outdoor air systems may be designed to supply neutral air, similar to the indoor space conditions, or conditioned air which assists the primary system in heating or cooling the space. This study focuses on DOAS which supply neutral air, similar to the indoor conditions of the space. In cold outdoor temperatures, a neutral air DOAS heats outdoor air to approximately room temperature. In hot and humid conditions, a neutral air DOAS dehumidifies and then reheats the fresh air, supplying air at a neutral dry-bulb temperature and below the dewpoint of the indoor space.

Within the Southeastern United States, electric resistance heating is commonly used as a heating source within packaged rooftop units in commercial buildings. For DOAS, electric resistance elements may be used in heating operation as the primary or backup heating source. In hot and humid conditions, a DOAS may use electric resistance heat to provide reheat of the dehumidified air to neutral air temperatures. Electric resistance heating is an inefficient method of heating with electricity compared to heat pump systems. Electric resistance heating consumes approximately two to three times the power of an appropriately

matched rooftop air-conditioner or heat pump. In aggregate, electric resistance heating can cause power demand issues for the local electric utility. This study examines a potential alternative to the use of electric resistance heating in DOAS for the Southeastern United States. This study examines a variable capacity heat pump based DOAS with an enthalpy wheel and modulating hot gas reheat capability. The study examines the ability of the described DOAS to provide neutral air in low temperature and hot/humid conditions within a laboratory setting. Power consumption results of the laboratory tested DOAS are compared to the usage of electric resistance heating.

2 OVERVIEW OF TECHNOLOGIES

This section provides a brief overview of the technologies which were included in the laboratory evaluated DOAS. The technologies include: variable capacity, enthalpy wheel, and modulating hot gas reheat. The section describes how the technologies were applied in the neutral air configured DOAS considered in laboratory testing.

Variable capacity technology enables a heat pump to modulate the amount of heating or cooling output provided by the system. Variable capacity is achieved through a variable speed compressor, variable speed blowers and fans, and a unit control system. Variable capacity heat pumps can operate at reduced speeds when the thermal load permits and therefore can offer increased efficiency over traditional, single speed systems. For neutral air DOAS, a variable capacity heat pump can operate at reduced operating levels and increased efficiency in maintaining the supply air at neutral conditions.

An enthalpy wheel is a device which transfers heat and moisture between two air streams. In HVAC systems as outdoor air is ventilated indoors, typically a similar quantity of indoor air is sent outdoors (exhaust air) in order to maintain pressure inside the building. In many buildings, exhaust air is simply sent into the atmosphere and the energy within the exhaust air is unused. With enthalpy wheels the exhaust air energy can be used to pre-condition the outdoor air, before the fresh air is conditioned by the DOAS. An enthalpy wheel reduces the needed capacity within a DOAS.

In hot and humid conditions, a DOAS may be designed to provide air at neutral dry-bulb temperature and a dewpoint temperature lower than the space. A DOAS accomplishes this process by cooling the air first and then reheating the cooled air. Reheat can be accomplished through multiple means including electric resistance, natural gas coil, or a refrigerant coil. When a refrigerant coil is used for reheat, hot gas from the outlet of the compressor is directed into two separate coils: the reheat coil and the condenser coil. Systems which have the ability to vary the amount of hot gas to each coil and therefore control the dry bulb supply temperature can be referred to as using modulating hot gas reheat.

3 LABORTATORY TESTING

A variable capacity rooftop unit was examined as a DOAS within a laboratory at the Electric Power Research Institute facility in Knoxville, TN. This section contains details on the experimental setup, unit specifications, instrumentation, and the procedures used in laboratory testing.

3.1 Experimental Setup

The laboratory setup consisted of a pyschrometric chamber, return and supply air ducts, a heat pump based DOAS, and performance monitoring instrumentation. The pyschrometric chamber air served as the outdoor air both to the fresh air intake and condenser coil of the DOAS. Return and supply air ductwork allowed for air to be controlled and measured during

the evaluation process. The laboratory tested DOAS contained a variable capacity digital scroll compressor, variable speed condenser fans, a modulating hot gas reheat coil, and an enthalpy wheel. The DOAS was a nominal 3 ton system and was set up to supply a constant volume of 1360 m^3/h at a neutral supply air temperature of 21.1°C. The DOAS was also set to supply air at a dewpoint below 10°C. Temperature and humidity were measured at various locations within the DOAS to capture the performance of the unit during operation. Figure 1 provides the layout of the DOAS considered in laboratory testing and locations of temperature and humidity (represented by numerical indicators) measurements within the data acquisition system.

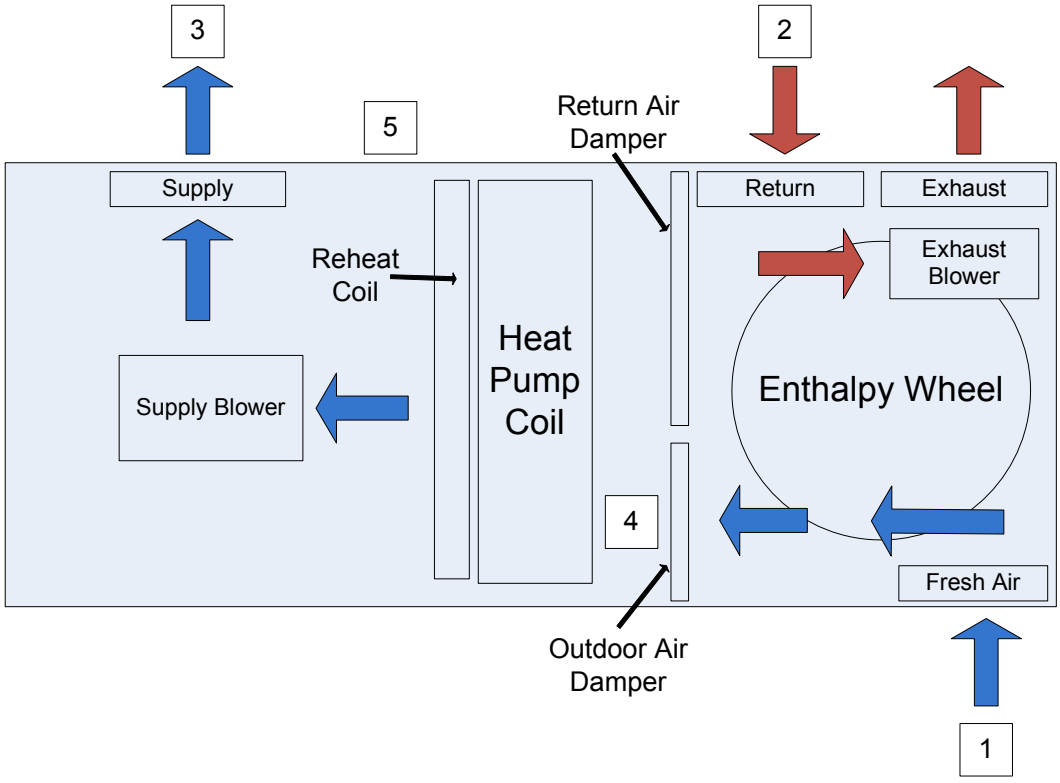


Figure 1: Layout of Unit and Temperature/Humidity Measurements

The locations (1 – 5) within Figure 1 refer to the information outlined in Table 1, which provides an overview of the experimental instrumentation. Each temperature and humidity measurement was also verified with a nine-point thermocouple and chilled mirror hygrometer air sample device. Along with the various temperature and humidity measurements, supply airflow and unit power consumption were also monitored. From the laboratory measurements, the performance on the DOAS could be examined.

Table 1: Experimental Instrumentation Overview

Location on Figure 1	Recorded Data	Instrumentation	Instrumentation Accuracy
1	Outdoor Air	Vaisala HMT333	±1% Relative Humidity; ±0.2°C
2	Return Air		
3	Supply Air		
4	Enthalpy Wheel Outlet		
5	Condenser Inlet		
-	Airflow	Fan-E Evaluator: Four Point Pitot Static Tube	±0.5%
	Power (W)	Shark Meter 200T	±0.2%

3.2 Procedures

Within the laboratory evaluation, the outdoor conditions were varied in accordance with typical meteorological year (TMY) data for two cities in the Southeastern U.S., the area of interest for this study. The selected cities were Atlanta, GA and Pensacola, FL. The dry-bulb temperatures and relative humidity used for the two cities can be seen in Table 2. The indoor or return air which was delivered into the enthalpy wheel of the DOAS in laboratory testing was maintained at a dry-bulb temperature of 23.9°C and a relative humidity of 50%.

Table 2: Outdoor Air Conditions used in Laboratory Testing

Atlanta, Georgia Climate		Pensacola, Florida Climate	
Outdoor Dry-bulb Temperature (°C)	**Outdoor Relative Humidity (%)**	**Outdoor Dry-bulb Temperature (°C)**	**Outdoor Relative Humidity (%)**
-9.4	80	-	-
-3.9	70	-3.9	60
1.7	60	1.7	65
7.2	70	7.2	70
12.8	70	12.8	75
18.3	70	18.3	75
23.9	65	23.9	75
29.4	52	29.4	60
35.0	40	35.0	45
37.8	35	37.8	38
40.6	30	40.6	33

For each of the outdoor conditions described in Table 2, a steady-state test was conducted while the system was set to supply the neutral air condition of 21.1°C. For outdoor dry-bulb temperatures at or below 12.8°C, the heat pump of the DOAS operated in heating mode. For dry-bulb temperatures above 12.8°C, the DOAS cooled/dehumidified and reheated the outdoor air. The DOAS was not controlled to supply a fixed dewpoint temperature. The system only operated in dehumidification mode when the dewpoint of air entering the heat pump system was above 10°C. From the laboratory testing, a ten minute period of steady-state data collection was used to consider the experimental results and for analysis. In heating operation, the system did activate defrost mode in certain tests. Defrost operation was not factored into the average results for a test case. If a system went into defrost mode, then the unit was not considered to be in a steady-state.

4 RESULTS

Results of the laboratory testing are presented for both heating and cooling-reheating operation. The results examine the progression of heating or dehumidification throughout the DOAS. Total unit power demand and energy consumption are presented for various test cases. The laboratory results do not present the performance of the variable capacity heat pump and enthalpy wheel individually due to measurement restrictions from the layout of the unit.

4.1 Heating Operation

For heating operation, the laboratory results are examined for the Atlanta, GA climate. The results of the Pensacola, FL climate were similar to those of Atlanta, and the Atlanta test matrix has a test point not included within Pensacola of -9.4°C. Figure 2 provides the dry-bulb progression throughout the DOAS or the outdoor temperature, wheel outlet temperature, and supply air temperature for two Atlanta test cases. The two test cases presented are the coldest (-9.4°C) and mildest (12.8°C) outdoor dry-bulb temperature at which the system operated in heating mode. In the figure, the coldest test refers to the -9.4°C condition, while mild test refers to the 12.8°C condition. Test cases which are not shown fall between the two curves presented. For both test cases shown, the DOAS was able to condition the outdoor air to the neutral condition of 21.1°C. The enthalpy wheel demonstrated an ability to significantly increase the dry-bulb temperature of the outdoor air. The usage of the enthalpy wheel allowed the heat pump system to operate at reduced levels and consume less energy.

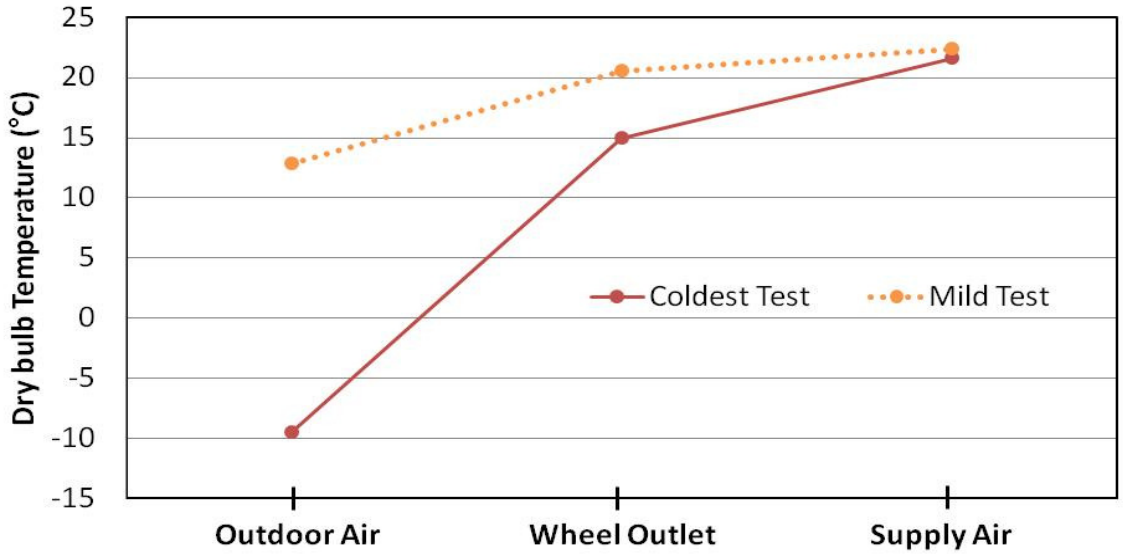


Figure 2: Dry-bulb Heating Progression within DOAS

Figure 3 provides the total unit peak power demand and energy consumption for all of the Atlanta heating test cases. The particular heating test case is indicated by the dry-bulb outdoor temperature along the horizontal axis. The unit peak power demand and energy consumption were obtained from a ten minute data period under steady-state operation. The peak power demand of the DOAS remained relatively constant across all test cases at approximately 3 kW. The energy consumption of the DOAS increased with decreasing outdoor dry-bulb temperature.

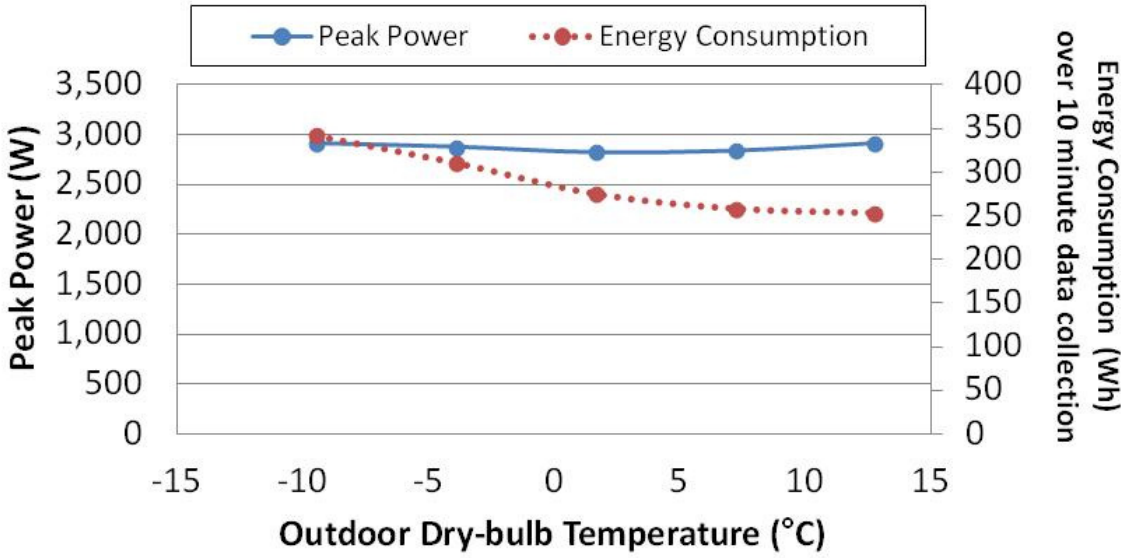


Figure 3: Peak Power and Energy Consumption of DOAS in Heating Operation

Figure 4 provides the operating level of the variable capacity heat pump within the DOAS for all of the Atlanta heating test cases. Figure 4 illustrates the ability of the variable capacity heat pump to adjust to the heating load. If the compressor was operating at nominal speed or full speed, then the operation level would be presented as 100% or 1.0. The particular heating test case is indicated by the dry-bulb outdoor temperature along the horizontal axis. As can be seen in the figure, as the outdoor temperature decreases the operation level within the compressor increases. At mild heating test cases, the variable capacity heat pump could operate at reduced levels to maintain the supply temperature of 21.1℃. At the coldest test case of -9.4℃, the heat pump within the DOAS was operating at ~49%, and thus the system can be considered oversized in heating mode for the selected climates.

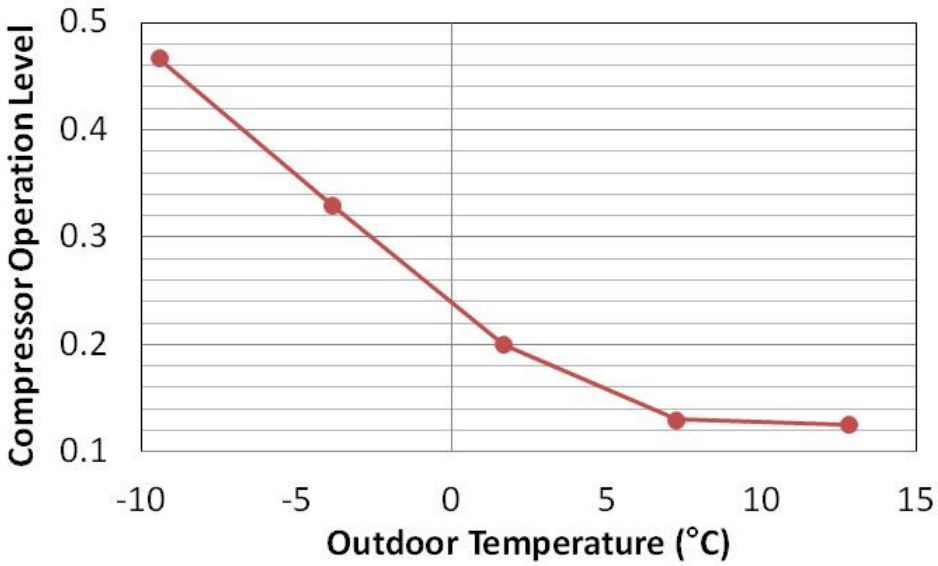


Figure 4: Variable Capacity Compressor Operation within DOAS in Heating Mode

Due to the ability of the variable capacity heat pump to operate at reduced levels, the DOAS was able to maintain a constant supply air temperature of 21.1℃ at a constant air volume across a broad range of outdoor conditions. A single speed compressor by design can either operate in the on state (full capacity) or the off state. A single speed heat pump would be

unable to supply a constant neutral air temperature at a constant air volume, unless other inefficient strategies were implemented into the system.

Although not considered in the steady-state testing portion of the laboratory assessment, defrost operation could have a significant impact on peak power demand or energy consumption if electric resistance backup heat was implemented within a DOAS. Commonly during defrost mode in a heat pump system, a backup heat source will offset the distribution of cold air into the space. A DOAS could potentially be outfitted without a backup heat source and allow the primary space conditioning system to offset the cold air distribution.

4.2 Cooling-Reheating Operation

For cooling-reheating operation, the laboratory results are examined for the Pensacola, FL climate. The results of the Atlanta climate are similar to the Pensacola climate, and the Pensacola test points are slightly more humid conditions. Figure 5 provides the test cases for the Pensacola climate at the outdoor dry-bulb temperatures of 23.9°C and 40.6°C. The 23.9°C test case represents a mild humidity test case, while the 40.6°C case represents a high humidity test case. Figure 5 presents the dewpoint progression through the DOAS or the outdoor air, wheel outlet, and supply air dewpoint temperature. The assumed indoor dewpoint of the occupied space was 12.8°C, and thus both the high and mild humidity test case was supplying air below the indoor dewpoint temperature. Although not shown in the figure, the dry-bulb temperature for all test cases in cooling-reheating operation was maintained at approximately 21.1°C. Therefore in cooling-reheating operation the DOAS demonstrated the ability to effectively use the modulating hot gas reheat capabilities and provide neutral of 21.1°C air at a dewpoint lower than the space.

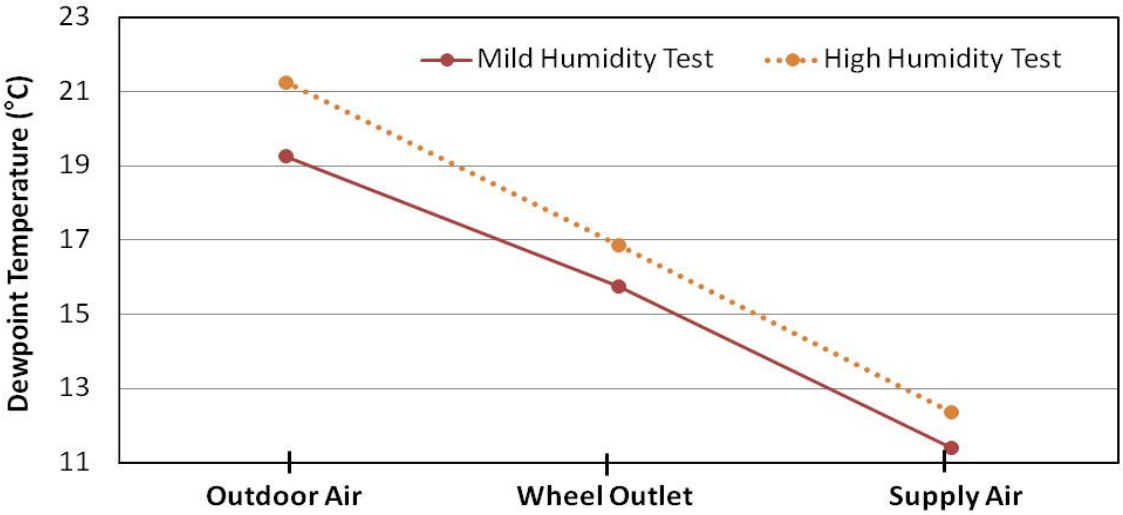


Figure 5: Dehumidification Progression by Dewpoint Temperature within DOAS

Figure 6 provides the peak power demand and energy consumption for all Pensacola test cases. Test cases are presented by the outdoor dry-bulb temperature along the horizontal axis. The peak power and energy consumption were determined by the ten minute data collection period. Both curves follow a similar trend as a function of outdoor dry-bulb temperature. As the outdoor dry-bulb temperature and humidity within the air increase, both the peak power demand and energy consumption increase.

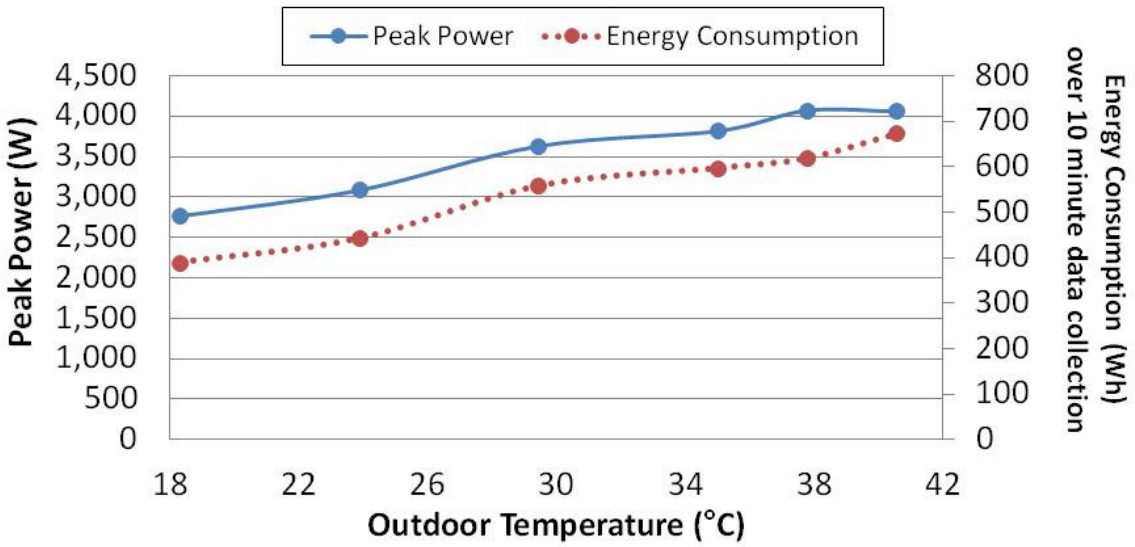


Figure 6: Peak Power and Energy Consumption of DOAS in Reheat Operation

Figure 7 provides the variable capacity compressor operation level for all Pensacola test cases. Figure 7 is meant to illustrate the ability of the variable capacity heat pump to adjust to the cooling-reheating load. Test cases are presented by the outdoor dry-bulb temperature along the horizontal axis. If the compressor was operating at nominal speed or full speed, then the operation level would be presented as 100% or 1.0. As seen in Figure 7, as the outdoor dry-bulb temperature (along with humidity) increased, the operating level of the compressor increased. During cooling-reheating operation, the compressor operated at higher levels than in heating operation. In cooling-reheating operation, the compressor was operating at an evaporator temperature below the dewpoint of incoming air and also supplying hot gas to be used for reheating. Because the compressor was operating at higher levels in cooling-reheating operation, the DOAS consumed more energy in cooling-reheating mode. At the peak outdoor dry-bulb temperature of 40.6°C, the heat pump DOAS operated at 100% capacity output, and thus the system can be considered properly sized for the peak cooling-reheating condition for the selected climates.

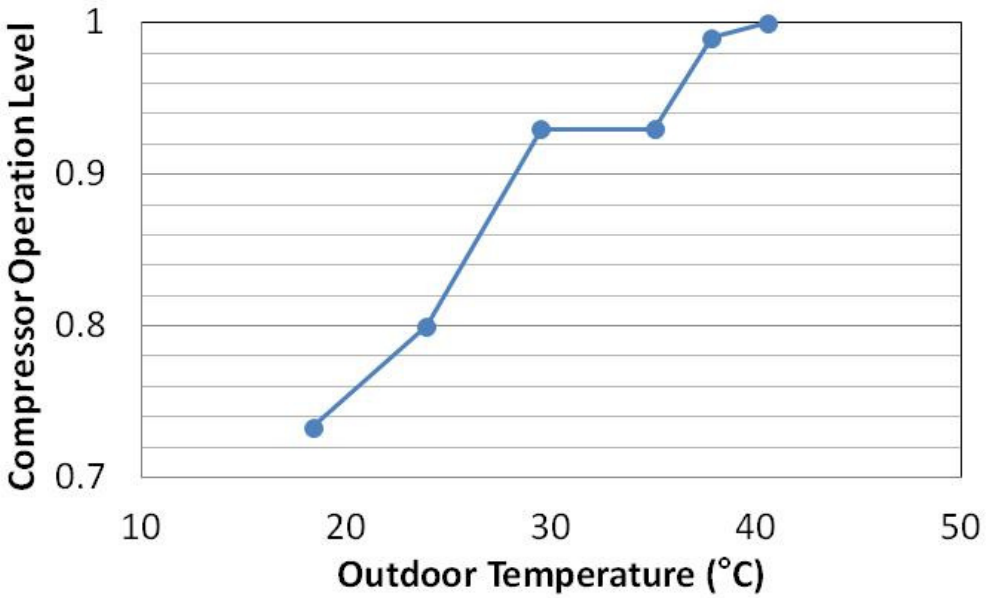


Figure 7: Variable Capacity Compressor Operation of DOAS in Reheat Operation

5 ANALYSIS

The analysis presented within this paper compares the laboratory results of the heat pump DOAS to a similarly operating DOAS using electric resistance heating. The DOAS comparison is made for a system operating to supply neutral air conditions of 21.1°C in both heating and reheating situations. For heating operation, the performance of the laboratory heat pump will be compared to electric resistance heating. For cooling-reheating operation, the modulating hot gas reheat capability of the laboratory system was compared to reheating with electric resistance heat.

5.1 Heating Operation

Table 3 provides an energy consumption comparison between the laboratory DOAS and a DOAS using electric resistance heating. The laboratory data of the heat pump DOAS is taken from the Atlanta heating test cases. The comparison is based on conditions identical to the laboratory testing with a constant air volume of 1360 m^3/h and maintaining a neutral supply temperature of 21.1°C. The energy consumption in Table 3 is based on a one-hour time frame. For electric resistance heating, energy consumption is presented both with and without the use of the performance of the laboratory tested enthalpy wheel.

Table 3: Energy Comparison of DOAS to Electric Resistance Heating

Outdoor Temp. (°C)	Laboratory DOAS (kWh)	Estimate with Electric Resistance Heat (kWh)	
		w/ Wheel	w/o Wheel
-9.4	2.05	3.74	14.49
-3.9	1.87	3.36	11.84
1.7	1.65	2.34	9.11
7.2	1.55	1.75	6.80
12.8	1.52	1.58	4.82

Based on the energy consumption comparison, the impact of the enthalpy wheel is further illustrated. The energy savings within electric resistance heating from without the enthalpy wheel to with an enthalpy wheel is approximately 74% at the lowest outdoor temperature of -9.4°C. The energy savings from the electric resistance heating with an enthalpy wheel to the laboratory DOAS is approximately 45% at -9.4°C. The energy savings from electric heat to the laboratory DOAS increases with decreasing outdoor temperature. The nominal size of electric heat comparable to the capabilities of the laboratory DOAS are approximately 7.5 kW. Therefore, the peak power reduction from electric heat with an enthalpy wheel to the heat pump DOAS is a reduction of approximately 7.5 kW to 3 kW or 65%.

5.2 Cooling-Reheating Operation

For analysis of the cooling-reheating operation, the laboratory data was compared to manufacturer data for standard operation of the DOAS. Standard operation or full capacity output is used to provide a standard system performance at an outdoor temperature of 35°C and 40% relative humidity. The laboratory test case which used this identical condition was from the Atlanta test matrix. This test point represents a peak summer and humidity condition. The standard operation manufacturer data assumes the unit is operating in cooling only mode. The manufacturer data for standard operation did not use reheat, so the impact of electric resistance heating was added into the standard operation. Based on laboratory

data from the Atlanta test point, the heat pump DOAS would operate at a peak power consumption of approximately 3.8 kW. From manufacturer data at standard operation and including electric resistance reheating to a neutral dry-bulb temperature, the unit would operate at approximately 7.4 kW. Thus the usage of modulating hot gas reheat compared to electric resistance reheating demonstrated a peak demand reduction of approximately 49%.

6 CONCLUSIONS

The heat pump DOAS evaluated under laboratory testing demonstrated an ability to provide neutral air in both heating and cooling-reheating operation for two climates in the Southeastern U.S, Atlanta, GA and Pensacola, FL. In heating operation, the heat pump DOAS supplied air at approximately 21.1°C down to an outdoor temperature of -9.4°C. In cooling-reheating operation, the DOAS supplied neutral air at 21.1°C and at a dewpoint lower than 12.8°C for extreme summer conditions. The enthalpy wheel within the DOAS demonstrated an ability to greatly impact the load that was needed by the heat pump system. The variable capacity heat pump demonstrated an ability to operate at reduced levels when the load was under the nominal output. Comparing the laboratory results to electric resistance heating alternatives illustrates the potential impact on peak demand reduction and energy savings. At the lowest outdoor temperature for laboratory testing, the laboratory DOAS demonstrated the potential to lower peak power demand by approximately 65% over electric resistance heating. For reheating applications at hot and humid conditions, the laboratory DOAS demonstrated a potential 49% reduction in peak power demand. The heat pump DOAS used in laboratory testing was slightly oversized for the maximum heating load and sized appropriately for the maximum cooling-reheating load for the selected climates. The laboratory tested heat pump DOAS could be applied in more northern cities where the heating load is somewhat greater and the cooling load is similar or slightly less.

7 REFERENCES

ANSI/ASHRAE Standard 62.1. “Ventilation for Acceptable Indoor Air Quality,” American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta.