Detailed performance assessment of variable capacity inverter-driven cold climate air source heat pumps

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Abstract. Enabled by the advancement and incorporation of inverter-driven compressors and controls, cold climate air source heat pumps (CC-ASHP) are being introduced in the Canadian marketplace. Such systems are capable of efficiently meeting space heating loads at much colder ambient temperatures in comparison to single speed compressor air source heat pump (ASHP) technologies and are additionally capable of efficiently modulating to meet heating loads at warmer ambient temperatures without cycling on/off. Coupled with their lower capital costs than ground source heat pump systems, significant interest in these systems has been generated; however their widespread adoption is hindered by the unknown performance and lack of tools to evaluate their energy saving potential.

This paper presents the results of detailed performance tests measuring the heating output and power input of two types of CC-ASHPs popular in the Canadian residential marketplace; a centrally ducted 3 ton split ASHP designed for whole house heating and cooling and a 1 ton ductless split ASHP designed for displacing zone heating and cooling requirements. The tests are completed by varying the outdoor temperature and indoor load (or compressor speed/capacity depending on the test approach) in climate controlled test facilities. The test results validate the systems' capability of efficiently heating at low ambient temperatures as well as modulating to meet more moderate part load conditions. However, several factors including the operating mode of the system as well as built-in protection controls for discharge temperature and pressure can serve to limit the maximum available heating capacity. Defrost settings can have a substantial impact on total system performance at cold temperatures. At mild ambient temperatures, relatively small heating load requirements can result in short cycling. The results highlight the importance of properly sizing and commissioning these heat pump systems for their application and indicate the type of data required to better simulate the performance and properly evaluate their energy saving potential.

Keywords: Air source heat pumps, air to air heat pumps, cold climate air source heat pumps, variable capacity, inverter-driven, cold climate.

1 Introduction

The Canadian residential sector accounts for 17% of Canada's secondary energy end use and 14% of the country's greenhouse gas (GHG) emissions [1]. Space heating represents 63% of this energy end use and space cooling represents only 1% of the residential sectors energy end use although the amount of floor space cooled through air conditioners has tripled since 1990 [1]. The use of heat pumps (HPs) to efficiently meet space heating and space cooling loads can be an attractive solution for reducing residential energy end use, especially if introduced through the space cooling market where HPs have little incremental cost over conventional air conditioners.

Conventional air-source HP (ASHP) systems often have difficulty providing sufficient heating capacity at the low outdoor temperatures common during a Canadian winter. With the advancement of variable capacity technologies, cold climate ASHPs (CC-ASHP) capable of efficiently meeting space heating loads at these low temperatures, have been introduced in the market. Previous studies [2, 3, 4] have shown that CC-ASHP systems can be a financially viable option for homeowners to reduce energy, utility costs and ultimately GHG emissions; however their exact performance characteristics and benefits are not widely known, which can hinder increased adoption. Some studies have been performed on field trialing CC-ASHPs; however their exact performance was often estimated from manufacturer performance curves [5] and thus a need was identified to better map the performance of these variable capacity systems.

CC-ASHPs come in two forms in the North American market: ducted and non-ducted systems. Ducted systems have the indoor coils installed in an 'indoor unit', which is connected to the ductwork delivering space heating and cooling throughout the household. Non-ducted systems have indoor coils inside one or several 'indoor unit(s)' mounted on the wall or ceiling to individually heat and cool a space(s). Through the variable capacity technology of CC-ASHPs, space heating loads can be met at low ambient temperatures while still providing the capability to modulate to low speeds (lower capacities) at warmer ambient temperatures. While these systems are claimed as being efficient, their actual performance, particularly at low ambient temperatures, is still largely unknown. Builders and design consultants have identified the need for a better understanding of these systems to increase market adoption.

Natural Resources Canada (NRCan)/CanmetENERGY laboratories in Ottawa, Ontario and Varennes, Quebec have built specialized test facilities to undertake performance tests on ducted and non-ducted CC-ASHP systems respectively, in order to:

1. Compare the manufacturer published performance curves to lab testing.
2. Acquire a wide range of performance data to develop robust simulation models for builders and design consultants.
3. Provide feedback on the proposed Canadian Standards Association Variable Capacity HP test draft standard [6] (CSAEXP07).
4. Identify potential areas of performance improvement.

This paper provides an overview of the test facilities, the measured energy performance and the observed operating limitations of both a ducted and ductless CC-ASHP.

2 Ducted and Ductless CC-ASHP Test Facilities

2.1 Ducted CC-ASHP Test Facility Description

The ducted CC-ASHP testing was undertaken using CanmetENERGY-Ottawa's Climate Controlled Test Facility. The facility consists of a "load and control station" with equipment that provides heating and cooling loads to the "indoor simulation" space, where the indoor side of the HP being tested is installed. The "outdoor simulation" space maintains the simulated outdoor ambient conditions and is where the outdoor side of the HP being tested is installed (see Fig. 1). The "tunnel air enthalpy test method arrangement" was used to measure the HP's capacity as outlined in the ASHRAE – 37 standard [7]. The "load and control station' was then used to impose maximum and minimum capacity loads on the HP to acquire the range of performance data.

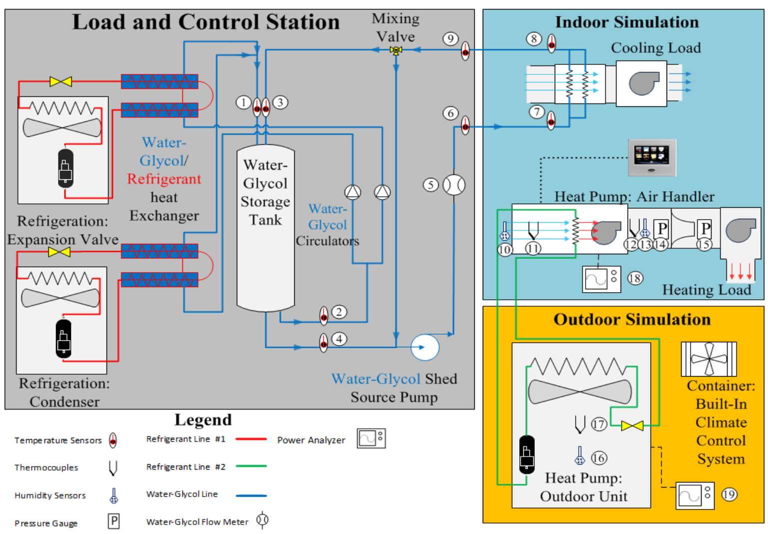


Fig. 1. Climate controlled test facility engineering schematic (heating mode)

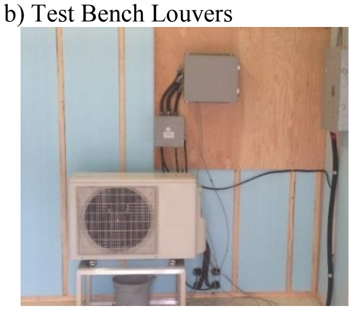
2.2 Ductless CC-ASHP Test Facility Description

Ductless CC-ASHP performance testing was conducted using an environmental controllable test chamber located at the CanmetENERGY-Varennes laboratory. The test bench consists of two insulated 3.6 m x 4.9 m x 3.6 m sheds equipped with three variable speed exhaust fans and intake louvers in order to induce heating and cooling loads using ambient conditions. The ductless split HP's indoor unit is installed in one shed representing the "demand side" (indoor shed), while the outdoor unit is installed in the second shed representing the simulated outdoor environment (outdoor shed) (Fig. 2). As no chiller was installed to induce a heating load on the demand side shed (indoor shed), performance testing could only be done when ambient temperatures were suitable (below indoor unit set-point).

a) Test Bench Exhaust Fans

b) Test Bench Louvers

c) Fully Instrumented Indoor Unit



d) Fully Instrumented Outdoor Unit

Fig. 2. Ductless CC-ASHP Heat Pump Test Bench

Performance of the HP is calculated according to the ASHRAE 37 standard [7] measuring the enthalpy difference and the refrigerant mass flow rate through the indoor unit. Enthalpies were estimated based on refrigerant temperatures and pressures measured and calculated using Coolprop [8] (Fig. 3). As the refrigerant temperature could be a liquid-vapour mixture entering the condenser, the heat output of the unit was also validated by measuring the inlet and outlet air temperatures and airflow rate. Power consumption and compressor frequency were measured with watt transducers and current transformers.

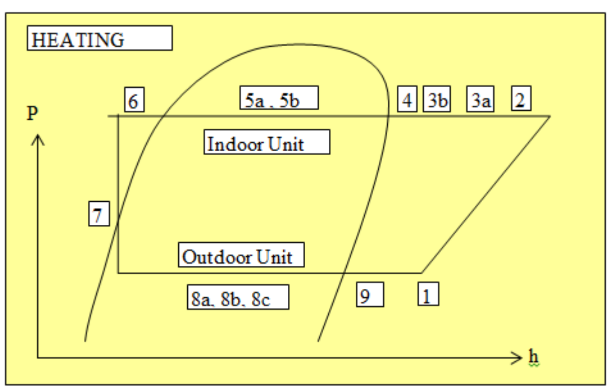


Fig. 3. Ductless CC-ASHP Refrigeration Cycle and Temperature Measurements

3 Ducted CC-ASHP Performance Testing

A market available ducted CC-ASHP system with a rated heating and cooling capacity of 10.3 kW at 8.3°C and 10.1 kW at 35°C, respectively, was selected for the ducted system testing. The system was chosen with the objective of meeting the majority of the design heating load of 7.8 kW at -25°C (estimated from simulation) of the Canadian Centre for Housing Technology (CCHT), a two storey high performance home. Performance tests on the HP were conducted to acquire the maximum and minimum heating/cooling capacity (based on steady state measured airflow and enthalpy difference between supply and return air streams) and COP across a wide range of operating temperatures. Additional longer duration tests were also conducted to facilitate exploration of defrost cycle impacts and different modes of operation.

3.1 Comparison with CCHT heating/cooling loads

Fig. 4 below compares the CCHT loads to the maximum and minimum measured capacity using the "as-shipped" default settings of the CC-ASHP tested (as measured during performance testing at the ducted CC-ASHP test facility). The shaded red area of Fig. 4 depicts heating mode while the shaded blue area of Fig. 4 depicts cooling mode. A white shaded area defines the area between the maximum and minimum capacity and includes capacity data for which COP is > 1. Any load that occurs above this area would require auxiliary heating or cooling and loads below this area would result in short cycling. Loads inside this area would result in normal operation. The heat capacity degradation from defrost is not taken into account in Fig. 4.

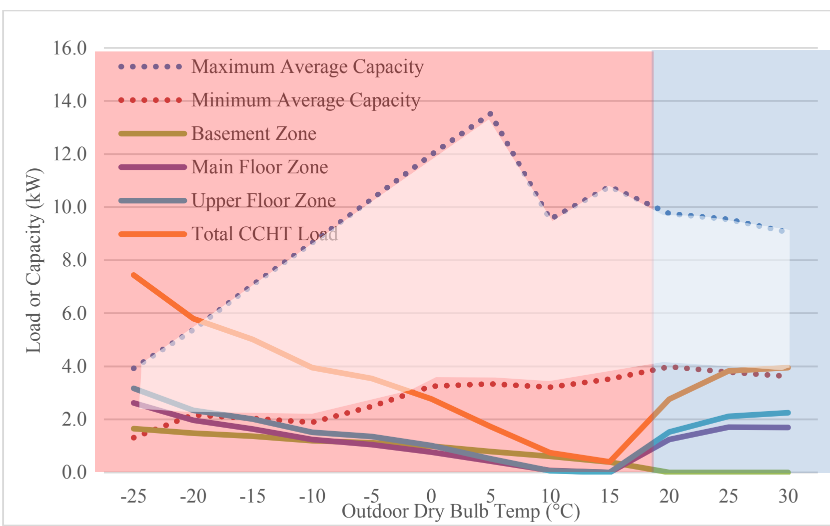


Fig. 4. Comparing Zone Loads at CCHT to Maximum and Minimum Measured Capacity of the CC-ASHP

Between 0°C to -20°C ambient temperatures in heating mode, one can see that the total CCHT load is within the maximum and minimum capacities measured. Above 0°C in outdoor temperature, the total CCHT load as well as individual zone loads are below the minimum capacity, implying the potential for on/off cycling. Below -20°C, the heat pump would operate at full capacity; however auxiliary heating would be required to meet the entire heating load.

In cooling mode, the total CCHT load is just above the minimum capacity measured at ambient temperatures above 25°C. However, the individual zone loads are each well below the minimum capacity of the unit, implying that individual zone loads would result in on / off cycling of the CC-ASHP. The degree to which individual zones would call for heating or cooling and thus result in on / off cycling would have to be assessed with detailed simulation.

3.2 Effects of Defrost Cycles on Maximum Capacity

Fig. 5 shows the impacts of defrost cycles on the maximum steady-state capacity when the unit is operated with a field selectable maximum defrost interval setting. Data are based on measured results. Defrost intervals were observed to be between approximately 1 and 1.5 hours and would last for a period of 1 to 16 minutes, depending on outdoor conditions. One can see that in the cold outdoor temperatures (i.e., -25°C to -10°C), capacity is reduced by 30-50% when defrost cycles are integrated into the test data. The degradation in performance is caused by the system injecting cold air into the zone, which needs to be reheated to maintain comfort conditions. Corresponding COPs (shown in green) in the cold outdoor temperatures are reduced by 20-30%. The effects of defrost become less pronounced as the outdoor temperatures increase (less frequent defrost cycles and for shorter durations) with no defrost occurring above 10°C ambient temperature. Note that return air to the indoor unit during defrost cycles often dropped below the 21°C typical return temperature, a condition unique to the testing undertaken. This may have served to over-state the impacts of defrost cycles on performance (modifications are being made to the lab to address this limitation).

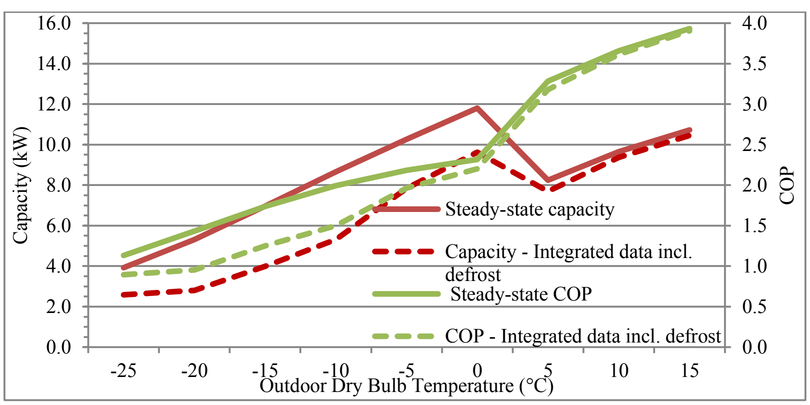


Fig. 5. Capacity and Coefficient of Performance of the CC-ASHP with and without Defrost

4 Non-Ducted Cold Climate Air Source Heat Pump Assessment

A market available ductless CC-ASHP system with a rated heating and cooling capacity of 4.0 kW (13,600 Btu/hr) at 8.3°C and 3.5 kW (12,000 Btu/hr) at 35°C, respectively, was selected for the ducted system testing. Testing was conducted from December 2016 to April 2017 in order to monitor the performance of the system under a wide range of conditions (ambient temperature and induced heating loads) in order to acquire sufficient data to develop a robust simulation model. The tests were also used to observe how the HP would perform if operated well beyond a typical load profile helping demonstrate the importance of properly sizing these systems for their application.

4.1 Monitored Ductless CC-ASHP Performance

Global performance results are given in **Error! Reference source not found.**, showing the heating capacity with respect to outdoor shed dry bulb temperature and compressor frequency. The ductless CC-ASHP was able to operate at very low outdoor temperatures below the manufacturer rated temperature of -25°C. The inverter-driven compressor also showed ability to modulate its frequency at different outdoor temperatures and heating loads, however, the frequency range seems partially limited. At mild outdoor temperatures, compressor frequencies higher than 75 Hz are rarely obtainable, and moreover, compressor frequencies lower than 20 Hz did not occur under any condition. Due to the limitations in the test bench being dependent on the HP unit to generate the cooling load in the outdoor shed, at test conditions below -20°C, only the maximum capacity was tested. It was also noted, that if the CC-ASH was not able to attain the desired indoor shed test temperature, the compressor would cycle to 75% of its maximum capacity regardless of the load to prevent the compressor from overheating.

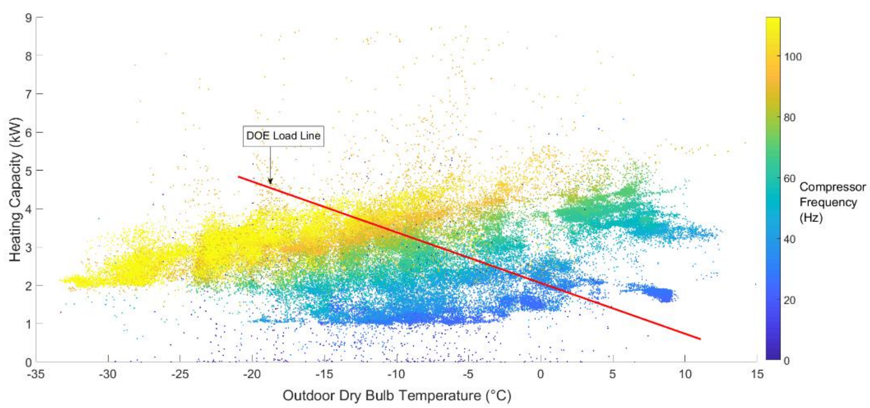


Fig. 6. Measured Heat Output versus Outdoor Dry Bulb Temperature and Compressor Frequency

The measured COP was found to be greater than 1.0 during normal test conditions and less than 1.0 when the heat pump would cycle into defrost. Fig. 7 plots the COP with respect to outdoor shed dry bulb temperature and compressor frequency. As seen, for equivalent outdoor temperature conditions, the COP of the system increases as the compressor speed reduces. However, it never operates below 20 Hz (20% of rated maximum compressor speed). This is of particular interest because if the heat pump is sized to meet the maximum heating load, it will begin to cycle at warmer ambient temperatures. Depending on the region, this could significantly impact the seasonal heating efficiency, and affect comfort conditions in cooling mode. Thus, it is critical to select a properly sized HP for the anticipated load to maximize the energy saving potential.

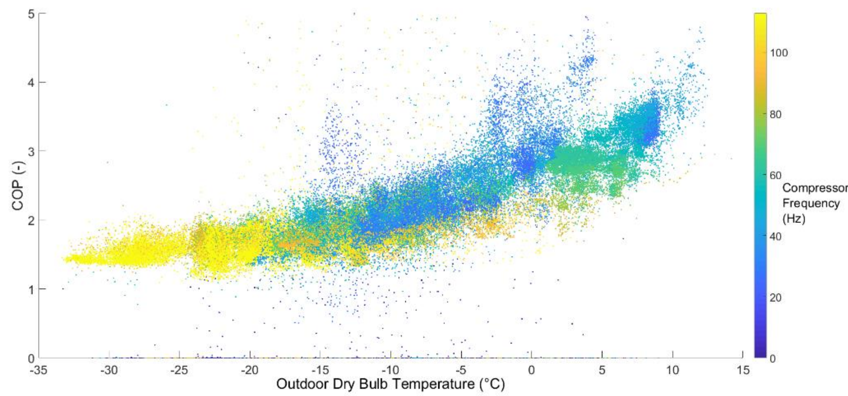


Fig. 7. COP versus Outdoor Dry Bulb Temperature and Compressor Frequency

Defrost intervals were observed to be between 2.5 to 2.0 hours depending on the ambient conditions and would last for a period of approximately 5 minutes. As such, the defrost would have minimal impact on the overall steady state capacity. It was noted however that when coming out of a defrost cycle the unit would operate at maximum compressor speed regardless of the ambient temperature condition.

5 Seasonal Coefficient of Performance in Heating (SCOPh)

The second objective of the testing was see how the CC-ASHP systems performed according to CSA EXP07 standard. While the test benches were not designed to meet the tolerances of the test standard, the test chambers could provide feedback on observed trends and challenges when conducting such a performance test. As such, loads were induced on the indoor coils at the respective outdoor air temperature as outlined in the standard. The SCOPh is then calculated based on the selected region and specified operating hours at each temperature bin interval and the annual heating load derived from the load curve prescribed in the draft standard. Table 1 summarizes the

SCOPh for various Canadian climatic regions at steady-state (no defrost) and with defrost included. The following additional assumptions were made:

1. Backup heat is electric and meets all of the load whenever the unit COPs drop below 1 and/or; the unmet portion of the load if there is insufficient HP capacity.
2. Improved COP at loads below the maximum capacity are interpolated between the COPs at maximum and minimum capacity for the ducted CC-ASHP tests.
3. Performance degradation due to cycling / standby power at loads below minimum capacity are not accounted for.

Table 1. Seasonal Coefficient of Performance for the Ductless CC-ASHP Tested According to the Proposed CSA EXP07 [5]

Climate Zone (HDD<18°C)	SCOPh (Ducted)		SCOPh (Ductless)		Canadian Region by Province / Territory
	steady-state	with defrost	steady-state	with defrost	
Marine (2500-4000)	3.34	3.21	3.09	3.04	Coastal BC
Cold/Humid (4000-5000)	2.31	1.96	2.23	2.13	Southern ON, QC, NB, NS
Cold/Dry (4500-5500)	2.57	2.23	2.38	2.28	Southern AB
Very Cold (5500-8000)	2.06	1.76	2.10	2.02	Northern BC, AB, SK, MB, ON, QC, NB, NS, NL, PEI
Sub Arctic (8000-9500)	1.63	1.42	1.72	1.67	Parts of YK, NWT, NU, Extreme North MB, QC, NL
HDD = Heating Degree Day					

The SCOPh results demonstrate the energy savings potential for a CC-ASHP in Canadian regions as compared to electric resistance based heating or high performance natural gas heating systems (maximum SCOPh of 1.0 and 0.98, respectively). The detrimental effect of defrost in the cold/humid region is seen, where over a 15% decrease in efficiency occurs due to the length and energy required for the ducted CC-ASHP system. In comparison to the ducted system, the defrost cycle of the ductless unit did not degrade the performance of the unit as significantly. Approximately a 3% decrease in the seasonal heating efficiency is seen in all regions.

6 Conclusion and Future Work

Enabled by the advancement of inverter-driven compressors and controls, CC-ASHPs are being introduced in the Canadian marketplace. Such systems are capable of efficiently meeting space heating loads at much colder ambient temperatures in comparison to single speed compressor ASHP technologies while also efficiently modulating to meet heating loads at warmer ambient temperatures with minimal cycling on/off. Coupled with their lower capital costs than ground source heat pump systems, significant interest in these systems has been generated; however their widespread adoption is hindered by the unknown performance and lack of tools to evaluate their energy saving potential. To address this, the NRCan/CanmetENERGY laboratories in Ottawa and

Varennes have built specialized test facilities to undertake performance tests on ducted and non-ducted CC-ASHP systems respectively, to acquire performance data and identify potential areas of improvement.

The maximum and minimum heating and cooling capacities at a wide range of simulated ambient temperature conditions were performed on both ducted and ductless CC-ASHPs. Testing showed that both CC-ASHPs were capable of efficiently operating well above a coefficient of performances of 1.0 confirming their energy saving potential in comparison to electric and natural gas space heating systems. Furthermore, the systems were capable of modulating efficiently to meet low heating load capacities, permitting efficient space heating operation at a wide range of ambient temperatures. However, it was also shown that the CC-ASHPs have a lower limit to their modulation capability before cycling on/off to meet the loads and as such it is important to properly size these units. Therefore, selecting a heat pump to meet the maximum space heating load condition is not always the most suitable design choice.

The effect of taking the defrost cycle into account in the heating capacity and COP was also shown. The higher capacity ducted CC-ASHP experienced a substantial reduction in capacity and COP, particularly at the coldest outdoor temperatures, resulting in up to a 15% decrease to system SCOPh. The smaller capacity ductless CC-ASHP experienced a lower performance degradation of 3% in system SCOPh.

Future work will look to continue detailed assessments of CC-ASHP systems to gain more in-depth knowledge of the performance and control strategies. A design guide and simulation tool are being developed to aid designers and contractors in properly sizing and assessing the energy saving potential of CC-ASHPs for Canadian applications.

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