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In-Situ Performance of Cold Climate Air-Source Heat Pumps in British Columbia

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ABSTRACT

Heat pump performance ratings are based on test procedures that generally test equipment in a laboratory under steady-state conditions. These operating conditions rarely occur in the real world and because there is limited research on how this equipment functions in service, it is difficult to understand their true efficiency at partial loads and throughout the year. This study provides a better indication of the real-world efficiency of air-source heat pump retrofits in existing homes in coastal temperate to cold interior regions of British Columbia. Twenty ductless and central heat pump systems were monitored at eighteen distinct single-family residential sites from Vancouver Island to the interior of British Columbia. In-situ measurements of key heat pump system parameters and corresponding outdoor environment conditions were collected for each site over a one-year monitoring period. Some factors affecting heat pump performance were also explored, including indoor unit volumetric flow rates, equipment sizing, short-cycling, defrost control, supplemental heating, and installation considerations. Results from this study show that ductless heat pumps generally performed lower than manufacturer rated efficiencies and central ducted systems performed as rated, where variations in performance are discussed throughout.

INTRODUCTION

Air-source heat pumps are increasingly being used as an efficient means of interior space conditioning. Rather than converting heat from fuel, heat pumps use a compressor with refrigerant to draw heat from the outdoors during the heating season and reject heat to the outdoors during the cooling season. Heat pump efficiency is measured as the coefficient of performance (COP), which is the amount of heat provided to a space divided by the input electrical energy to power the fans and compressor. These systems have been known to operate at a COP of 3.0 to 3.5 in laboratory testing environments, with variations tied primarily to outdoor operating temperatures (Carroll, Chesser & Lyons, 2020). Heat pump performance ratings are based on test procedures that generally test the equipment in a laboratory under steady-state conditions. These testing conditions do not utilize the on-board algorithms that are an essential component of variable-speed systems during in-field operation (CSA Group, 2019). Because there is limited research on how this equipment functions in service, it is difficult to understand their true efficiency at partial loads and throughout the year. This study provides a better indication of the real-world efficiency of air-source heat pump retrofits in existing homes in temperate coastal to cold interior regions of British Columbia. Results from this paper are key takeaways from a larger report prepared by RDH Building Science Inc. (RDH, 2020).

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METHODOLOGY

Twenty heat pump systems (13 ductless and 7 central ducted) previously installed in existing single-family detached homes as part of retrofits were selected from Vancouver Island to the interior of British Columbia, ranging from ASHRAE Climate Zone 4 to 5. A variety of system sub-types were monitored including central systems with single or variable speed compressors, and variable speed ductless mini-split systems with either a single or multiple indoor units (i.e., multi-split). To qualify as a cold-climate heat pump, a minimum Heating Seasonal Performance Factor (HSPF) greater or equal to 10 is required for ductless systems and 9 for central systems, respectively (Desai & Wu, 2022).

Field Data Collection

System & Fan Consumption Power and energy meters with current transformers were installed to measure the total heat pump system, indoor unit fan and supplemental heating consumption. Energy consumption from central heat pump supplemental heating systems (i.e., electric resistance heating coil) were measured in all applicable instances. Electric baseboards as a supplement to ductless units as well as other means of supplemental heat (e.g., propane, wood-burning stove, etc.) were not measured as they were outside the general scope of this study. Linux-based cellular modems were installed in each home to facilitate collection and cloud-based transfer of the data.

Air Temperature & Relative Humidity Sensors measuring air temperature and relative humidity were installed in the airstream of the return and supply louvers of each ductless heat pump indoor unit. For central systems, sensors were installed within the supply and return ductwork near the central unit (see Figure 1). On-site measurements of outdoor ambient air temperature and relative humidity were collected to correlate heat pump efficiency with outdoor operating conditions.

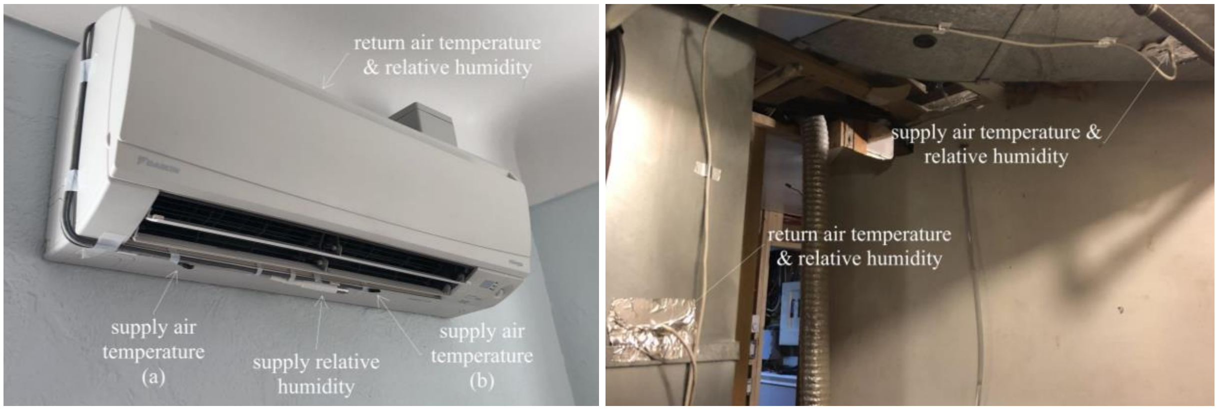

Figure 1 Temperature and relative humidity sensors placement for ductless (left) and central (right) systems.

Airflow Measurements For central systems, the cumulative flow rate was measured at all supply louvers with a powered flow hood for each fan setting. The volumetric flow rate of ductless indoor units was measured at each fan setting during the initial site visit (see Figure 2). Indoor unit fans were sub-metered throughout the monitoring period and their power demand was used as a proxy for fan speed, to which measured flow rates were assigned depending on the fan speed setting (Williamson and Aldrich, 2015). Note that filters were cleaned prior to testing and occupants were encouraged to clean filters monthly. The method used to determine the volumetric flow rate of ductless indoor units is as follows:

1. Seal an airtight box around the supply louver and connect a flexible duct from the box to a variable speed test fan
2. Measure both pressure difference inside box in relation to the ambient indoor environment and pressure difference across the test fan with a dual channel manometer
3. Adjust test fan speed until pressure difference is null between airtight box and indoor ambient environment (i.e., until flow of variable speed fan matches heat pump fan)
4. Record volumetric flow rate across the test fan as the flow rate of the indoor unit.

Figure 2 Volumetric flow rate measurement configuration for ductless indoor units.

Field Data Analysis

Heating & Cooling Capacity The heating and cooling capacity, or energy output from the return to supply airstream was calculated using their respective psychrometric properties, which were derived from the measured dry-bulb temperatures and relative humidity (ASHRAE, 2021). The temperature difference between return and supply air, combined with the volume of air passing through the unit, results in the amount of sensible heat being supplied or removed by the indoor unit (Equation 1). Latent energy was included when the difference in measured conditions between return and supply air suggested that condensation had occurred on the evaporator coil (Equation 2). Note that a cooling cycle is expressed as a negative energy balance. The COP is then calculated by dividing the heating or cooling capacity by the heat pump electricity consumption.

$$\Delta E = \dot{V}_2 \rho_2 (h_2 - h_1) \tag{1}$$

$$\Delta E = \dot{V}_2 \rho_2 [(h_2 - h_1) - (W_2 - W_1) h_{w2}] \tag{2}$$

where

ΔE = energy balance
$\dot{V}$ = volumetric flow rate, m^3/s
ρ = density of moist air mixture, kg/m^3
h = specific enthalpy of moist air, kJ/kg
W = humidity ratio, kg/kg
h_w = specific enthalpy of condensed water, kJ/kg
1 = return air
2 = supply air

Heating & Cooling Cycles A cycle was defined as a period of heating or cooling when both the fan and the compressor were on and there was a temperature difference between return and supply air of at least 1°C (1.8°F) for ductless units and 5°C (9°F) for central units. These criteria were established to exclude periods when either the units were operating in a fan-only setting or if there was any difference in return and supply air temperature while the fan or compressor was off. For example, Figure 3 illustrates how at the end of a heating cycle, defined by the annotated gold box, a sharp spike in return temperature can occur as residual heat from the coil rises over the return temperature sensor due to the buoyancy of the warmer air. Without the exclusion criteria, these periods could be misrepresented as cooling cycles.

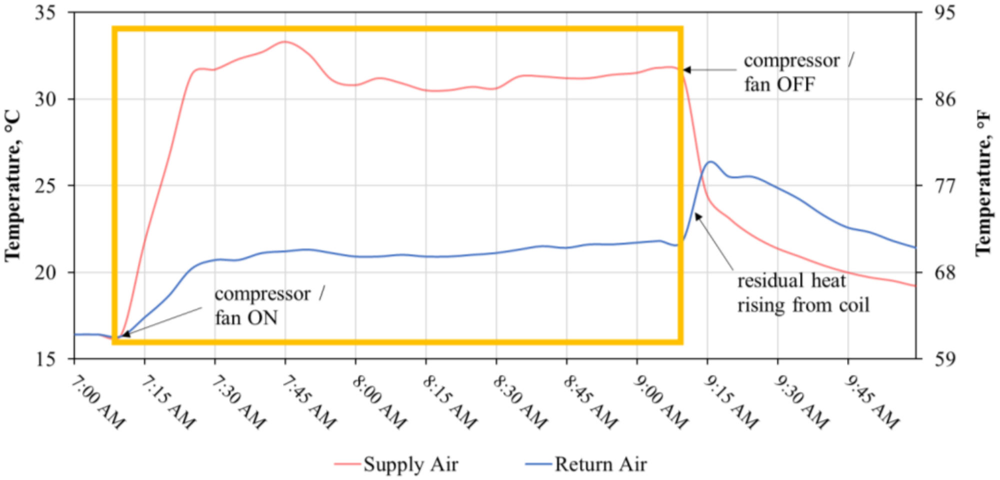

Figure 3 Sample heating cycle for ductless mini-split heat pump. The heating cycle is defined by the gold box, excluding residual heat rise from the coil exhibited after the compressor and fan are off.

RESULTS & DISCUSSION

Indoor Unit Flow Rates The volumetric flow rate of each pump was measured at all fan settings and compared with manufacturer data sheets. Table 1 shows that the majority of measured volumetric flow rates of ductless units were lower than manufacturer published data. The measured flow rates of the central systems were found to be relatively closer to their published data for most cases. Interestingly, differences in flow rates were also observed in many cases based on whether the units were in heating or cooling mode.

Table 1. Measured Flow of Indoor Unit Supply Air as Percentage Relative to Manufacturer Data

	Heating Mode	Cooling Mode	Central	Ductless
Maximum	79 %	100 %	100 %	93 %
Average	59 %	63 %	72 %	63 %
Minimum	20 %	24 %	46 %	20 %

Lower than rated volumetric flow rates for ductless units are likely due to current lab testing methodologies that typically exclude back pressure caused by the presence of the supply louvers. It was also found that many of the ductless indoor units were installed with limited ceiling clearance (less than 76mm or 3”), which may be restricting the flow of air to the return louver located at the top of the units (Figure 4). Interestingly, manufacturers listed minimum clearance ranges between 100mm (3.9”) and 30mm (1.2”). Limited ceiling clearances also presents greater risk of recirculating supply air through the return airstream, causing units to prematurely end their cycle (i.e., short-cycling). Premature mixing of supply and return air and short-cycling events were exhibited in some cases where indoor units were installed with limited ceiling clearance.

Figure 4 Ductless indoor units with limited ceiling clearance.

Heating Cycles The greatest degradation in the efficiency of residential air-source heat pumps has been observed when the compressor is working for cycles that are less than six minutes and therefore it is recommended that units run for at least eight-minute cycles (CSA Group, 2019). Findings showed that, on average, roughly 30% of ductless units from this study had operating cycles of eight minutes or less during their respective average outdoor winter operating conditions. However, when those units worked during extreme colder conditions, the ductless systems generally operated for cycles greater than ten minutes, suggesting that the units were oversized. Typical operating cycles for central heat pump systems were greater than ten minutes for both average and extreme cold winter conditions. It is also important to note that homeowners were not provided with any formal heat pump sizing documentation based on standard building heat load calculations.

Supplemental Heating The use of supplemental heating in central systems during the heating season varied between each home. Table 2 lists the total consumption breakdown of central heat pump systems, including total space conditioning, heat pump and supplemental heating. The table shows that the percentage of supplemental heat usage ranged between 1% and 15% for homes in Climate Zone 4, with an average outdoor operating temperature of 8°C (46°F). Interestingly, both buildings in Climate Zone 5 had similar total space heating consumption, though one system used 63% supplemental heat whereas the other did not require any supplemental heating, despite operating during similar average outdoor temperatures of 1.1°C (34°F) and 0.6°C (33°F), respectively. It was also observed that the central heat pumps had cut-off temperatures anywhere between 5°C (41°F) and -5°C (23°F). Given the absence of formal heat pump sizing documentation, the switch to solely supplemental heating for most units appears to be a conservative temperature-based set point rather than based on a heat pump capacity and calculated home heating demand.

Table 2. Total Consumption Breakdown of Central Heat Pump Systems

Climate	Space Heating, kWh (kBtu)	Heat Pump, kWh (kBtu)	Supplemental Heat, kWh (kBtu)	Supplemental Heat, %
4	1,488 (5,077)	1,445 (4,931)	43 (147)	3 %
4	1,128 (3,849)	1,117 (3,811)	11 (38)	1 %
4	1,574 (5,371)	1,344 (4,586)	230 (785)	15 %
4	1,024 (3,494)	902 (3,078)	122 (416)	12 %
5	3,009 (10,267)	1,114 (3,801)	1,895 (6,466)	63 %
5	3,520 (12,011)	3,520 (12,011)	-*	-

*central heat pump system did not include supplemental heating

Results show how supplemental heating is a less efficient means of delivering heat relative to a heat pump and should be reserved for instances when either the heating demand of the building exceeds the heating capacity of the heat pump (e.g., at cold outdoor operating temperatures) or when the heat pump refrigerant cycle temporarily switches to cooling during a defrost cycle. For example, Figure 5 is the energy consumption of the supplemental heating (i.e., electric resistance coil) relative to the indoor indoor fan and overall heat pump system consumption.

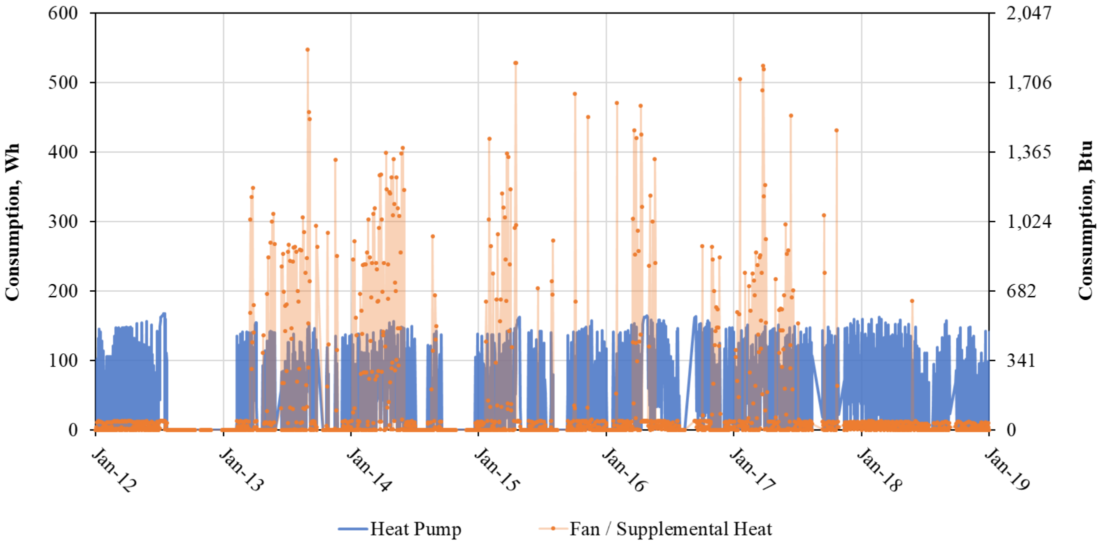

Figure 5 Example of overall central heat pump system, indoor fan and supplemental heat consumption for a sample week during heating season. Note that the fan consumption is consistently around 15Wh (50 Btu).

Defrost Cycle Condensation can occur on the refrigerant lines of an outdoor unit and turn to ice when the outdoor ambient temperature is around freezing, observed generally between -5°C (23°F) and 5°C (41°F). Heat pump units are typically equipped to remove this ice build-up by temporarily reversing the refrigerant cycle to deliver heat to the outdoor coil. Unless the heat pump is equipped with a built-in supplemental heating source (e.g., electric or propane heating element), the unit will temporarily provide cooling to the indoor space while in defrost mode. Though both ductless and central systems can be equipped with built-in supplemental heating during these cycles, they are more commonly found in central systems.

The defrost cycles for some ductless systems were estimated by isolating periods of sporadic cooling during the heating season (Table 3). Analysis suggests that the average defrost energy for ductless units was around 1% of the total heat pump consumption. Not all ductless heat pumps exhibited moments of cooling during the heating season as some units may have been equipped with built-in frost-control heating, which would be included in the total system consumption as they were not sub-metered. Also, because most central heat pumps were equipped with supplemental heating, it was not possible to determine whether supplemental heating was being used for either defrost or increased indoor heating capacity and was therefore not analyzed.

Table 3. Defrost Cycle Summary for Ductless Systems

Climate	System Consumption, kWh (kBtu)	Defrost, kWh (kBtu)	Defrost, %	Average Outdoor Temperature, °C (°F)
4	1712 (5843)	5.9 (20.1)	0.3 %	-0.6 (30.9)
4	899 (3068)	1.4 (4.8)	0.2 %	-2.0 (28.4)
4	1743 (5948)	2.2 (7.5)	0.1 %	1.3 (34.3)
5	1279 (4364)	1.6 (5.5)	0.1 %	0.9 (33.6)
5	1212 (4136)	1.8 (6.1)	0.1 %	0.9 (33.6)
5	1736 (5924)	19.1 (65.2)	1.1 %	-1.2 (29.8)
5	1185 (4044)	17.9 (61.1)	1.5 %	-3.7 (25.3)

Seasonal Cooling and Heating A summary of the estimated seasonal cooling efficiency of each system type compared to manufacturer data and corresponding average outdoor operating temperatures is presented in Table 4. Results show that the estimated seasonal cooling COP for all systems was greater than 4 and as high as 5.2 for ductless multi-split units. However, the average estimated Seasonal Energy Efficiency Ratio (SEER) was still lower than the average rated SEER in all cases.

Table 4. Average Seasonal Cooling Summary

System Type	Average Outdoor Operating Temperature, °C (°F)	Estimated COP	Estimated SEER	Rated SEER
Central – Single Stage (n=5)	23.9 (75.2)	4.1	13.7	14.8
Central – Variable Speed (n=2)	25.2 (77.4)	4.5	15.5	17.3
Ductless Mini-Split (n=9)	20.7 (69.3)	4.7	16.1	22.1
Ductless Multi-Split (n=4)	21.2 (70.2)	5.2	17.8	19.7

Table 5 is a summary of the estimated seasonal heating efficiency of each system type compared to manufacturer data and corresponding average outdoor operating temperatures. For this study, the estimated seasonal COP and Heating Season Performance Factor (HSPF) for central systems includes the performance both with and without supplemental heating. For example, as isolated units, the average HSPF of central heat pump systems was higher than manufacturer ratings. However, when the energy consumption associated with supplemental heating is included in the total efficiency of the systems, the HSPF was reduced closer to the manufacturer ratings. Although supplemental heating is not included when rating system efficiency, it provides insight to the total energy required by the systems to satisfy heating demand of the homes.

The average heating seasonal efficiency of mini-split and multi-split heat pump systems was lower than manufacturer ratings. Two likely reasons why ductless units are under-performing relative to their rated efficiencies are that the units, as discussed, have significantly lower than rated indoor flow rates and that they are being operated at relatively lower temperatures compared to central systems. Although the average outdoor operating temperatures are similar for all system types, the central heat pump systems did not operate below -7°C or 19°F (in some cases switched to supplemental heat at 5°C or 41°F), with the exception of one system that had not been equipped with built-in supplemental heating.

Table 5. Average Seasonal Heating Summary

System Type	Average Outdoor Operating Temperature, °C (°F)	Estimated COP	Estimated HSPF	Rated HSPF
Central – Single Stage (n=5)	5.6 (42.1)	3.2 (2.6*)	11.1 (8.8*)	8.8
Central – Variable Speed (n=2)	4.5 (40.1)	3.5 (3.3*)	11.6 (11.1*)	10.9
Ductless Mini-Split (n=9)	4.0 (39.2)	2.3	7.9	11.8
Ductless Multi-Split (n=4)	6.1 (43.0)	2.6	8.7	11.2

* including supplemental heating

Figure 6 is a scatter plot of the average heating and cooling COP at a range of outdoor operating conditions for ductless and central heat pump systems. For cooling, it is evident that occupants with either ductless and central systems are using active cooling at relatively milder outdoor temperatures compared to heating conditions, and in some instances when outdoor temperatures are below the typical indoor temperature range (i.e., temperatures where linear regression lines intersect roughly between 20°C or 68°F and 25°C or 77°F). Occupants appear to be using active cooling more often during the shoulder seasons when the COP of the units is highest, which corresponds with the overall higher average COP results for cooling compared to heating.

For heating, the greater performance of central systems relative to ductless systems is clearly shown by the scatter. As mentioned, this is partly due to the ductless systems being operated at lower outdoor temperatures, though even at temperatures above -5°C (23°F) the central systems are operating at higher COP. The plot also shows how all the central systems switch to supplemental heating around -7°C (19°F), except for one case (and the general trend) suggesting they could be operating at lower temperatures while maintaining a COP greater than 1.

Ductless units were generally able to maintain an average COP at or above 1 when operating to -14°C (7°F); however, two units failed to operate at a COP greater than 1 at temperatures below 0°C (32°F). Occupants of these units confirmed that they had issues with their heat pump units particularly throughout the winter and that significant refrigerant leakage was determined by service technicians as the main cause of poor performance, reporting a 70% loss of refrigerant in one case.

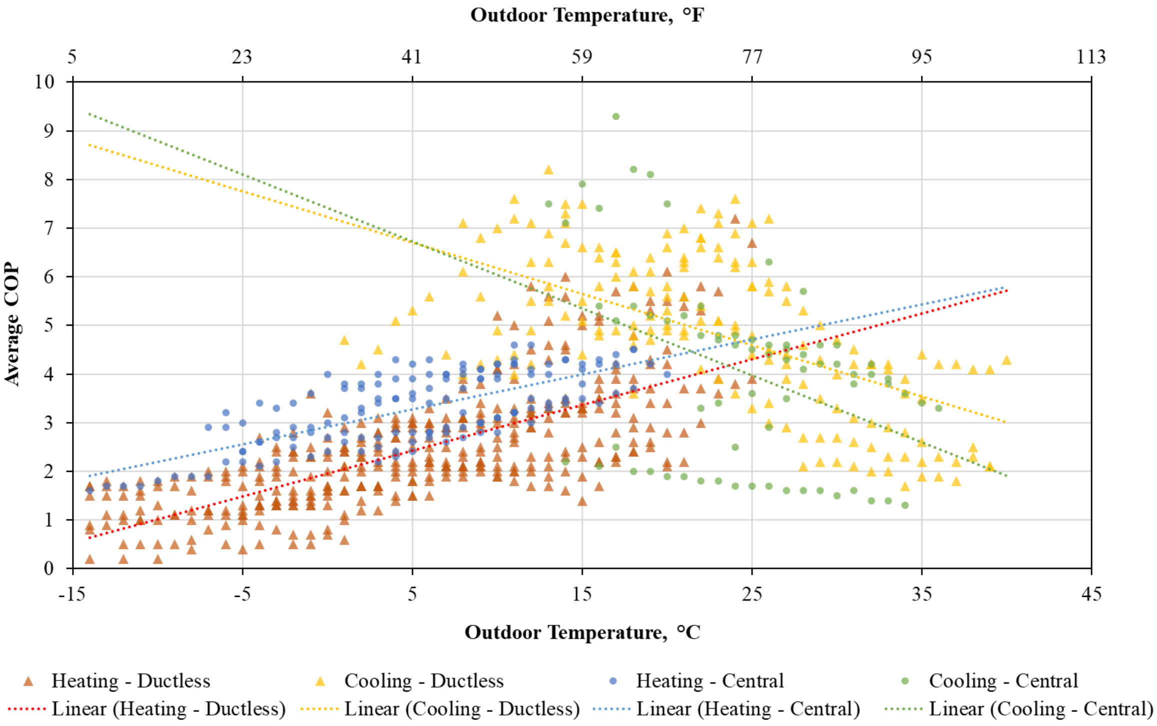

Figure 6 Scatter of average heating and cooling COP at a range of outdoor operating conditions for ductless and central heat pump systems.

CONCLUSION

Air-source heat pumps are becoming an increasingly popular option for space conditioning for their ability to provide efficient means of both heating and cooling. Rated performances of ductless ductless and central systems, measured under steady-state conditions, can fail to represent the performance of units installed, operated and maintained under a variety of conditions. The intent of this study was to provide a better indication of the real-world efficiency of air-source heat pump retrofits in existing homes in cold and moderate regions of British Columbia. Results from this study have shown that ductless heat pumps generally performed lower than manufacturer rated efficiencies, with an overall difference in performance of around 30%. Central systems generally met or exceeded manufacturer rated performance, even when energy from supplemental heating was included in total system consumption. During heating season, central systems operated during relatively milder conditions on average compared to ductless systems, as most central systems were set to switch to supplemental heating at a specified outdoor temperature. Results from the study suggest that some central heat pumps may be prematurely switching to supplemental heating given the absence of formal heat pump sizing documentation in all cases. In all, the examples from this study show how current rating procedures, sizing, installation practices and maintenance are important considerations for overall heat pump efficiency and can significantly affect the performance of units, particularly for ductless systems.

ACKNOWLEDGMENTS

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