RESEARCH HIGHLIGHT

December 2014 Technical Series 14-102

Performance Assessment of a Cold-Climate Air Source Heat Pump

INTRODUCTION

Most Canadians are familiar with air source heat pump technology in the form of air conditioners. In fact, air conditioners provide cooling in 52% of Canadian homes and in 80% of homes in Ontario alone.[1] Heat pump technology works by circulating a refrigerant between a compressor and an evaporator coil to pump heat from one location to another. Reversible heat pumps are capable of providing both cooling and heating by moving heat into and out of the home.

Cold climates provide a challenge for air source heat pump manufacturers. As the outdoor temperatures drop, it becomes more difficult for a heat pump to move heat from outdoors to indoors. The efficiency of the system suffers as a consequence, and backup heating is typically required at cold temperatures (below a threshold of -5 to -15°C for most conventional systems, depending on the system). Thanks to recent technological advances, a few systems now appearing on the Canadian market are specially designed for cold-climate operation: so-called cold-climate air source heat pumps. One such technology was recently evaluated at the Canadian Centre for Housing Technology in summer and winter.

The purpose of this set of experiments was to examine the performance of a cold-climate air source heat pump in an R-2000 house, its ability to maintain indoor air temperatures, and its energy consumption during cooling and heating season operation.

Figure 1 Outdoor section of the air source heat pump installed at the CCHT test house

[1] NRCan Office of Energy Efficiency, 2007 Survey of Household Energy Use (http://oee.nrcan.gc.ca/publications/statistics/sheu-summary07/air-conditioning.cfm?attr=0)

RESEARCH PROGRAM

The evaluation of the cold-climate air source heat pump (CC-ASHP) was carried out at the Canadian Centre for Housing Technology[2] (CCHT) in Ottawa, Canada. The unique nature of the CCHT twin-house facility not only allows for the examination of energy savings but also provides a complete picture of house performance.

Methodology

The CC-ASHP was installed in the CCHT test house (see figure 1). The CC-ASHP, with a 40,000 Btu/hr maximum capacity and rated heating seasonal performance factor of 9.4, was coupled with an air handler fitted with an electronically commutated motor (ECM). Backup heating (if required) was provided by a 10-kW electric resistance heating coil installed on the supply side of the air handler.

To examine cooling performance, during summer benchmarking, a 2-ton air conditioner with a seasonal energy efficiency ratio of 13 provided cooling in each house, circulated by an older furnace fan with a permanent split capacitor (PSC) motor (which is less efficient than an ECM motor) that was installed at the time in the experiment. During the summer portion of the experiment, the traditional air conditioner continued to cool the reference house, while cooling in the test house was provided by the CC-ASHP. The central thermostats were set to 24°C, and air was circulated continually at low speed by the furnace fan or air handler when not in cooling mode.

Following the cooling season performance assessment, to compare the energy consumption of the CC-ASHP to that of a typical heating system, the CCHT houses were benchmarked in winter under identical conditions, with heat provided by a new high-efficiency condensing gas furnace (94 % measured steady state efficiency) that had an ECM (note: summer testing was done with an older furnace that used a less efficient PSC fan motor). Subsequently, space heating in the test house was provided by the CC-ASHP, while the reference house continued to be heated by the benchmark system. Throughout the benchmarking and the experiment in winter, the central thermostats were set to 22°C, and air was circulated continually at low speed by the furnace fan with an ECM motor or air handler with an ECM motor when not in heating mode.

Furnace gas and electrical consumption, water heater electrical consumption, air conditioner electrical consumption, CC-ASHP electrical consumption, and room air temperatures were collected throughout the experiment and benchmarking periods.

FINDINGS

Cooling comparison

On average, during the experiment period, the CC-ASHP system produced 6.2 kWh (32%) in cooling energy savings per day (see figure 2). However, most of these cooling system savings resulted from the ECM motor in the CC-ASHP air handler. This motor was far more efficient than the benchmark furnace fan motor used for air circulation in the reference house and consumed 60% (6.0 kWh/day) less energy. The average consumptions of the air conditioner compressor and CC-ASHP compressor were similar.

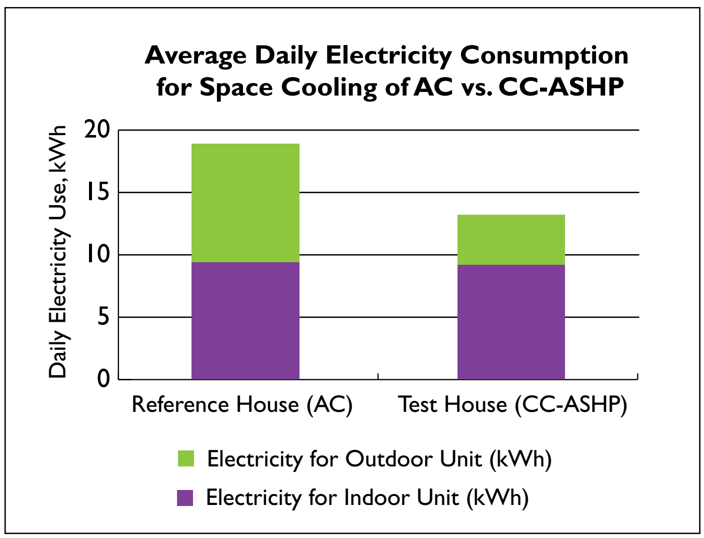

Figure 2 Average daily electricity consumption for cooling during the experiment period

[2] The Canadian Centre for Housing Technology is jointly operated by the National Research Council, Natural Resources Canada and Canada Mortgage and Housing Corporation. This research and demonstration facility features two highly instrumented, identical R-2000 homes with simulated occupancy to evaluate the whole-house performance of new technologies in side-by-side testing. For more information about the CCHT facilities, please visit http://www.ccht-cctr.gc.ca.

Indoor air temperature fluctuations during the cooling season were larger in the test house with the CC-ASHP than in the reference house with the traditional air conditioning system. The average daily fluctuation in the main-floor temperature in the test house was 2.9°C, while the average daily fluctuation in the main-floor temperature in the reference house was 1.9°C. This is likely a result of the thermostat control strategy that allows the CC-ASHP to operate for long cycles by having a large temperature deadband.

Heating comparison

During the heating experiment period, the CC-ASHP's backup resistance heating system was only required for defrost cycles. The CC-ASHP was able to meet all heating demands, even on the coldest day when the average outdoor temperature was -19.1°C.

On average, during the experiment, the air source heat pump system produced 182.2 MJ (49%) heating energy savings per day (see figure 3).

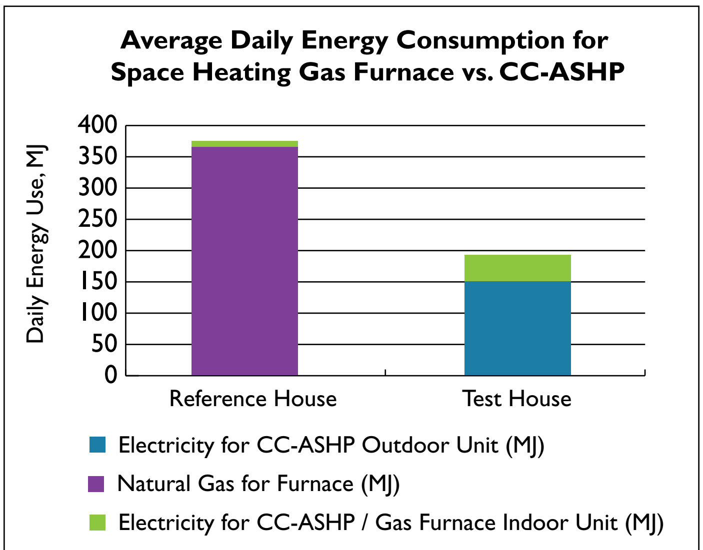

Figure 3 Average daily energy consumption for space heating during the experiment period

Annual performance

The coefficient of performance (COP) is a measure of the energy supplied divided by the energy consumed by the CC-ASHP. The COP for the CC-ASHP during operation by cooling summer conditions, heating shoulder season conditions and heating winter conditions is summarized in figure 4.[3] Note that the COP values referenced here include air handler fan electricity used to sustain low speed continuous fan circulation for ventilation.

One can see the COP values for the CC-ASHP ranged from an average of 2.4 at 20.4°C outdoor temperature to 3.7 at 28.3°C outdoor temperature during cooling season operation. Capacities ranged on average from 1.69 kW (5,766 Btu/h) to 6.11 kW (20,848 Btu/h) at these outdoor temperatures respectively. COP results in cooling actually increase with outdoor temperature due to the fact that the system spends proportionally less time in low speed continuous operation for ventilation purposes, which tends to decrease overall COP.

As expected, the CC-ASHP system operation was adversely impacted by cold outdoor temperature. This can be seen in the change in the COP. On the warmest day of the experiment winter heating period (when the average outdoor temperature was 10.3°C), the measured COP of the system was 3, meaning that the heat pump delivered three times as much heat as the energy it consumed. On this day, the system produced about 31 MJ in savings (52%). On the coldest day of the experiment winter heating period (average outdoor temperature of -19.1°C), the COP of the system was 1.5. While the magnitude of energy savings for this day was higher, at about 220 MJ, the percentage savings was lower, at 38%, given the lower COP.

The COP data calculated at "shoulder season" heating temperatures, above about 6°C, drops off substantially and even becomes negative, as shown in figure 4. This may be due to a number of factors identified: high solar gains offset the heat loss of the house and, therefore, very few calls for heating take place (and thus very little "useful" work is done

[3] COP results were calculated based on output power divided by input power. Output power is a calculated value based on the enthalpy difference between return air to the system and supply air from the system. Output power includes output heat provided by the auxiliary electric resistance heating element when it operated during defrost cycles. Note that the heat recovery ventilator (HRV) installed in the house had a fresh air supply that was connected to the return air system. Return air temperature therefore included the influence of fresh air supplied by the heat recovery ventilator. Input power includes electricity consumption of the auxiliary heating element occurring during defrost cycles as well as electricity consumed by the air handler during low speed continuous air circulation. These factors, as well as factors unique to the CCHT test house may result in performance data that differs from standard performance results according to CSA 656. Refer to the full report for a more detailed explanation of testing.

by the CC-ASHP); the continuous operation of the blower fan to maintain heat recovery ventilation (HRV) consumes energy while doing effectively negative work (that is, the HRV adds cool fresh air to the air stream, causing conditions in which the return air is slightly warmer than the supply air); and/or the CC-ASHP circulates refrigerant while the fan is running without the compressor, which may result in a very slight cooling effect of the supply air stream.

The winter heating season operation of the CC-ASHP also produced larger temperature swings in the test house than in the reference house. On average, the reference house main-floor temperature was maintained within a band of 1.6°C around the thermostat setpoint, whereas the test house main-floor temperature was maintained within a band of 2.8°C. As during the cooling season, this temperature fluctuation is likely due to the control strategy for the CC-ASHP. The thermostat deadband is large to allow for longer cycles of the CC-ASHP.

Operating cost

The cost of operating the CC-ASHP was compared to the cost of operating the benchmark system. The analysis was based on local energy costs for Ottawa in summer 2012 and winter 2012/2013. During the cooling season experiment, the CC-ASHP system saved an average of $0.75 per day, for cooling cost savings of 29%. Most of these savings are attributable to the use of an ECM for air circulation.

During the heating season experiment, at current average electricity prices that are about 200% higher than current average natural gas rates in this location, the operation of the CC-ASHP system required an additional $3.66 per day, for an increase of 124% in heating costs. It should be noted however that, if the CC-ASHP were compared instead to an all-electric heating system, cost savings of a magnitude similar to energy savings (~50%) would be expected. Similarly, were the CC-ASHP compared instead to fuel oil, the cost savings would be about 60%, and versus propane,

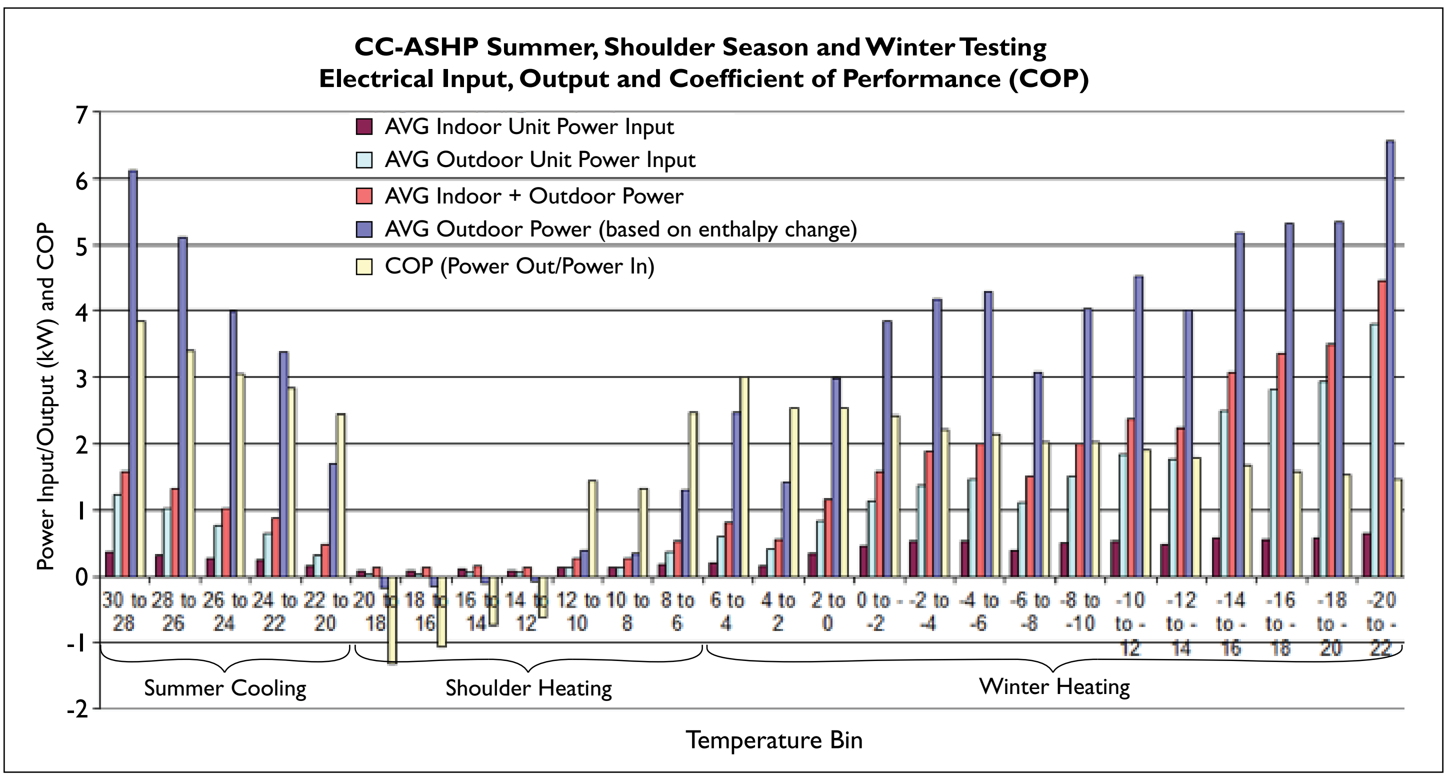

Figure 4 CC-ASHP annual performance testing electrical input, output and coefficient of performance

again about 60% (these being very expensive heating fuels). Further, if natural gas costs would return to the rates at which they were in 2006 (about double today's prices), the operation of the CC-ASHP system in heating would be about equal to that of the benchmark furnace.

Electricity
(source: Hydro Ottawa, January 2013 – prices include rate, transmission, Hydro Ottawa delivery, low voltage services charge, regulatory charges, debt retirement charge)

- Off-peak: $0.10674/kWh
- On-peak: $0.15274/kWh
- Mid-peak: $0.13674/kWh

Natural gas
(source: Enbridge, January 2013 – prices include cost, gas supply charge, transportation to Enbridge, cost adjustment)

- First 30 m^3: 24.66 cents/m^3
- Next 55 m^3: 24.20 cents/m^3
- Next 85 m^3: 23.84 cents/m^3
- Over 170 m^3: 23.57 cents/m^3

Fuel oil
(source: Statistics Canada, January 2013, prices for Ottawa)

- 129.5 cents/litre

Propane
(source: Ontario Ministry of Energy, January 2013, prices for Ottawa)

- 87 cents/litre

LIMITATIONS OF THIS STUDY

The impact of air source heat pump operation will vary for all different houses and mechanical setups. Care should be taken in applying these results to other homes, on account of certain attributes of the CCHT facility.

The following are some of the issues that should be kept in mind:

- The summer benchmark system included a PSC furnace fan for air circulation. As a result, it is likely that the cooling season savings realized thanks to the CC-ASHP were largely attributable to its air handler equipped with a more efficient ECM. Comparison to a standard cooling system with air circulation provided by an air handler or furnace with an ECM would likely have shown about equivalent energy use.
- The houses feature a heat recovery ventilator that runs continuously and uses the furnace fan in continuous circulation mode to distribute fresh air into the house while losing little heat. This is a feature of R-2000 houses, thanks to their high airtightness, and is not common in older, "looser" houses, where air exchange occurs without mechanical help and without heat recovery.
- The thermostat control strategy for the CC-ASHP in this project involved a large temperature deadband and long cycles of CC-ASHP operation. A control strategy with a small deadband would result in smaller daily temperature fluctuations. Additional testing, investigating thermostat functionality, would be needed to assess the impacts of such a control strategy.

CONCLUSIONS AND IMPLICATIONS FOR THE HOUSING INDUSTRY

Through these experiments, the CC-ASHP system was shown to have a significant impact on overall house energy consumption. The impact of a CC-ASHP operation will be different for all types of homes and mechanical setups. For this reason, it should be noted that these findings are valid for the CCHT twin houses, and an energy model should be used when projecting the results to other situations.

The CC-ASHP system assessed in these experiments was able to meet both the cooling needs and heating needs of the CCHT test house, a 210-m² home built to R-2000 standards.

Summer energy and cost savings from the CC-ASHP system were largely attributable to the use of an air handler with an ECM. In past experiments at the CCHT, ECMs have been shown to produce substantial energy savings for air circulation (~48%), compared to standard PSC split capacitor motors, and are becoming more common in new mechanical equipment.

Winter heating energy savings from the CC-ASHP were substantial (~49%), compared to those from a natural gas furnace. However, for the Ottawa region, the cost of heating by electricity with the CC-ASHP system was much higher than the cost of heating with natural gas. Regional fuel costs and availability should be taken into consideration in the choice of heating and cooling systems that produce both energy savings and cost savings for homeowners.

A full report on this project is available from Natural Resources Canada's CanmetENERGY or from the Canadian Centre for Housing Technology.

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Printed in Canada
Produced by CMHC 11-12-14