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Performance Investigation of Indoor Air Source Heat Pump Water Heater for Canadian Winter Conditions

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Abstract

Air Source Heat Pump Water Heater (ASHPWH) is a relatively new addition for delivering hot water at reasonable high efficiency. However, ASHPWH undergoes a considerable drop in its coefficient of performance (COP) under cold conditions and may face challenges to maintain the water temperature in the storage tank at over 55 ºC. In this paper, an investigation is reported on the performance of an air source heat pump water heater (ASHPWH), recently installed for this study at the Archetype Sustainable House, Woodbridge, Ontario, Canada. The experiments were performed for an extended period under controlled conditions to establish the impact of house's indoor parameters (temperature and humidity) on the performance (e.g., COP and energy savings) of these water heaters in a typical Canadian house. It was noticed that the COP varies between 1.5 and 5 for the range of indoor conditions, and the operational energy saving potential of this system is evaluated about three times than the conventional electric water heater.

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Key Words: Water heater; Air source heat pump water heater; Sustainable house; Experimental data; Coefficient of performance

1. Introduction

Water heating accounts for about twenty percent of energy consumption in Canadian domestic sector, and it is one of the biggest contributors to the greenhouse gas (GHG) emissions [1-2]. Efforts have been made to improve the efficiency of domestic water heating process by introducing several new and innovative processes/technologies, including air source heat pump water heater (ASHPWH) [3-4]. ASHPWH is a mechanical system driven by electrical energy, extracts heat from the surrounding air (indoor or outdoor

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depending on the location of the system) and transfers it to the water in the tank. These water heaters are considered compact (as the heat pump is integrated with water storage tank), safe, environment-friendly, operate year round, and produce the same volume of hot water with relatively lower operating cost [5-6]. Though, ASHPWHs are usually recommended for the hotter climates where these systems are installed in the unconditioned garage/porch and outside of the house, and provide excellent performance year-round [7].

The climatic conditions are different in colder countries (such as Canada), where for the most of the year, space heating is needed, and the temperature of ambient air is well below the freezing temperature for several months. Under cold conditions, ASHPWH undergoes a considerable drop in its efficiency and may face a challenge to maintain the water temperature in the storage tank at over 55 ºC to prevent the possibility of Legionella bacteria [8]. As a result, the installation of these water heaters in an unconditioned garage/porch or outside conditions is not an effective solution for the consistent performance in Canada [9-10].

In this study, the ASHPWH system performance was evaluated in the indoor space (conditioned basement) in a semi-detached Archetype Sustainable House (ASH) [11], and the heat is extracted from the interior of the house. The experiments were performed for an extended period under controlled conditions to establish the impact of house's indoor parameters (temperature and humidity) on the performance of ASHPWH. This paper has the following objectives: (1) establish long-term performance of this technology in a typical Canadian house by a systematic testing; (2) determine the values of coefficient of performance (COP) for a range of indoor conditions (ambient temperature and humidity); and (3) examine the savings in the energy consumptions for varied indoor conditions.

2. Experimental system, house and setup

Experimental studies were carried out over a recently installed ASHPWH system in the Archetype Sustainable House, Kortright Center, Woodbridge, Ontario [12]. The plumbing system and other modifications were made in the basement of the house to integrate the unit. The data acquisitions (DAQ) were designed and built to record and analyze the data for extended periods. The more details about the system, house, and experimental setup are as follows:



Fig. 1: Actual experimental system of tested ASHPWH

2.1 Air source heat pump water heater

The tested ASHPWH (Figure 1), has a self-contained heat pump, integrated on the top of the water tank, which absorbs heat from the surrounding air and transfers it to the refrigerant (R134a) inside the heat pump. The specification of the experimental system is shown in Table 1. The condenser is a coil wrapped around the water tank. The capacity of the system is 190 liters (50 US gallons) of water intended for single family residential use. The water temperature can be adjusted from 35°C to 60°C set point temperature. The system operates in four different modes: (a) Heat Pump mode, (b) Electric mode, (c) Hybrid (heat pump plus electric) mode, and (d) vacation mode (this operates in hybrid mode and maintain temperature at 15.6 °C).

Table 1: Specification of tested ASHPWH, supplied by system manufacturer

System		Dimension		Energy Factor		
	Capacity	Height	Diameter	HP Mode	Electric Mode	Hybrid Mode
ASHPWH	50 US gal	1.6 m	0.56 m	2.78	0.89	2.75

2.2 Archetype Sustainable House

The experimental investigation was carried out at the Archetype Sustainable House (ASH), Kortright Center, Woodbridge, Ontario. As shown in Figure 2, the ASH project is composed of two almost similar semi-detached experimental twin houses (House A and House B). These houses are equipped with different mechanical equipment and a state-of-art monitoring system with more than 300 sensors. The ASHPWH system was installed in the basement of House B, integrated with the plumbing of House B (Figure 1), and worked as a standalone water heating unit to meet the hot water demand of the House B.



Fig. 2: Southwest view of Archetype Sustainable Houses

2.3 Experimental setup

The monitoring facility used in this research was previously developed for the performance monitoring of other mechanical equipment. However, a modification was made in the existing data acquisitions (DAQ) system, which consisted of sensors, controllers, modules, connector blocks, power supplies, LabVIEW software platform and a central computer. The required experimental data such as indoor temperature and

relative humidity, inlet water temperature and flow rate, outlet/supply water temperature (tank water to the service), electric element and heat pump power consumptions and tank temperatures were collected. Six temperature sensors have been installed inside the tank at different elevations in order to estimate the average water temperature based on the readings of these six nodes. The maximum set point temperature for all the experiments was taken 55 °C. The total system error has been estimated based on the individual errors of all the measuring devices and their calibration results. MATLAB scripts have been developed to read the experimental data and analyze the thermal energy and coefficient of performance of the system along with their corresponding total error. Figure 3 displays the setup of the installed ASHPWH and sensors for the monitoring system. Table 2 provides a description of various sensor symbols of Figure 3.

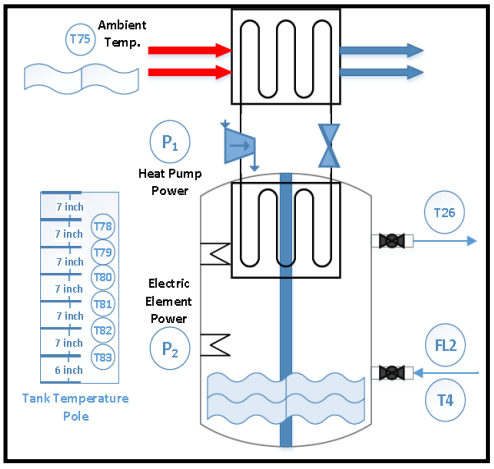


Fig. 3: Schematic of experimental setup and sensor location

Table 2: Description of symbols of experimental setup

Tag	Description	Tag	Description
FL2	Tank inlet water flow rate	T78	Tank water temperature probe 1 at 42" from top
P1	Heat pump power consumption	T79	Tank water temperature probe 2 at 35" from top
P2	Electric element power consumption	T80	Tank water temperature probe 3 at 28" from top
T4	Tank inlet water temperature	T81	Tank water temperature probe 4 at 21" from top
T26	Tank outlet water temperature	T82	Tank water temperature probe 5 at 14" from top
T75	Ambient air temperature	T83	Tank water temperature probe 6 at 7" from top
T77	HP evaporator coil surface temperature	RH22	Ambient air relative humidity

3. Experimental Results and Discussion

The water draw profile used in the experiments was 1-minute draw interval for 200 litres/day as per the IEA Annex 42 average draw schedule [13]. The water draw was considered for two full days schedule (48 hours) for each experiment. Figure 4 shows the water draw profile for the present study.

In order to analyze the performance of the ASHPWH, data for the basement air conditions was recorded along with the system parameters. The tank water started to heat up from 16 °C (supply temperature), and the

final set point temperature for all the experiments was fixed at 55 °C. The successive experiments were followed with two days of scheduled water draw profile as per Figure 4. The indoor conditions (air temperature and relative humidity) were chosen using the psychometric chart to represent the basement conditions of different types of houses (Table 3). The temperature and humidity of the basement air are maintained at constant values for each set of experiments (Table 3) by house's central heating/cooling system.

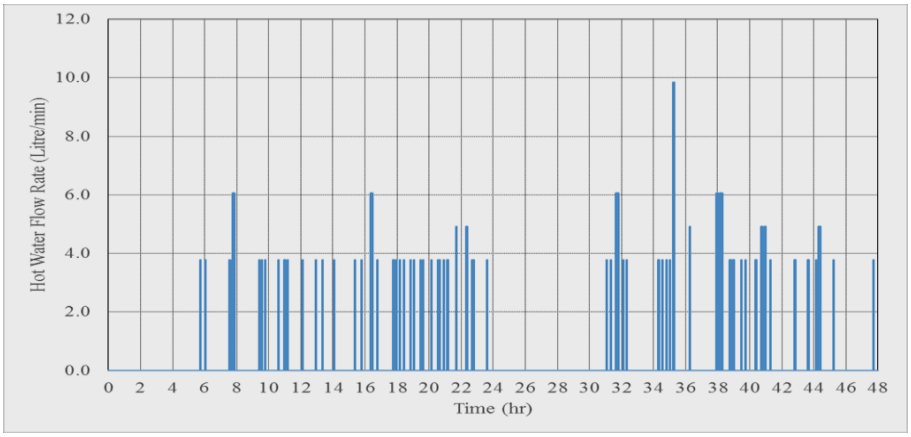


Fig. 4: Average daily hot water draws profile based on 1-minute time step

Table 3: Test conditions for experimental study

Mode of operation	**Test room air condition**		**Representative condition**
	Temperature (°C)	Humidity (%)	
Heat Pump Mode	19.7	50	Validate system performance
Electric Mode	15	70	Older house basement (cool and damp)
Hybrid Mode	20	35	Winter (heating) comfort condition
	25	50	Summer (cooling) comfort condition

To analyze the recorded data, MATLAB scripts have been developed. All the standard equations were programmed, the COP and the thermal energy delivered have been computed. The experimental data was confirmed with the manufacturer specifications to validate the results. The COP, Energy Factor, and electricity savings for different operational modes were analyzed and discussed. Figure 5 compares the calculated coefficient of performance (COP) from the experimental data to the manufacturer's laboratory performance data. Based on the error propagation analysis, the calculated error for the COP was estimated 2.8%. It is evident from Figure 5 that the experimental results are in a reasonable agreement with manufacturer's performance data. The minor discrepancy in the experimental results may be understood in terms of propagation error in the experimental data and some deviation in the ambient air conditions during the tests (due to the movement of the people in the basement).

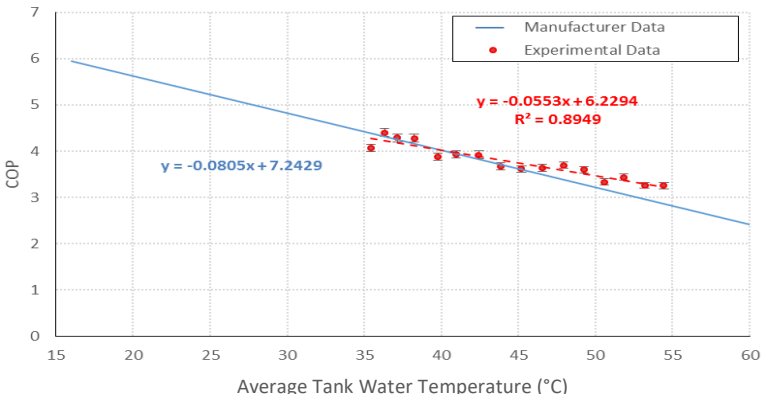


Fig. 5: Comparison of experimental data with manufacture's performance

*3.1. **Performance of ASHPWH***

The tank water heating from the cold start temperature to the final set temperature (55 °C) took about 4 to 8 hours for different experiments, depending upon the initial temperature of water and the ambient room air conditions (air dry bulb temperature and relative humidity). The water heating was performed only by the electric elements until the water temperature reached to 30°C, subsequently the heat pump continued the water heating until the set point was reached.

As apparent from Figure 6, the COP becomes relevant as soon as the electric heaters terminate their operation (at 30°C). The values of COP are plotted in Figure 6 for different sets of temperature and humidity as per Table 3. It is understandable from the Figure 6 that the experimental data are spread, as mentioned earlier it could be interpreted as the conditions in the basement are varied (due to the movement of people), and 2.8% propagation error in the test data. It is obvious that the ambient conditions make a significant impact on the system COP. Ambient air temperature is critical, but the humidity of air also played a part in the overall performance. As per the linear curve fit, the best COP was achieved for 20°C and 35% RH. In addition, as the temperature of water increases, a drop of about 15% was noticed in the COP for the selected temperature range.

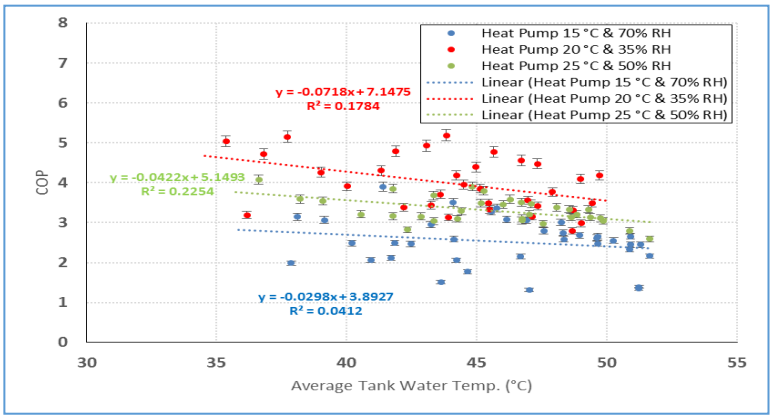


Fig. 6: HP mode coefficient of performance in three indoor conditions

3.2. *Energy Factor of ASHPWH*

A water heater's energy efficiency is defined in term of the energy factor (EF), which is based on the amount of hot water produced per unit of energy consumed over a specified time frame (day). Therefore, the greater the EF, the more efficient is the system based on the Natural Resources Canada Water Heater Guide (2012) [14]. The following equation is used for the estimation the energy factor of water heater,

$$EF = \frac{\dot{m}_{water} \cdot C_p(T_{out} - T_{in})}{P_{ASHP} + P_{Elec}} \quad (1)$$

In which $\dot{m}_{water}$ is the water withdrawal rate from the tank, C_p is the heat capacity of water, T_{in} and T_{out} are the temperatures of water at the inlet and the outlet of the tank, respectively. P_{ASHP} and P_{Elec} are the electricity consumptions in the heat pump and electric element of the water heater, respectively. Equation (1) is further simplified as per the symbols of Table 2,

$$EF = \frac{q \cdot \rho_{water} \cdot C_p(T_4 - T_{26})}{P_{ASHP} + P_{Elec}} \quad (2)$$

In which q is the volume flow rate of water, ρ_{water} is the density of water, and T_4 and T_{26} are the temperatures of water at the outlet and inlet of tank, respectively.

Figures 7 compare the EF for the electric and the heat pump modes of water draw schedule as per Figure 4. Based on the results, the EF for the ambient air conditions 15 °C and 70% RH (represents the winter basement conditions) is estimated 2.64 for the heat pump mode and 0.82 for the electric mode, which implies that while the useful transferred energy to the supplied water is similar, the value of consumed electrical energy for the electric mode is about three times more than in the heat pump mode. Figure 7 results are also additional confirmation of the EF of the water heater with manufacturer's specifications (Table 1).

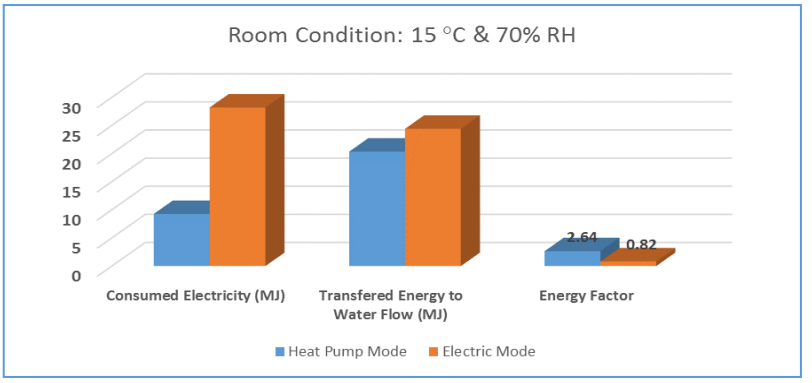


Fig. 7: Energy Factor in HP and electricity modes at 15 °C and 70% RH

*3.3. **Electricity cost reduction from ASHPWH***

In this research, the electric mode of the experimental system is considered as a representative of the traditional electric water heater. The cost associated with consumed electricity for all the modes of operation (Electric, Heat Pump, and Hybrid) will be calculated and compared. The electricity price used in the analysis is based on the Ontario's time of use (TOU) rates, presented in Figure 8 [15].

Tables 4 summarizes the results for the energy consumption for different modes for chosen indoor conditions. While, Table 5 summarizes electricity cost during two days of water draw for all three modes. It is comprehensible from the results for 15 °C and 70% RH, in the hybrid and HP modes the electricity cost will be reduced by 64% and 51% on summer heating and 64% and 49% on winter heating, respectively. On the other hand, in the hybrid mode compared to the HP mode, electric elements operate for longer times to maintain water temperature at the set point, therefore the saved electricity in hybrid mode is little less than HP mode and as a result, more electricity is saved. Figure 9 shows the distribution of the water draw schedule in various TOU electricity price zones. In summer, most water heating is performed during high TOU rate, whereas, in the winter it was done during the medium TOU rate.

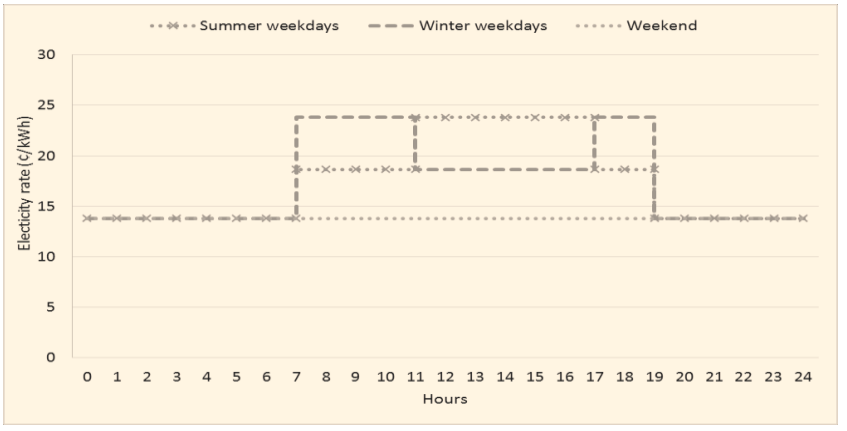


Fig. 8: TOU electricity rates in Ontario (Canada)

Table 4: Energy consumption (kWh) in 2-day water draw

Test Conditions	Electricity Consumption (kWh)		
	Electric Mode	HP Mode	Hybrid Mode
15°C & 70% RH	9.34	3.56	5.05
20°C & 35% RH	N/A	3.98	4.19
25°C & 50% RH	7.66	3.60	N/A

Table 5: Water heater electricity cost ($) in 2-day water draw

Test Conditions	Cost of Electricity Consumption ($)					
	Summer			Winter		
	Electric Mode	HP Mode	Hybrid Mode	Electric Mode	HP Mode	Hybrid Mode
15°C & 70% RH	2.04	0.74	1.00	1.96	0.71	0.99
20°C & 35% RH	N/A	0.84	0.88	N/A	0.79	0.83
25°C & 50% RH	1.57	0.75	N/A	1.53	0.71	N/A

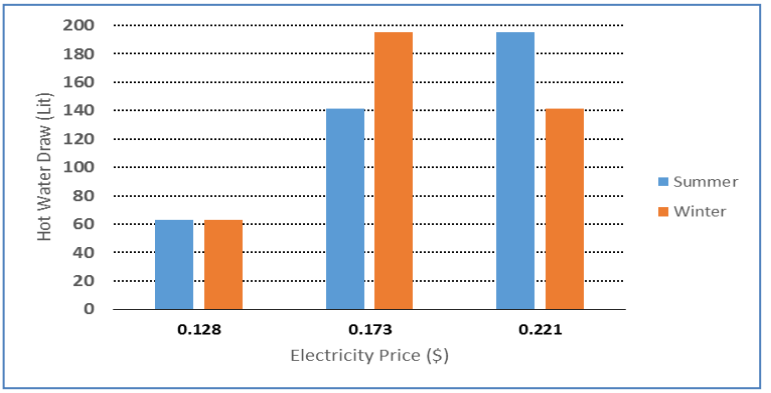


Fig. 9: The price distribution of the experiment's water draw schedule

4. Conclusions

The focus of this research was to investigate the performance of the air source heat pump water heater system in cold climate condition of Canada. The experiments were performed in the TRCA Archetype Sustainable House B in three different indoor conditions (dry bulb temperature and relative humidity) and three system modes (electric, HP and hybrid). Each of the indoor conditions is representative of the typical house condition encountered in Canada. Examining data from the experiments, it can be concluded that the COP of the system is changing mostly between 1.5 to 5 depending on the indoor dry bulb temperature, indoor humidity, average water temperature and water inlet temperature. As expected, by increasing the average water temperature, the COP reduces while in most of the cases the COP was higher for the experiments with higher indoor temperature in both Hybrid and HP modes. Although this system can operate more efficiently in warmer environments, the cold and damp condition of the room, representative of basement condition of older homes, does not deteriorate the performance of the system. One of the parameters in the evaluation of energy efficiency of the water heater is the Energy Factor. The calculated Energy Factor from the experiments for the heat pump and electric modes are 2.64 and 0.82, respectively. The estimation of cost for different modes for two days of water draw shows that the electricity cost of the water heating system can be reduced up to 64% in hybrid and HP modes respectively compared to the electric mode.

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Future Research

The future work will include: (1) development and validation of TRNSYS Type to model ASHPWH; (2) estimation of potential (including space heating and cooling in addition to DHW heating) benefits of ASHPWH for different Canadian housing types/vintages through detailed TRNSYS simulation; (3) optimal configuration

and control of ASHPWH with AHU/ventilation system and for demand response to further reduce energy demand and operating cost while maintaining thermal comfort.

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