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ENERGY PERFORMANCE COMPARISON OF THREE SPACE HEATING SYSTEMS: EXPERIMENTAL FIELD STUDY

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Abstract: Buildings (residential, commercial and institutional) are major energy consumers. The energy consumption of air conditioning systems such as space heating systems directly affects building energy performance. However, there are various systems available that can provide space heating; there are limited emparical data about their relative energy consumption. That is the necessary information for making system selection to achieve a high-performance building. This study aims to compare the energy consumption of three space heating systems: a heat pump, hydronic radiator heater, and electrical baseboard heater using experiment investigation. Two full-scale test buildings are used to conduct the comparison in which two of the space heating systems simultaneously run to deliver similar indoor air temperature. The result indicated that heat pump consumed 53% less energy compared to both hydronic radiator heater and electrical baseboard heater. Whereas, the electrical baseboard heater consumed 5.4% more energy than hydronic radiator heater. However, the result also indicated that the relative energy performance of the heating systems varies with the outdoor air temperature.

1 INTRODUCTION

Residential, commercial and industrial buildings are major energy consumers responsible for 40% of global energy usage (Olesen et al. 2011). Part of the energy used is for indoor air conditioning including heating/cooling and ventilation. In Canada, both residential and commercial buildings together account for 30% of the energy consumption (Lijun et al. 2008), and in the past two decades, the trend showed an increment (Cai et al. 2009). Therefore, there is a demand to improve building energy performance.

Improving building energy performance drives building sector to reduce heat loss through the envelope by increasing the U-value of the wall assembly, making the envelope more air tight and reducing the thermal bridge in the structure (Theodosiou et al., 2008). However, this isn't the only way where energy saving could be achieved. However, the building energy performance could be further improved by mechanical system heating/cooling (Schøtt et al., 2016). Relatively, the heating system is widely used in residential houses than the cooling system. Therefore, by selecting a heating system that consumes less energy, it is possible to reduce building energy consumption.

However, there are different mechanical systems that could deliver the desired space heating; the most common one is forced air system which combines space heating and ventilation. But, in the past the forced air system showed high energy consumption, which led to the practice of separating of space heating and ventilation systems. Krajcik et al. (2012) studied forced air heating system, and found that separating and treating ventilation as well as heating results in energy saving. However, there are different independent space heating systems available in the market.

One group of the space heating systems is hydronic/electrical heat distribution units of which hydronic radiator heater and electrical baseboard heater are members. Both the radiator heater and baseboard heater was tested in a climate chamber for a steady state condition while simulating winter conditions (Olesen et al. 1980). Moreover, radiator heaters combined with low-temperature heating system was studied in five occupied houses and found to be energy efficient (Hesaraki et al., 2013). That is why the use of both electrical baseboard heaters and hydronic heaters is expanding for residential buildings.

The heat pump is another type of space heating available in the market. There are two common types of heat pumps, ground source heat pump, and air source heat pump. The air source is mostly used for residential buildings because of the cost related to installation. Different types of heat pumps were studied for space heating/cooling in extremely cold/hot environment (Stefen et al., 2008). Moreover, air to water heat pump also studied using energy efficient building (Jacob et al., 2011). These two studies showed that pump is one of the efficient space heating systems.

Despite these studies, limited information is available regarding the relative energy performance of different space heating systems. Moreover, some of these studies were conducted in a controlled climate chamber. However, the weather is more dynamic and involves different elements such as rain, wind wash, snow, solar, unlike climate chamber. Therefore, this study aims to evaluate the relative energy consumption of heat pump, hydronic electrical heater, and electrical baseboard heaters in full-scale test buildings. In addition, the energy consumption of each system in contrast to the outdoor air temperature change was statistically analyzed and discussed in this study.

2 METHODOLOGY

The relative energy consumption of three space heating was studied using two identical full-scale experimental buildings at BCIT (Figure 1) simulating small independent or semi-detached buildings exposed to a similar real environment. Three field studies were conducted comparing heat pump(HP), Electrical baseboard heater(EBH), and hydronic radiator heater(HRH) systems. The comparisons are ERH Vs HP, FAH Vs ERH, and FAH Vs HP. In all tests, the systems run to provide similar indoor air temperature of 21^{O}C. Two of the three heating systems run side by side simultaneously. The energy consumption required to maintain the same indoor temperature of two test buildings were recorded, compared to each other, and analyzed. Before testing, the buildings were calibrated by running similar systems at the same indoor temperature, which helps to normalize thermal mass effect differences that may exist prior to testing.

3 FIELD EXPERIMENT SETUP

3.1 Test buildings

The test buildings are wood-frame construction with an overall dimension of 12ft x 16ft x 10ft, which includes a small mechanical room adjacent to conditioned space. The buildings (Figure 1) have two 3x4 ft^2 argon filled double glazed windows on the south and north walls and had identical wall and roof construction. The wall and roof assemblies have nominal thermal insulation values of R20 and R28, respectively. The buildings are constructed to be air tight with an effective leakage area of 0.48 cm2/m2 at 50 pa. Therefore, the buildings are categorized as air-tight buildings based on ASHRAE classification, since they are below 0.7 cm2/m2 at 50 pa (Tariku et al., 2010).

(a) South test building (STB) (b) North test building (NTB)

Figure 1: Whole Building Performance Research Laboratory (WBPRL)

3.2 Heating systems description

The test buildings are equipped with space heating systems that include an independent air conditioning unit for the mechanical rooms as well. The heating systems are a heat pump, hydronic radiator heater, and electrical baseboard heater. All of the heating systems installed resembling common practice. The heat pump has two parts: the indoor unit mounted on the mechanical room wall toward the conditioned space, and the other parts (compressor and evaporator) were on the roof top. The hydronic radiator heater was positioned infront of a south-facing window. The electrical baseboard heater is mounted on the wall under the south facing window. The capacity of the systems is 2.3kw, 1.5kw, and 1kw for heat pump, hydronic radiator heater, and electrical baseboard heater respectively (Figure 2).

Heat Pump Hydronic Radiator Heater Electrical Baseboard Heater

Figure 2: Heating Systems

3.3 Test Conditions

The indoor temperature was set to be 21^0C and Ventilation was provided through ceiling-mounted supply unit at a rate of 15cfm in which the incoming air is treated to 18^Oc. Whereas, the outdoor weather data was collected by a locally available weather station close to the test buildings. Two important elements of the weather were recorded; the horizontal solar radiation and air temperature. These parameters have a direct impact on the energy consumption of the heating systems. As shown in Figure 3, the solar radiation was high in the first experiment and second experiment. Following the solar radiation, the outdoor temperature also spiked during the day time. However, between the first and second experiment, there wasn't experiment. The energy consumption measurement was conducted for a total of four days, during which two of the systems were running simultaneously for each experiment. The energy management system employed in the buildings measured the energy consumption of the heating systems.

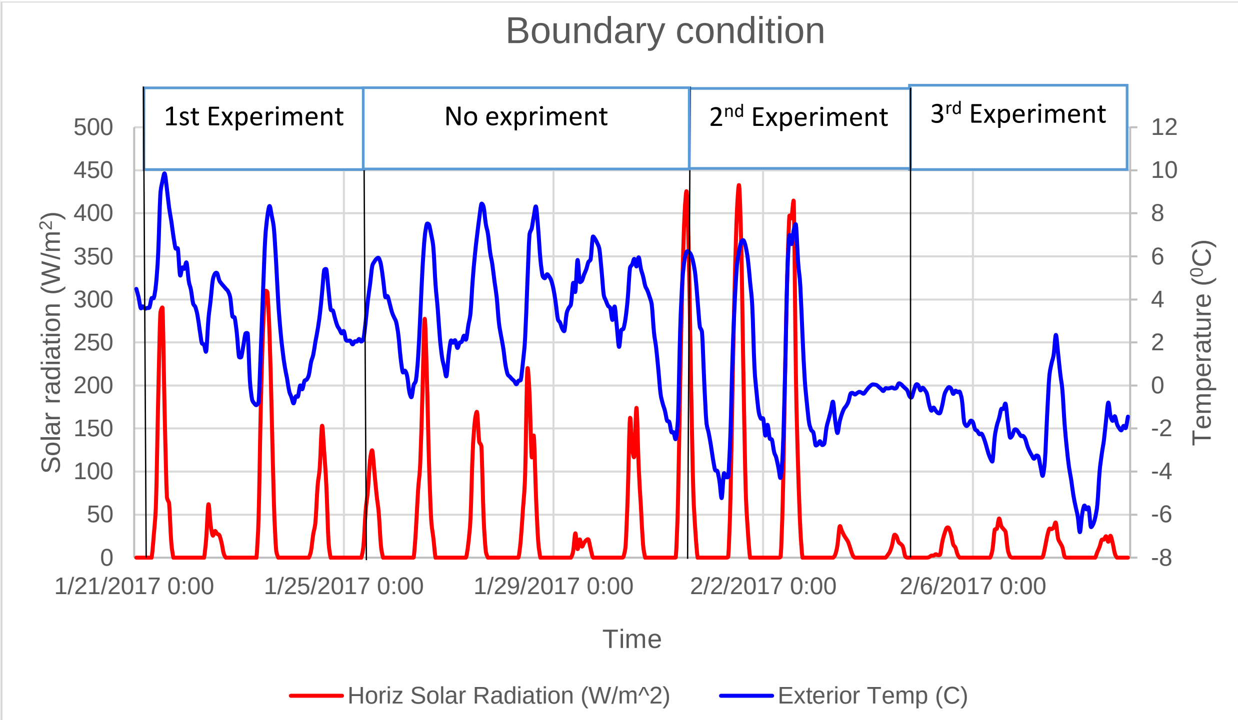

Figure 3: Indoor and outdoor climatic conditions during experiments

3.4 Results and discussion

In this sesction, the hourly total energy measurements results are discussed.

1. First Field Experiment: Heat pump vs Hydronic Radiator heater

Over the four-day period of the test the outdoor air temperature varied between -2.5^{O}C and 8.5^{O}C with an average of 2.5^{O}C, whereas, the average room remained above 19^{O}C in both buildings. However, energy consumption profile of the two heating systems (heat pump and hydronic radiator heater) was different. The energy profile of the hydronic radiator heater showed fluctuation throughout the test. In contrast, the heat pump energy profile showed smooth trend and change with outdoor air temperature, increasing when the outdoor air temperature fail and decreased when the outdoor air temperature increased. Despite the change, the energy consumption of hydronic heater remained unaffected by the outdoor air temperature (figure 4). In total, the hydronic radiator heater consumed 56.2kwh, conversely, the heat pump used 26.1kwh of energy. Relatively, the hydronic radiator heater consumed 53.5% more than the heat pump (Table 4).

The result also indicated that, when the outdoor air temperature was above the average, the total energy consumed by the hydronic radiator heater was 58.2% more than the heat pump. But, when the outdoor temperature was less than the average, the total energy consumption of hydronic radiator heater was 48.9% more than the heat pump. Furthermore, during the period when the outdoor temperature was below average, the total energy consumption of the heat pump was 23.5% more compared to when it was above average. Beside, the hydronic radiator heater consumed 6.6% more while it was below the average than when it was above the average (Table 1). The outdoor temperature was above the average on the days that the solar radiation was high (Figure 5). Therefore, the energy consumption of the heat pump was more affected by the outdoor conditions than hydronic radiator heater.

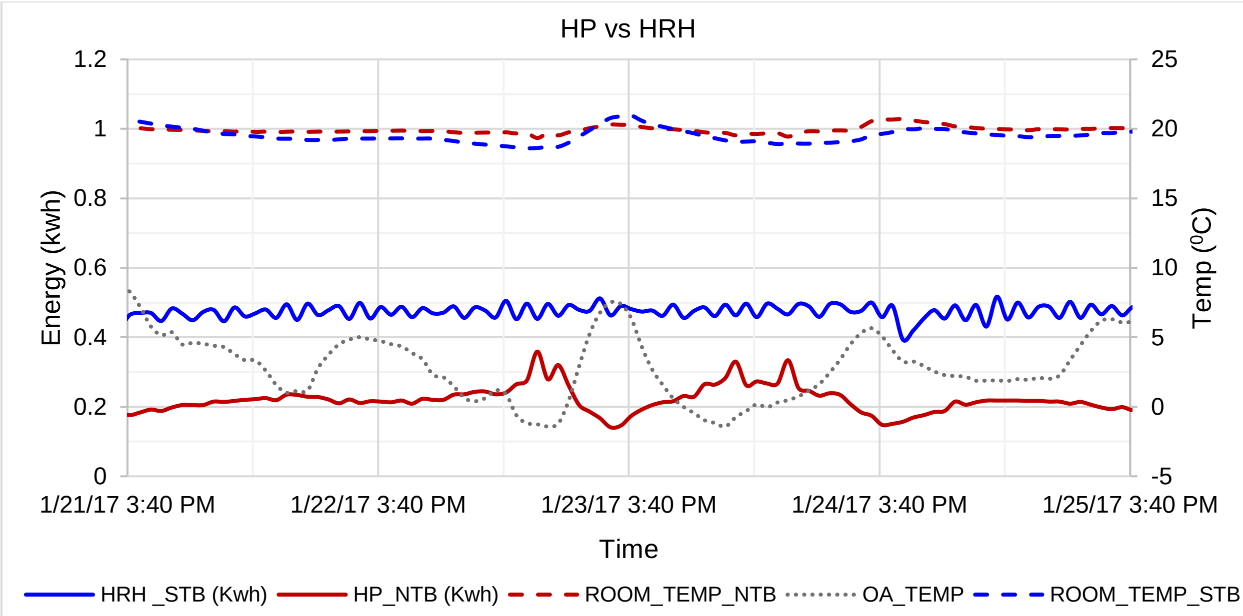

Figure 4: The hourly energy consumption of heat pump and hydronic radiator heater.

Table 1: First field experiment: the energy consumption of hydronic radiator heater and heat pump about average outdoor air temperature.

		Test Building	STB	NTB		
	OA Temp (^{0}C)	Heating systems	HRH	HP		
		When OA Temp	Energy (KWH)		Diff	%
Max	8.6	Above average OA	22.0	9.2	12.8	58.2
Average	2.5	average	0.47	0.22	0.25	53.5
Min	-2.6	Below average OA	23.58	12.0	11.5	48.9
Range	11.1	Difference	1.5	2.8		
		%	6.6	23.5		

2. Second Field Experiment: hydronic radiator heater vs. electrical baseboard heater

During the second test, the outdoor air temperature reached to -6.9^{O}C in the first two night of the test period and the average outdoor air temperature was -0.5^{O}C over the four-day measurement period. The average room temperature was above 20^{O}C for both buildings. The energy consumption pattern of the electrical baseboard heater and hydronic radiator heater showed a different trend, although the average consumption was very close. In the case of hydronic radiator heater, the energy usage fluctuated during four days; during the coldest period, the energy consumption peaked to 0.7kwh (Figure 5). Unlike the hydronic heater, the energy profile of the electrical baseboard heater remains smooth and varied with outdoor temperature when the outdoor temperature increased the energy usage decreased and vice versa. Moreover, the energy consumption rate also showed the electrical baseboard heater responded faster to the outdoor condition change than the hydronic heater. Overall, the two space heating systems use nearly similar amounts of energy; the electrical baseboard heater consumed 5.4% over the hydronic radiator heater. But, when the outdoor temperature was above the average the total energy consumption of the hydronic radiator heater was 4.8% more than electrical baseboard heater. Otherwise, when the outdoor temperature was below the average, the total energy consumption by the electrical baseboard heater was 9.6% more than the hydronic radiator. In the same period where the outdoor temperature remained below the average, the electrical baseboard heater consumed 5.1% more energy than when the outdoor temperature was above average

(Table 2). In the case of the hydronic radiator heater, it consumed 9.2% energy while the outdoor temperature was above the average. Therefore, the energy consumption of the electrical baseboard heater was less influenced by the outdoor temperature than the hydronic heater.

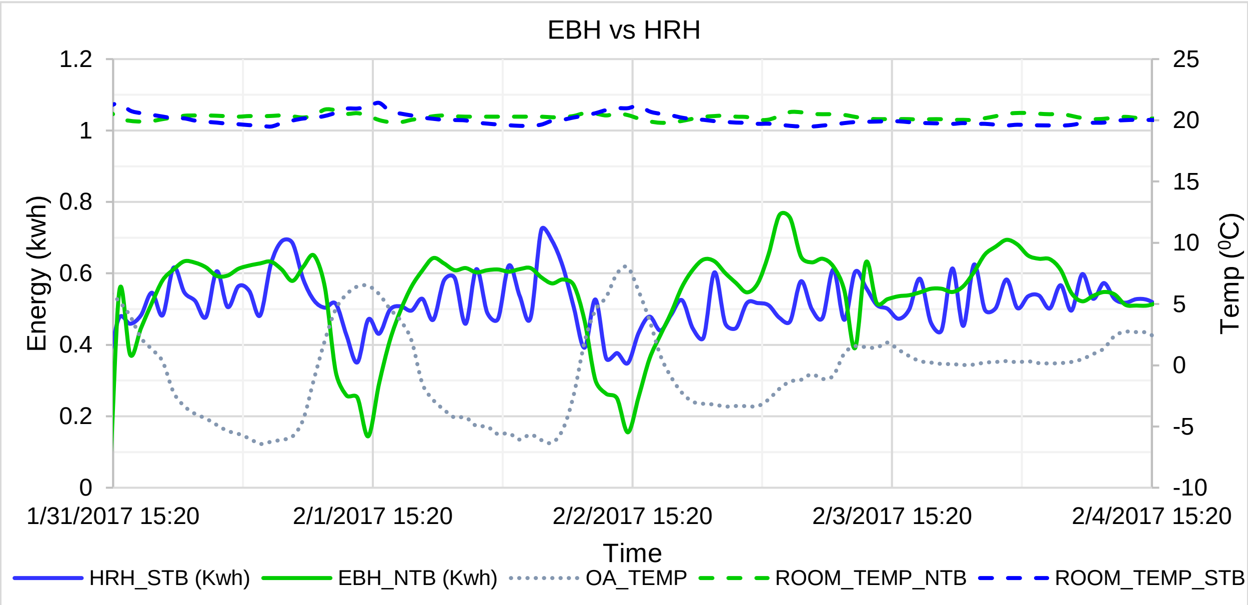

Figure 5: The energy consumption of hydronic radiator heater and electrical baseboard heater

Table 2: Second field experiment: the energy consumption of hydronic radiator heater and electrical baseboard heater about average outdoor air temperature.

		Test Building	STB	NTB		
	OA Temp (^{0}C)	Heating systems	HRH	EBH		
		When OA Temp	Energy (KWH)		Diff	%
Max	9.0	Above average OA	26.74	25.47	1.28	4.76
Average	-0.5	average	0.54	0.52	0.028	5.13
Min	-6.9	Below average OA	24.28	26.85	2.57	9.56
Range	15.9	Difference	2.46	1.3		
		%	9.21	5.14		

3. Third Field experiment: heat pump (HP) vs. electrical baseboard heater (EBH)

In the third experiment, both the heat pump and hydronic radiator heaters maintained the room temperature close to 20^{O}C. The outdoor temperature varied from -9 to 7^{O}C, and the average was -1.5^{0}C. During the majority of the measurement period, the energy consumption of the heat pump remained around 0.3kwh. But in the case of the baseboard heater, the energy consumption varied from 0.3 kWh to over 0.7kwh. Moreover, when the outdoor temperature increased above 0^{0}C, the energy consumption of the baseboard heater decreased more than the heat pump (Figure 6). Overall, the electrical baseboard heater used 55.4kwh of energy which is 53.6% more than the heat pump. The total energy consumption of the electrical heater baseboard heater was 56.1% and 52.5% more than a heat pump, when the outdoor temperature was below the average and above the average outdoor air temperature respectively. During the period when the outdoor air temperature was below average, the electrical baseboard heater consumed 9.9% more than when it was above the average. The heat pump used 4.8% when the outdoor air temperature was below average compared to when it was above the average (Table 3). Therefore, the energy consumption of electrical baseboard heater was more affected by the outdoor conditions than the heat pump.

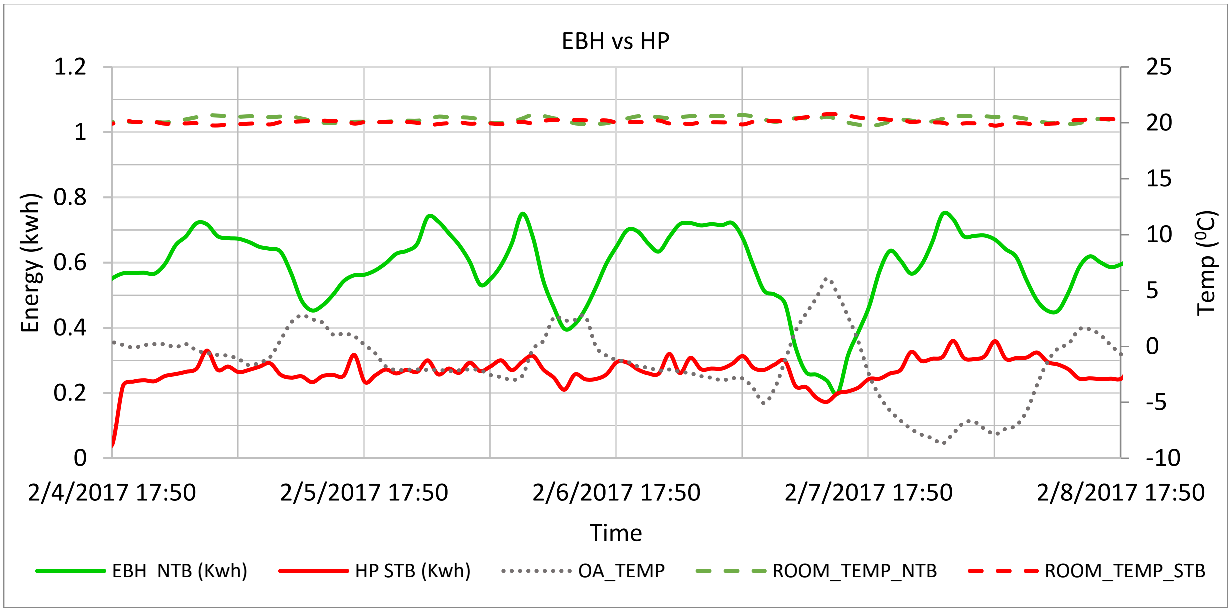

Figure 6: The energy consumption of electrical baseboard heater and heat pump.

Table 3: Third field experiment: the energy consumption of heat pump and electrical baseboard heater about average outdoor air temperature.

		Test Building	STB	NTB		
	OA Temp (^{0}C)	Heating systems	HP	EBH		
		When the OA Temp	Energy (KWH)		Diff	%
Max	7.0	Above average OA	12.64	26.62	13.98	52.53
Average	-1.5	average	0.26	0.58	0.31	54%
Min	-9.0	Below average OA	13.28	29.55	16.28	55.08
Range	16	Diff Difference	0.64	2.93		
		%	4.81	9.92		

Table 4: Field experiment results

Field test	Average OA temperature(^{O}C)	Building	Average room air temperature(^{O}C)	Heating system	Energy (KWH)	Relative Percentage(%)
Test 1	2.5	STB	19.5	HRH	45.0	53.1%
		NTB	19.9	HP	21.1	
Test 2	-0.5	STB	20.0	HRH	49.0	5.4%
		NTB	20.3	EBH	51.8	
Test 3	-1.5	STB	20.1	HP	25.7	53.6%
		NTB	20.3	EBH	55.4	

3.5 Conclusion

Various mechanical space systems are available for heating including heat pump, hydronic radiator heater, and electrical baseboard heater. The energy consumption of these systems affects the building performance. Therefore, the relative energy performance of the systems would be useful in system selection to achieve energy efficient building. The energy consumption of these three space heating systems are compared experimentally in this study.

- The outcome of this field study indicates that the both the hydronic radiator heater and electrical baseboard heaters consumed 53% more than a heat pump.
- The Electrical baseboard heater used 5.4% more energy consumed by hydronic radiator heater.
- The outdoor air temperature showed influence on the relative energy consumption of space heating systems.

The results indicates that the outdoor conditions such as air temperature and solar radiation have affected the relative energy performance of the heating systems. Therefore, further study is recommanded to study the impact of outdoor conditions on the energy consumption of heating systems.

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