Estimation of Reduction in Energy Consumption, Energy Cost and Greenhouse Gas Emissions Achieved through Gas-fired Absorption Heat Pump using a Calibrated Building Energy Simulation Model in eQUEST

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Abstract

This paper presents analysis of the impact of gas-fired absorption heat pump (GAHP) on energy consumption for heating and cooling of a library building in Canadian climate. A building simulation model for a gas-fired absorption heat pump (GAHP) installed at a library building in Tweed, Ontario was developed using eQUEST and calibrated using energy consumption data from the utility bills for the building from 2012–2014. The energy consumption, energy cost and greenhouse gas (GHG) emissions of the GAHP were compared with conventional HVAC equipment. After calibration, the eQUEST model was run for various cities and weather data in Canada. Results show that gas-fired absorption heat pump could have great potential for heating applications as a replacement for conventional heating equipment in Canada.

Introduction

The gas absorption heat pump (GAHP) is a type of heat pump that uses a natural gas burner to drive the absorption heat pump cycle. Absorption based heat pump cycle has been in use since late 19th century when electricity from grid was not readily available. The first mention of a heat pump based on absorption cycle appeared in U.S patent literature in 1909 while its commercial application in refrigerators started in 1920s. However, as the production, supply and use of electricity increased, electric heat pumps based on vapor compression cycle became prevalent (Miles et. al., 1993). Absorption technology showed resurgence in 1960s with application in air conditioning (Velasquez, 2002). The primary energy conversion potential of GAHP systems has been estimated to be as high as 150% if designed with a ground coupled heat exchanger, and up to 135% with an air based heat exchanger (Wu et. al., 2014).

A GAHP consists of a closed thermodynamic cycle, generally with an ammonia-water solution that acts as the working fluid. The principle behind the gas-fired absorption heat pump (GAHP) is the vapor absorption cycle in which the generator is directly fired by natural gas combustion. Except for the addition of a gas burner in the generator the rest of the heat pump has the same components as the absorption heat pump cycle, i.e., evaporator, absorber, generator, condenser and rectifier (in the case of ammonia-water working pair). The schematic of an ammonia-water gas-fired absorption heat pump is shown in Figure 1 (McLinden and Radermacher, 1985).

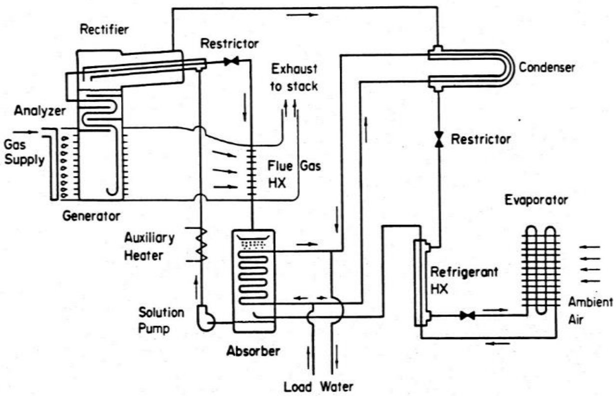

Figure 1: Schematic of an ammonia-water gas-fired absorption heat pump (McLinden and Radermacher, 1985)

This paper presents a simulation study, on the potential benefits of a GAHP installed at a library building, using eQUEST. The objective is to identify and quantify the potential benefits of gas-fired absorption heat pump for not only the site of installation but for various other Canadian cities as well.

The building under consideration is a single-story library building located in Ontario having 469.8 square meters area. The building is used as a library as well as a venue for community events (Baig and Fung, 2016). Three units of Robur GAHP-AR have been installed at the library and have been in operation since its construction in 2011. Installation of three units provides the HVAC system with the capability to modulate as individual units can turn “on” or “off” based on the demand rather than just one-unit cycling “on” or “off” as the demand increases or decreases throughout the day. Table 1 provides a summary for the major parameters of the building and the heat pump. Gas utilization efficiency (GUE), which is the ratio of thermal output to energy input from the burner, for the heat pump is 1.26 and 0.6 for heating and cooling respectively.

Methodology

Building energy simulation model was created in eQUEST using the parameters from Table 1 (Baig and Fung, 2016), equipment specifications and information regarding building construction. Subsequently the model was calibrated using the energy consumption bills from 2012 to 2014 for comparison. Table 2 shows the established criteria for calibration of building energy simuation models (Fabirizio and Monetti, 2015; FEMP, 2008; IPMVP, 2003)

Normalized mean bias error (NMBE) and coefficient of variance of root mean square error CV (RMSE) for building energy simulation models were calculated using (1) and (2) respectively (Reddy, 2015). Calibration results are shown in Table 3. As shown in Table 3 the NMBE and CV(RMSE) for calibration of simulation models developed for the GAHP installed at the library building met the criterion for calibration established by International Measurement and Verification Protocol (IPMVP).

$$\text{NMBE} = \frac{1}{\overline{\text{M}}} \frac{\sum_{i}^{n}(M_I - S_i)}{n} \qquad (1)$$

$$\text{CV (RMSE)} = \frac{1}{\overline{\text{M}}} \sqrt{\frac{\sum_{i}^{n}(M_i - S_i)^2}{n}} \qquad (2)$$

Table 1: Library building and GAHP parameters

Hours of Operation	
Sunday and Monday	Closed
Tuesday	9 am – 5 pm
Wednesday and Thursday	1 pm – 7 pm
Friday	10 am – 5 pm
Saturday	10 am – 3 pm
Electrical Design Loads	
Lighting	25 W/m^2
Air Handling Unit	3 @ 1467 W
Heat Pump	3 @ 2200 W
Computer Loading	2000 W
Temperature Set Points	
Cooling	Occupied: 25 ºC (77 ºF) Unoccupied: 28 ºC (82.4 ºF)
Heating	Occupied: 22 ºC (72 ºF) Unoccupied: 18 ºC (64.4 ºF)
Heat Pump (integrated package of three modules)	
Heating Capacity (per module)	10 tons (120,400 BTU/h)
Gas Utilization Efficiency (GUE)	Heating Mode: 1.26 Cooling Mode: 0.6
Operational Temperature Range for Heating Mode	Max: 35 ºC (95 ºF) Max: -20 ºC (-4 ºF)
Hot Water Temperature	Max to hydronic system: 60 ºC (140 ºF) Max inlet to unit: 50 ºC (122 ºF)
Cooling Capacity (per module)	4.8 tons (57,700 BTU/h)
Operational Temperature Range for Cooling Mode	Max: 49 ºC (120 ºF) Min: 0 ºC (32 ºF)
Chilled Water Temperature	Max to hydronic system: 3 ºC (37.4 ºF) Max inlet to unit: 45 ºC (113 ºF)

The calibrated simulation model was used to estimate the natural gas and electricity consumption for the library building in various Canadian cities corresponding typical weather data.

Table 2: Commonly used calibration criteria

Index	ASHRAE	IPMVP	FEMP
NMBE$_{month}$	± 5 %	± 20 %	± 5 %
CV (RMSE)$_{month}$	± 15 %	N/A	± 15 %
NMBE$_{hour}$	± 10 %	± 5 %	± 10 %
CV (RMSE)$_{hour}$	± 30 %	± 20 %	± 30 %

Table 3: Calibration results for GAHP simulation models

Year	NMBE (%)		CV(RMSE) (%)	
	Natural Gas	Electricity	Natural Gas	Electricity
2012	– 2.0	–4.0	– 16.1	–16.0
2013	–1.5	– 3.5	–15.2	– 15.0
2014	– 1.1	– 3.1	– 16.5	– 16.2

Equation (3) gives the savings achieved by using GAHP in heating season in terms of cubic meters of natural gas.

$$NG_{savings} = NG_{HVAC} – NG_{GHP} \qquad (3)$$

Similarly, for electricity the savings in kWh were calculated using (4).

$$E_{savings} = El_{HVAC} – Elect_{GHP} \qquad (4)$$

Overall energy savings in megajoules (MJ) were found using (5).

$$\text{Energy savings} = HHV_v * NG_{savings} + 3.6 * Elect_{savings} \qquad (5)$$

Using marginal cost and energy savings the cost savings can be determined using (6).

$$\text{Cost savings} = (NG_{marginal} * NG_{savings}) + (Elect_{marginal} * Elect_{savings}) \qquad (6)$$

GHG emission reductions was estimated using (7).

$$GHG_{reduction} = (GHG_{NG} * NG_{savings}) + (GHG_E * Elect_{savings}) \qquad (7)$$

Greenhouse gas emission factors for natural gas and electricity for Canadian provinces and territorites are shown in Table 4 (McCann, 2000) and Table 5 (NEB, 2017).

Table 4: GHG emission factors for natural gas in Canadian Provinces and Territories (McCann, 2000)

Province	GHG Emission Factor (gCO_2/m^3)
Alberta	1,928
British Columbia	1,926
Manitoba	1,886
New Brunswick	1,901
Newfoundland and Labrador	1,901
Northwest Territories	2,466
Nova Scotia	1,901
Ontario	1,888
Saskatchewan	1,829
Quebec	1,887
Yukon	1,901

Table 5: GHG emission factors for electricity in Canadian Provinces and Territories (NEB, 2017)

Province	GHG Emission Factor for Electricity (gCO_2 eq/kWh)
Alberta	790
British Columbia	12.9
Manitoba	3.4
New Brunswick	280
Newfoundland and Labrador	32
Northwest Territories	390
Nova Scotia	600
Nunavut	750
Ontario	40
Prince Edward Island	20
Saskatchewan	660
Quebec	1.2
Yukon	41

Results

Table 6 shows the energy savings achieved by using the GAHP in heating mode only. It can be seen that GAHP operation in heating mode results in considerable energy savings depending on the location and weather data for the city being considered. Energy savings in heating mode were found to be as high as 29% for Vancouver. The results imply that the GAHP could be a good replacement for conventional natural gas-fired heating equipment.

Table 7 shows the energy savings achieved by using the GAHP in both heating and cooling mode. Comparing with Table 6 it can be seen that the energy savings are far less than that achieved in heating mode only. In some cases, the energy savings are negative which means that GAHP operation in both heating and cooling mode for those locations would result in an increase in annual energy consumption of the HVAC system for the building under consideration. This is because of the relatively lower energy performance of GAHP in cooling mode as compared to the performance in heating mode. Also, conventional cooling equipment i.e., air conditioners, are more energy efficient than the GAHP under consideration in cooling mode. Hence, GAHP under consideration does not appear to be a viable option for replacing conventional cooling equipment.

Table 6: Energy savings achieved by using GAHP in heating mode only

City	Percentage Energy Savings in Heating Mode Only
Tweed	22.2%
Toronto	25.2%
Ottawa	21.4%
Thunder Bay	18.4%
Windsor	25.7%
Edmonton	19.9%
Fredericton	21.1%
Winnipeg	18.3%
Montreal	21.6%
Vancouver	29.0%
Regina	18.6%
St Johns	21.2%

The annual energy savings are affected by the heating and cooling degree days which in turn depend on the magnitude of frequency of temperature data points being below or above the reference temperature, respectively. However, for a building which has operational days and off-days the instances of operation of the heating and cooling equipment coinciding with temperatures relatively colder or hotter than the reference temperature respectively, also becomes a factor. This can possibly be better shown by temperature bin and operational hour analysis for the building and HVAC equipment. But since, this paper is focussed on the results of the simulation analysis bin analysis was not included in this paper. This could be added in future work.

Although the energy savings achieved in heating mode are diminished when the GAHP is operated in cooling mode, still for most cities positive energy savings can be seen. Similarly, for the energy cost savings it can be seen that operation of GAHP in both heating and cooling mode results in considerable savings in energy costs as shown in Table 8. This is due to the relatively shorter cooling season compared to the heating season in Canada and the relatively higher price of electricity which is used to drive conventional cooling equipment.

Table 7: Annual Energy savings achieved by using GAHP in heating and cooling mode

City	Percentage Energy Savings in Heating and Cooling Mode
Tweed	2.6%
Toronto	-1.7%
Ottawa	0.1%
Thunder Bay	-0.4%
Windsor	-2.5%
Edmonton	-0.5%
Fredericton	3.4%
Winnipeg	2.8%
Montreal	0.0%
Vancouver	0.5%
Regina	2.2%
St Johns	-2.0%

Table 8: Energy Cost savings achieved by using GAHP in heating and cooling mode

City	Percentage Cost Savings in Heating and Cooling Mode
Tweed	12.1%
Toronto	13.8%
Ottawa	12.5%
Thunder Bay	7.6%
Windsor	14.5%
Edmonton	9.3%
Fredericton	16.6%
Winnipeg	14.6%
Montreal	26.7%
Vancouver	17.3%
Regina	13.8%
St Johns	9.9%

Table 9 shows the GHG emission reduction achieved when GAHP is operated in both heating and cooling mode. Reduction in GHG emissions depends on the relative duration of local heating and cooling seasons and the GHG emission factors of natural gas and electricity. It can be seen that for most cities under consideration the GHG emission reduction is negative which means that GAHP operation in both heating and cooling mode increases the GHG emissions. This is due to the use of GAHP in the cooling season since, the natural gas used for the GAHP has very high GHG emission factor compared to electricity which is generally used to run air conditioners in the cooling season. It is possible for GAHP to achieve net positive reduction in GHG emissions when the cooling season is relatively shorter or the GHG emission factor of electricity for the location is relatively higher. As seen from Table 9 this is the case for Edmonton, Regina and Fredericton in Alberta, Saskatchewan, and New Brunswick respectively, which have relatively higher GHG emission factors for electricity and hence, show considerable reduction in GHG emissions even when the GAHP is operated in both heating and cooling mode.

Table 9: Reduction in GHG emissions achieved by using GAHP in heating and cooling mode

City	Percentage GHG Emission Reduction in Heating and Cooling Mode
Tweed	2.4%
Toronto	-2.0%
Ottawa	-0.1%
Thunder Bay	-0.5%
Windsor	-2.8%
Edmonton	8.7%
Fredericton	6.9%
Winnipeg	2.1%
Montreal	-1.0%
Vancouver	-0.3%
Regina	10.1%
St Johns	-2.2%

Conclusion

An eQUEST model was generated for GAHP installed at a library building in Tweed, Ontario. The accuracy of the eQUEST simulation was verified by using criterion for calibration of building energy simulation models. The simulated model complied with the calibration criterion established by IPMVP. The calibrated eQUEST model was used for conducting energy simulation analysis for the library building for various cities in Canada to ascertain the effect of weather conditions on potential benefits of GAHP in different parts of Canada. Potential benefits of GAHP in terms of energy savings, energy cost savings and reduction in GHG emissions were quantified for various Canadian cities. It was found that GAHP under consideration could be a viable replacement for conventional natural gas-fired heating equipment and also potentially achieve net positive energy savings, energy cost savings and GHG emission reduction for some weather conditions and cities in Canada. Operation of GAHP in only the heating mode appears to be more beneficial in terms of energy savings and associated energy cost savings along with the reduction in GHG emissions. However, operating the GAHP in cooling mode reduces the energy savings achieved in heating mode and diminishes the potential benefits of the GAHP.

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Nomenclature

$Elect_{GHP}$	natural gas consumption of GHP (kWh)
$Elect_{HVAC}$	electricity consumption of conventional HVAC equipment (kWh)
$Elect_{marginal}$	marginal cost of electricity ($/kWh)
$Elect_{savings}$	saving in electricity consumption (kWh)
GHG_E	GHG emission factor for electricity (gCO_2 eq/kWh)
GHG_{NG}	greenhouse gas emission factor for combustion of natural gas (gCO_2 eq/m^3)
$GHG_{reduction}$	reduction in greenhouse gas emissions (gCO_2 eq)
HHV_v	higher heating value of natural gas (MJ/m^3)
$\bar{M}$	average of actual energy consumption during the period of simulation
M_i	measured or actual energy consumption during the i-th period
n	number of data points in the simulation
NG_{GHP}	natural gas consumption of GHP (m^3)
NG_{HVAC}	natural gas consumption of conventional HVAC equipment (m^3)
$NG_{marginal}$	marginal cost of natural gas ($/$m^3$)
$NG_{savings}$	saving in natural gas consumption (m^3)
S_i	simulated energy consumption during the i-th period

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