European Regional Climate Zone Modeling of a Commercial Absorption Heat Pump Hot Water Heater

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Abstract

High efficiency gas-burning hot water heating takes advantage of a condensing heat exchanger to deliver improved combustion efficiency over a standard non-condensing configuration. The water heating is always lower than the gas heating value. In contrast, Gas Absorption Heat Pump (GAHP) hot water heating combines the efficiency of gas burning with the performance increase from a heat pump to offer significant gas energy savings. An ammonia-water system also has the advantage of zero Ozone Depletion Potential and low Global Warming Potential. In comparison with air source electric heat pumps, the absorption system can maintain higher coefficients of performance in colder climates.

In this work, a GAHP commercial water heating system was compared to a condensing gas storage system for a range of locations and climate zones across Europe. The thermodynamic performance map of a single effect ammonia-water absorption system was used in a building energy modeling software that could also incorporate the changing ambient air temperature and water mains temperature for a specific location, as well as a full-service restaurant water draw pattern.

Keywords: Absorption system, Heat pump, water heating

1. Introduction

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Commercial water heating accounted for 12.6 kW/m^2 of floor area in western Europe in 2010 [1]. As a perspective, the total commercial floor area in Germany was 1.104 Mm^2 in 2008 [2]. The Gas Absorption Heat Pump (GAHP) can provide hot water at efficiencies greater than that of conventional boilers or water heaters. Unlike, conventional boilers where the desired heating is achieved completely with combustion of gas, the GAHP uses ambient air as an additional heating source along with gas heating. Thus, the coefficient of performance, ratio of useful output work to the energy input, of conventional boiler (<1) is less than that of GAHP (>1). In operation, the GAHP is similar to that of a vapor compression system except that a thermal compressor is used in place of the mechanical compressor (Fig. 1). The thermal compressor consists of a series of heat and mass exchangers (absorber, desorber, solution heat exchanger) and a low flow, higher pressure difference pump. As a result of its higher COP values; the GAHP uses less fuel and has the potential to significantly reduce annual operating cost.

Geoghegan *et al*. [3] highlighted average energy savings of 35% in the Southern and South Central climate zones of the United States when comparing a GAHP water heat system to a conventional high efficiency gas burning configuration.

However, due to higher cost premium and limited availability of Gas Absorption Heat Pumps in comparison to the standard storage hot water heaters, GAHP's have had little penetration in the commercial hot water market. Also, lack of familiarity and training about GAHP among customers, contractors and service personnel acts as a barrier for adoption of these systems. With an increasing global push towards low carbon emission choices, the consumers are growing more aware of their energy footprint leading to investigation of more energy efficient technologies, like the GAHP, as a replacement for the conventional systems. To elucidate on these points, this paper sets out to evaluate the performance of a GAHP in ten cities across all five climate zones of Europe, shown in Table 1 and Figure 2, availing of the ambient air temperature data, mains water temperature models and the hot water heater storage tank models available in EnergyPlus [4]. This would provide the energy performance comparison of a gas absorption heat pump to a standard hot water storage water heater.

2. Modeling

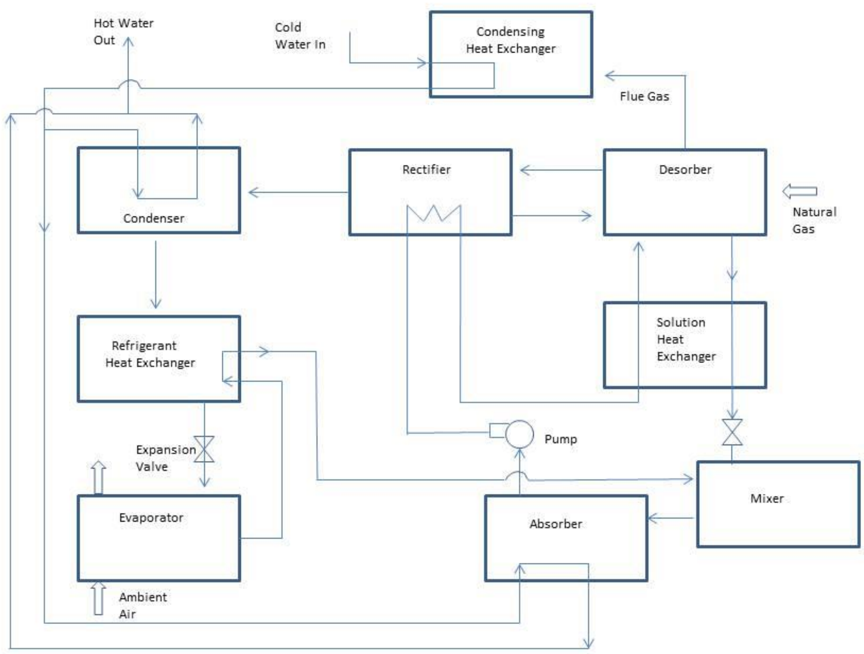

Fig. 1. Schematic of the Gas Absorption Heat Pump

This work compares a standard hot water heating configuration for a full-service restaurant with a GAHP alternative layout. The former consists of two 0.3785 m^3 tanks operating in series (Figure 3). The first is a high efficiency condensing 58.3 kW unit followed in series by a standard efficiency non-condensing 58.3 kW unit. The set point of each tank is set at 60°C. In practice, the second tank is a topping off tank to cater for peak demand. During an average water draw day, it should see little use. A high efficiency unit could be used in place of the standard efficiency unit but the benefit of the condensing heat exchanger would be lost because of the high inlet water temperature into this second tank. The restaurant has a recirculation loop that returns unused water back to second tank, in which no heat losses are assumed.

Table 1. Zones and cities of Europe

City	Zone
Madrid	1&2
Rome	1&2
Athens	1&2
Moscow	3
Vienna	3
London	4
Paris	4
Oslo	5
Reykjavik	5
Helsinki	5

Fig. 2. Zonal map of Europe [5]

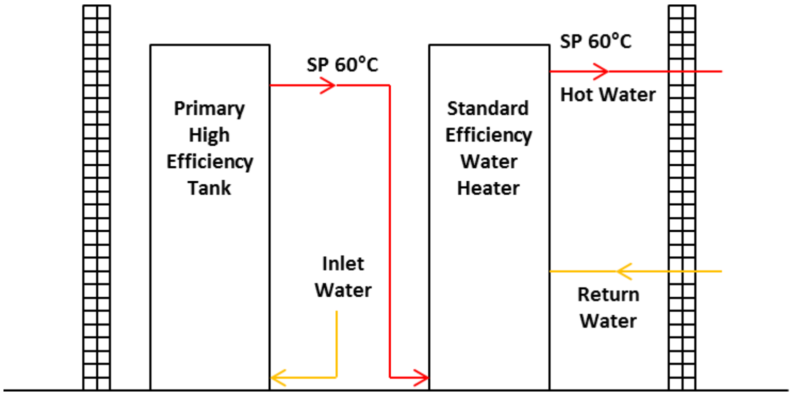

Fig. 3. Standard Heat pump configuration

The GAHP configuration is shown in Figure 4. The heat pump itself resides outside the building and heat exchanges with a coil that circulates water from the first tank. This tank is effectively a 0.3785 m^3 storage tank with water from the coil entering in the middle of the tank and water to the coil exiting at the bottom. The heat pump switches off when the temperature sensor reaches 60°C.

The second tank in series is again a standard non-condensing efficiency 0.3785 m^3 tank. In both systems, the first tank is modelled as stratified whereas the second is considered a well-mixed tank, due in part to the mixing brought on by the circulation loop.

2.1. Absorption System Modeling

Geoghegan *et al*. [3] developed and optimized a 41 kW heating single-effect ammonia-water gas absorption heat pump (GAHP) as part of a larger study to investigate the potential for energy savings in a commercial water heating application in the South and South Central regions of the United States. Modelling of the system was performed using the Engineering Equation Solver software platform [6] and the modelling was performed in steps similar to those outlined by Herold *et al*. [7]. A parametric study of the optimized cycle model was performed over a range of ambient (-20 to 40°C) and hydronic return (14 to 52°C) temperatures. Tabulated performance data (higher heating value gas based COP and the heating duty as a function of ambient and hydronic return temperatures) was then used in the building modelling software Energy Plus [6] to evaluate performance as part of a commercial water heating system. The tabulated performance data from the previous investigation was modified for this study to reflect estimated GAHP performance in cold and very cold climates where there will be periods of operation that will result in a frost build-up on the evaporator coil and will require defrost.

Table 2 presents the modification guidelines applied to the GAHP performance data in this study. The ambient conditions where a de-frost penalty was applied are the temperature bands most likely to experience the right

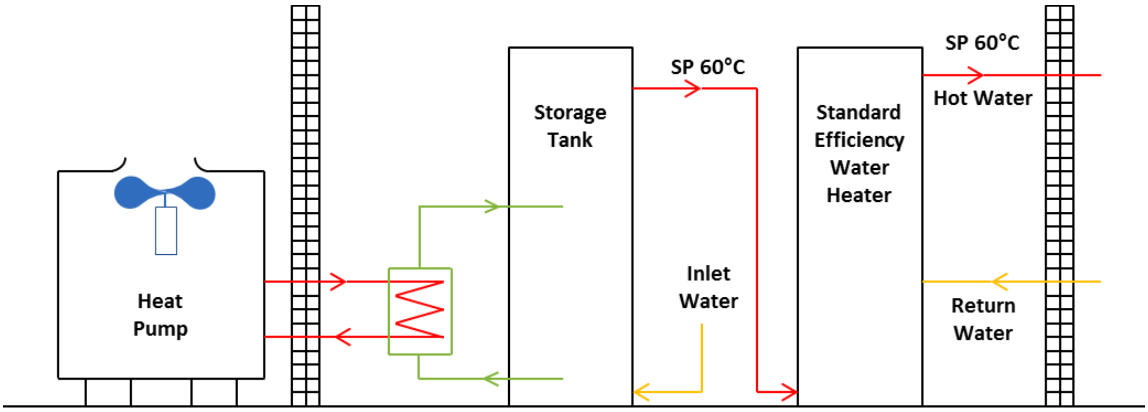

Fig. 4. Gas Absorption Heat Pump (GAHP) configuration

mix of temperature and humidity to require regular and periodic defrost. It is expected that a defrost cycle will be required for the 3.5°C to -2.7°C and -2.8°C to -9°C temperature bands every 120 and 180 minutes, respectively.

GAHP systems can actively defrost while still providing heat at a reduced capacity. This is very different than electric heat pumps which typically must run in reverse (removing heat) to defrost its outdoor coil. The defrost cycle of the modeled GAHP takes approximately 5 minutes and then another 5 minutes to recover to pre-frost performance.

Table 2. Performance curve adjustment to account for periodic active defrost

Ambient Temperature Range, °C	GAHP Performance Penalty
$T_{amb} > 3.5$	No penalty
$3.5 > T_{amb} > -2.7$	4% reduction
$-2.8 > T_{amb} > -9$	3% reduction
$-9 > T_{amb}$	No penalty

The percent reduction in system performance was determined by determining the average COP_{gas} for a heating period where the defrost and recovery are included. The percent difference between this average COP_{gas} and the standard COP_{gas} were used to determine the performance reduction for the temperature bands of interest. The tabulated COP_{gas} and heating duty values for the 41 kW GAHP were then modified using these guidelines and used in Energy Plus for simulation of Cold and Very Cold climates of interest.

2.2. Energy Plus Modeling

EnergyPlus single-speed, air-source heat pump water heating coil, and the stratified tank model were used for the full-service restaurant hot water heating simulation. The performance data, which includes rated COP, water heating capacity, and normalized part load performance curves were inputted to the EnergyPlus IDF file. It was assumed there is no cyclic degradation of the absorption heat pump.

The GAHP was coupled with a stratified water tank. A skin loss coefficient per unit area to ambient temperature, 1.7 $W/m^2 \cdot K$, was defined to calculate heat loss from the hot water to the surrounding air. The water tank was configured to have six nodes, i.e. six control volumes with different water temperatures, which are uniformly distributed from the top to the bottom of the tank. The return water to the heat pump water heater (HPWH) was drawn from the bottom node and the heated water out of the HPWH flows to the middle node of the tank. The hot water is discharged to the second tank from the top node. The makeup temperature is from the city mains, which goes to the bottom of the tank. The sensor controlling the HPWH On/Off was placed at 1 m up from the bottom of the 1.4 m tall tank. The HPWH set point is 60°C, which has a 2°C temperature dead band. No supplemental heaters were used in the tank and a one minute time step was set for the simulation. The HPWH model in EnergyPlus currently has a cut-off operating switch at 5.5°C ambient. This cut-off was disabled for the current analysis to allow the GAHP to operate at lower ambient temperatures. The cut-off is intended for electric heat pumps (EHP) whose performance is significantly reduced at low ambient operating temperatures. The GAHP experiences a minimal reduction in performance when compared to the EHP and is therefore able to operate to much lower ambient temperatures.

2.3. Water Draw Pattern

The authors were unable to find a water draw pattern for restaurants in Europe, thus, the pattern used by

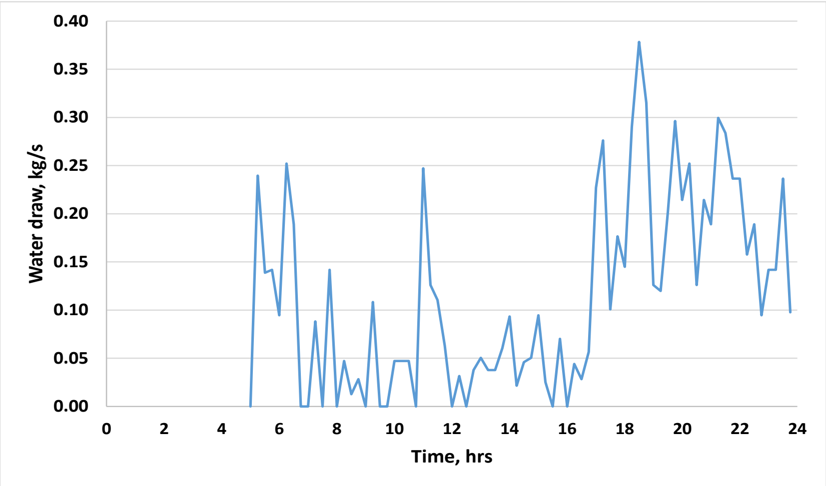

Fig. 5. 15-minute period full service restaurant water draw pattern (Fisher, D., & Pietrucha W. [8])

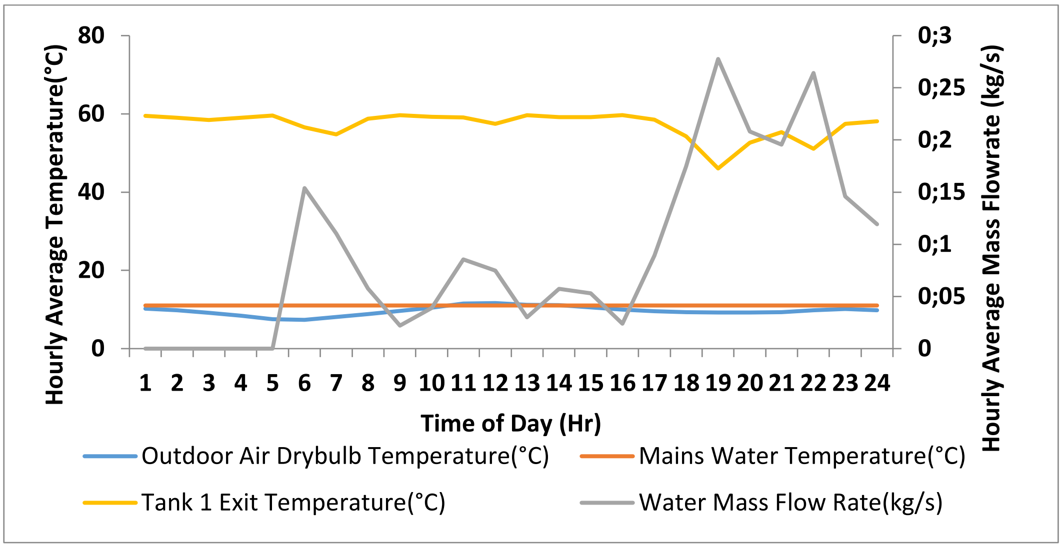

Fig. 6. GAHP tank performance for a nominal day in London

Geoghegan *et al.* [3], Figure 5, was utilized in this study. This pattern provides a hot water load profile for a full-service restaurant with an average usage of 7.95 m^3 per day. Using this load profile, the performance comparison between the two water heating configurations was conducted in ten cities across five climate zones of Europe. The data was averaged to a 15-minute period so as to function properly with the EnergyPlus time step of 1 minute. It should be noted that the purpose of this work is not to size the hot water equipment for specific tasks but to make a comparison between two possible configurations.

3. Modeling Results

EnergyPlus provided performance data for a full year of operation at the selected site locations. Figure 6 displays the exit temperature from Tank 1 of the GAHP system for a nominal day in London. March 20th was chosen because the daily average ambient temperature of 10.2 °C is close to that of the annual average. The inlet water temperature remains constant throughout the day at 11.03 °C whereas the ambient air temperature varies from 9.2 to 11.64°C. The exit temperature from the GAHP storage tank remains close to the set point of 60 °C for much of the day. When the heavy water draw occurs, the exit temperature drops to as low as 46.04 °C and the system relies on the second tank to reach the 60°C set point temperature. On this day, the GAHP delivered a higher heating value gas based COP of 1.39. The 58.3 kW high efficiency tank 1 of the standard installation ensured the set point was maintained throughout the nominal day but this was achieved at a lower COP of 0.87.

The annual gas usage for the ten cities, based on the high efficiency configuration, is shown in Figure 7. The mains water temperature differentiates the cities where Athens and Rome have on average the warmest inlet temperatures. Overall annual gas usage ranged between 525 GJ/year and 691 GJ/year for the conventional high efficiency system. The ratio of Tank 1 usage (high efficiency) to Tank 2 usage (standard efficiency) imply the two tanks in series offer a reasonable configuration for the full service restaurant daily water draw. This is because the first tank (condensing storage) provided the majority of the water heating load. The second tank (non-condensing storage) provides additional capacity to handle more peak demand. The equivalent annual gas usage for the GAHP system is shown in Figure 8. The overall annual gas usage values range between 342 GJ/year and 495 GJ/year for the GAHP system. In comparison to the standard high efficiency system in Figure 7, the ratio of Tank 2 usage to Tank 1 usage is higher. This is not only because Tank 2 is a 58.3 kW unit and the GAHP is a peak 41 kW unit but also because the heating configuration of the heat pump system is focused towards the bottom of the tank. During the large draw periods, water above the circulation loop will not be heated as quickly as it would in the standard high efficiency system. This occasionally results in colder water being delivered to the second tank in the GAHP configuration. As a result, some care should be taken when sizing the system for peak water demand.

Table 3 presents the annual percentage of gas savings provided by the GAHP system in comparison to the standard high efficiency system for the 10 cities investigated. The table shows that the GAHP offers a significant gas savings. Gas savings ranged from 28.3 % in Reykjavik, Iceland, to 35.0% in Athens, Greece. The average annual gas savings for the cities investigated is 31.1%. These results are reiterated by a comparison of the COPs for both systems in terms of water heated to gas usage (Figure 9). As expected the GAHP system is able to maintain system level COP values above 1 while the standard high efficiency system is limited to COP values well below 1. The annual average COP of the GAHP system is 1.4 in comparison to average gas heating COP of 0.92 across ten cities. Annual COP values of the GAHP system ranged from 1.37 in Reykjavik Iceland to 1.44 in Athens Greece. Overall performance of the GAHP system was impacted by mains water and ambient temperatures. The annual COP values of the standard high efficiency system ranged from 0.9 in Athens Greece to 0.93 in Oslo Norway and Moscow Russia. Overall performance of the standard high efficiency system was impacted by mains water temperatures only and performance was highest where mains water inlet temperatures were coldest. The colder water temperatures allowed the condensing water heater to extract more heat from the flue gas stream, resulting in higher annual COP values.

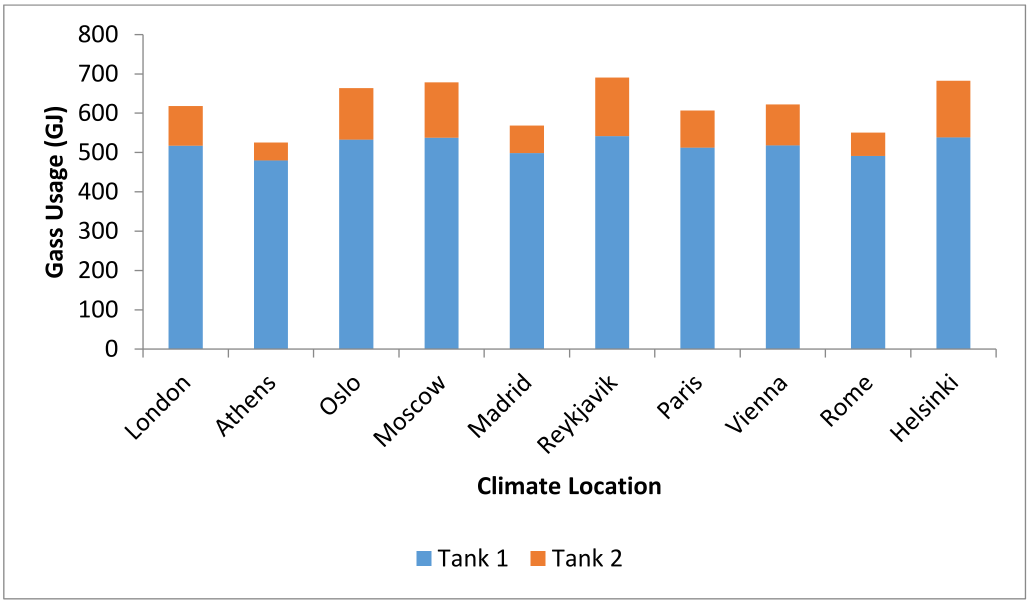

Fig. 7. Annual gas usage (Giga-Joules) for the high efficiency configuration

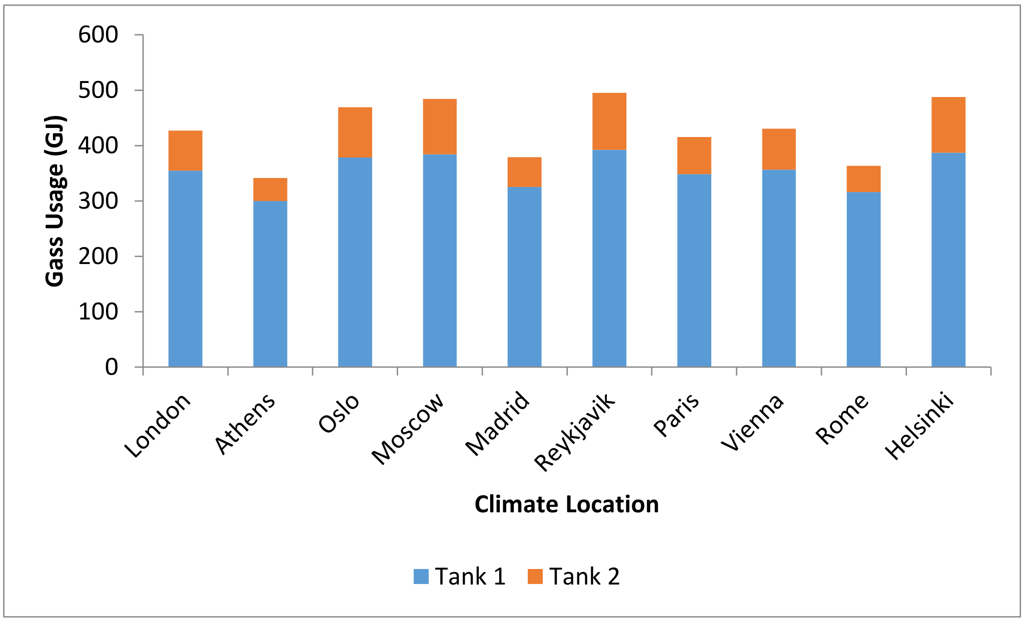

Fig. 8. Annual gas usage (Giga-Joules) for the GAHP

Table 3. Annual Percentage Savings of the GAHP in comparison to the High Efficiency configuration.

Climate Zone Location	Annual Percentage Gas Savings (%)
London	31.01
Athens	34.98
Oslo	29.33
Moscow	28.68
Madrid	33.36
Reykjavik	28.33
Paris	31.56
Vienna	30.83
Rome	34.00
Helsinki	28.59

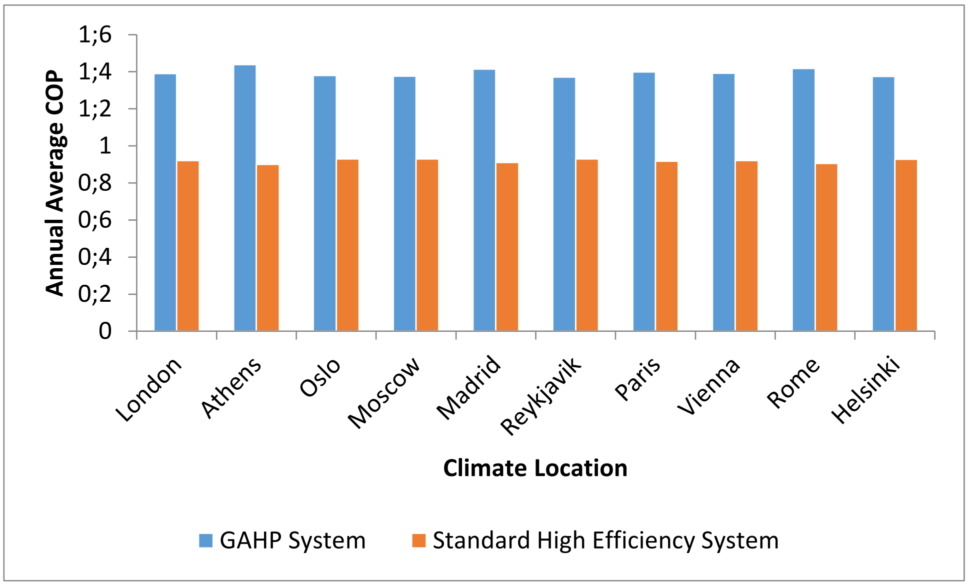

Fig. 9. Comparison of Annual Average COP

The payback period of the GAHP system against the standard high efficiency system was investigated for the 10 locations modelled and their average. For this comparison the total installed cost of the GAHP and standard high efficiency systems were assumed to be 17,300 and 10,600 euros, respectively. The payback period was then calculated for a range of natural gas prices. Figure 10 presents the payback period as a function of natural gas price. The figure shows that for all of the natural gas prices considered, the average payback period is 4 years or less. For the first half of 2016, natural gas prices in the European area for industrial consumers were on average 0.033 euros/kWh [10] which is the lowest it has been in 6 years. At this natural gas price, the payback is expected to be 3.85 years. The plot also presents payback data for Athens and Reykjavik. Athens had the highest natural gas savings by percentage for the GAHP but has longer payback periods when compared to Reykjavik which had the lowest savings by percentage. This is because the total energy savings in Reykjavik is larger even though its percentage of total energy use is smaller. Colder water main temperatures are the main cause of this result.

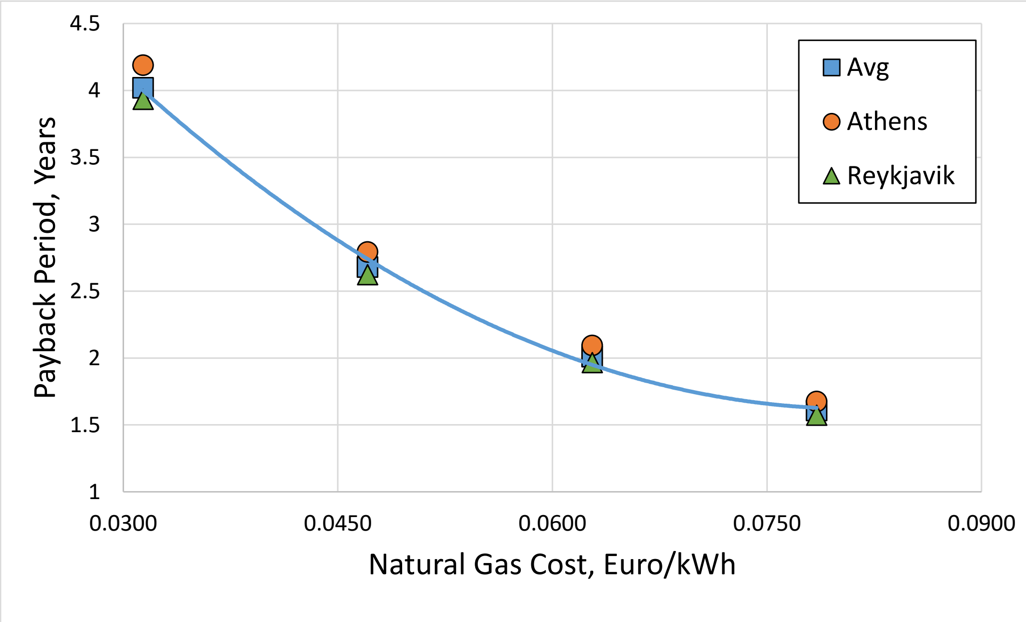

Fig. 10. GAHP Payback versus standard high efficiency as a function of natural gas cost

4. Conclusions

Standard high efficiency and Gas Absorption Heat Pump (GAHP) hot water heating configurations for a full service restaurant were investigated, using EnergyPlus, for the ten cities in five climate zones across Europe. The performance of the GAHP system was compared to that of the standard high efficiency system utilizing a condensing gas water heater. Performance of the GAHP was very favourable in terms of annual gas energy savings for cities located in all five climate zone in Europe. Percentage of savings was between 28.3% in Zone 5 and 35% in Zone 3 with an average annual savings of 31.1%. Higher heating value gas based COP values ranged from 1.37 to 1.44 for the GAHP system and 0.9 to 0.93 for the standard high efficiency system for the cities investigated. A payback period analysis showed that the GAHP system offered payback in 4.2 years or less compared to the standard high efficiency system for all 10 cities investigated at natural gas prices of 0.0314 euro/kWh or higher.

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