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ABSTRACT

This paper presents the experimental evaluation of two packaged prototype single-effect ammonia-water absorption heat pump systems designed to provide 23.45 kW of space heating with a cycle COP of 1.65 at ambient air and hydronic return temperatures of 8.3°C and 37.8°C, respectively. These prototypes were fabricated with materials and methods that would allow for mass production and significantly reduce total system cost when compared to commercially available absorption heat pump systems. Both prototypes were investigated at their design ambient and hydronic return temperatures, and performed within 94% of their target. Their performance was investigated for a range of ambient and hydronic return temperatures to allow for characterization of system performance. The impact of parasitic power on overall system COP and reduction strategies were investigated. The ability to modulate system output was investigated and both units were able to achieve 4:1 modulation. Performance of the single-effect prototypes was compared to that of a commercially available GAX absorption heat pump system and was found to be comparable. Additional testing on one of the prototypes was performed to estimate the Annualized Fuel Utilization Efficiency (AFUE) for the climate region IV. An economic payback of 3-5 years compared to a condensing boiler was predicted based on the projected cost and measured performance of the prototypes.

1.0 INTRODCUTION

Gas-fired residential space heating in the United States is predominantly supplied by furnaces and boilers. These technologies have been approaching their thermodynamic limit over the past 30 years and improvements for higher efficiency units have approached the point of diminishing return. Electric heat pumps are growing in popularity but their heating performance at low ambient temperatures is poor. Commercially available gas absorption heat pumps are not economically viable for most applications. The development of a low-cost gas absorption heat pump would offer a significant improvement to current furnaces and boilers, and in heating dominated climate zones when compared to electric heat pumps. Gas absorption heat pumps (GAHP) exceed the traditional limit of thermal efficiency encountered by typical furnaces and boilers, and maintain high levels of performance at low ambient temperatures. This paper presents the experimental evaluation of two packaged prototype single-effect ammonia-water absorption heat pump systems designed to provide 23.45 kW of space heating with a cycle coefficient of performance (COP) of 1.65 at ambient air and hydronic return temperatures of 8.3°C and 37.8°C, respectively.

2.0 PRIOR WORK

Absorption heat pumps have been investigated for a range of heating and cooling applications at the residential, commercial and industrial scales. Several prior investigations are highlighted below.

Priedeman *et al.* (2001) investigated a 17.6 kW ammonia-water Generator-Absorber heat eXchange (GAX) absorption system for residential and light-commercial space-conditioning applications. The breadboard system achieved a cycle COP of 0.68 at full cooling capacity. The authors noted that a cycle COP of 0.70 or greater could result in an economically viable system. This investigation preceded a commercialization effort by a U.S. start-up company, Cooling Technologies Inc., focused on residential and commercial cooling. Unfortunately, the commercialization effort stalled during the field test stage and the system did not make it to production.

Garrabrant et al. (2014) experimentally investigated three 2.78 kW nominal residential capacity heat pump water heaters fabricated with conventional heat exchangers based on designs and analyses presented by Garrabrant et al. (2013). Nominal operating conditions were a 32°C hydronic fluid temperature into the absorber and condenser, and a 20°C ambient. During normal operating conditions, the hydronic fluid temperature into the absorber and condenser ranges from 14 - 60°C. Steady state performance was investigated over a range of hydronic water supply temperatures and Energy Factors (EF) of 1.2 - 1.3 were demonstrated. Field testing of this gas absorption heat pump water heater design was presented by Glanville *et al.* (2016). The field test was performed over a 10 month period and showed that in-field unit performance was similar to laboratory results.

The performance of an 18 kW GAX GAHP for domestic hot water for retrofits of existing buildings was the focus of concerted effort in Europe. This system was developed as part of the HEAT4U project to aid in the development of GAHP solutions for existing European buildings. This was a consortium effort that included the only manufacturer of GAHP systems in this capacity range, Robur. Toppi *et al*. (2014) used the results from performance testing of the 18 kW unit to develop a characteristic model of the systems performance for a range of operating conditions (external air temperature, water temperature, and heating load).

Erickson *et al.* (2014) presented a commercialized heat-activated heat pump/chiller for commercial and industrial applications. The system is able to provide 88 kW of cooling at a footprint of 0.9 m by 1.5m. It should be noted that all externally coupled components were liquid coupled to their source or sink. This allows for a significant reduction in absorption system size. The implementation and results from field testing of this system in several applications (meat packing plant, poultry processing plant, pulp and paper processing plant) were presented and showed the potential for significant energy and economic savings.

3.0 PROTOTYPE SYSTEM DESCRIPTION

Two packaged prototype single-effect ammonia-water gas-fired absorption heat pump units were investigated as part of this study. Figure 1 presents images of the units (Unit 01 has silver paneling and Unit 02 has blue paneling). The units were built in sequence and initial testing on Unit 01 was completed before Unit 02 was fabricated. As a result, there are minor differences between the two units. The width, depth and height of the packaged units are $1.19 \times 0.97 \times 1.12$ meters, respectively. The majority of the absorption system is housed towards one end of the unit (Figure 2) and occupies a space of $0.43 \times 0.97 \times 1.12$ meters. This space contains the absorber, condenser, condensing flue gas heat exchanger (CHX), desorber, rectifier, refrigerant heat exchanger, solution heat exchanger, and solution pump and motor. The remaining space is occupied by the direct air coupled evaporator. The evaporator is the largest component and occupies 64% of the total footprint. The packaged prototypes, when coupled with accompanying control boxes, are standalone units that are designed to maintain a set hydronic return or supply temperature when a call for heat is present. The units have the ability to modulate which helps them to better match loading with ambient temperatures and limits the number of start-up and shut-downs experienced.

4.0 EXPERIMENTAL EVALUATION

Testing of the two packaged units was performed within temperature controlled chambers to allow for evaluation for ambient air and hydronic return temperatures of -17.8 to 12.8°C and 27 to 52°C, respectively. Figure 3 is a schematic of the test facility used. In-stream temperature measurements at the hydronic inlet and outlet of the units were made using RTD's (accuracy of $\pm$ 0.1°C) and the hydronic flow rate was measured using a volumetric flow meter (Omega, FMG-705). The total gas rate in was measured using a volumetric gas meter (Elster American Meter, DTM-200A) and the combustion efficiency was determined using a flue gas analyzer (ENERAC, MEA 500).

Figure 1: Packaged prototype units (Unit 01 – Left, Unit 02 – Right)

The coefficient of performance (COP) was calculated from the measured data in several different ways which are discussed below. The cycle COP was calculated using Equation 1 where the inputs were determined using Equations 2-4. This COP is representative of the absorption heat pump performance and accounts for heat exchange in the absorber, condenser and desorber.

$$COP_{cycle} = (Q_{Heating} - Q_{CHX}) \div Q_{Desorber} \tag{1}$$

$$Q_{Heating} = \dot{m} \times c_p \times (T_{hyd,supply} - T_{hyd,return}) \tag{2}$$

$$Q_{CHX} = Q_{Gas} \times (CE_{CHX} - CE_{Desorber}) \tag{3}$$
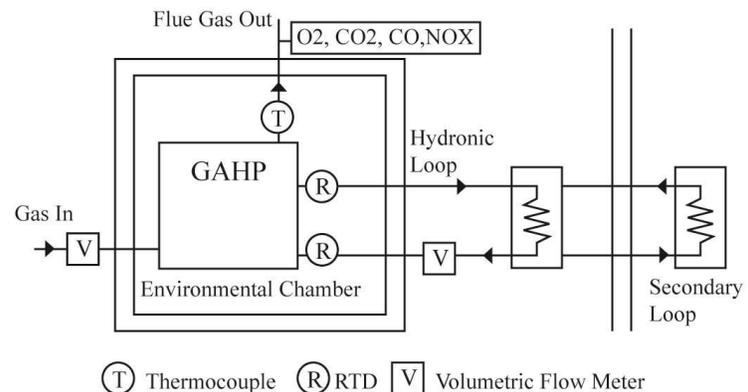
$$Q_{Desorber} = Q_{Gas} \times CE_{Desorber} \tag{4}$$

The gas COP was calculated using Equation 5. This equation accounts for the heat provided by the absorber, condenser and condensing heat exchanger. The denominator is the bulk gas input to the system.

$$COP_{Gas} = Q_{Heating} \div Q_{Gas} \tag{5}$$

Figure 2: Heat pump components housed within unit

Figure 3: Test facility schematic

The system COP was calculated using Equation 6. The numerator is the heat provided by the absorber, condenser and condensing heat exchanger. The denominator is the bulk gas input and the parasitic power of the system.

$$COP_{System} = Q_{Heating} \div (Q_{Gas} + P_{Electric}) \tag{6}$$

It should be noted all of the natural gas based calculations use the higher heat value (HHV) unless otherwise noted.

5.0   RESULTS AND DISCUSSION

Performance of both units was investigated at the design ambient (8.3°C) and hydronic return (37.8°C) temperatures. Unit 01 achieved cycle, gas and system COP values of 1.62, 1.42 and 1.36, respectively. Unit 02 achieved cycle, gas and system COP values of 1.57, 1.39 and 1.35, respectively. Both units performed near the target cycle, gas and system COP values of 1.65, 1.45 and 1.4, respectively. At this operating condition Unit 01 and 02 provided 22.3 and 22.1 kW of heat, respectively. The target heating duty is 23.5 kW. Unit 01 performed at slightly higher COP values than Unit 02. This is in part due to the absorber of Unit 02 being damaged during shipping from the fabricator. Parasitic power consumption was reduced between Unit 01 and 02 by up to 100 W which contributed to closer system COP values.

After initial testing of the units was completed, parametric sweeps were performed to characterize system performance over a range of expected ambient (-18 to 12.8°C) and hydronic return (27 to 52°C) temperatures. Unit 01 and 02 Gas COP values are plotted as a function of ambient and hydronic return temperatures in Figure 4. The plots show the expected trend of increased COP as ambient temperature increases and hydronic return temperature decreases. Both systems performed well over the experienced conditions. This is important because a unit installed in a real world application will be required to operate over a large range of conditions without issue.

In addition, the ability to modulate is important because it will limit the number of start-up and shut-down periods experienced by the unit in an actual application. These are periods of less efficient operation which is why they should be limited. In addition, heating systems are typically sized for the coldest 5% ambient condition and most residential systems will spend the majority of their life operating between 40 to 80% of capacity. Modulation of both units was investigated for a range of ambient temperatures (-17 to 12.8°C) at the design hydronic return temperature of 37.8°C and both systems were able to achieve 4:1 modulation. Figure 5 presents plots of System COP as a function of the gas input fraction to the desorber for both units. The plots show that System COP peaks between 50 and 80% for both units. System performance initially increases with the reduced heat input because the effective UA of the heat exchangers increases. This is also the reason why the peak for both units shifts to lower firing rates with reducing ambient temperatures. At less favorable ambient conditions, more effective area will result in increased performance.

Limiting parasitic power is important to maximizing the System COP because it is an additional energy input to the system. Figure 6 is a plot of parasitic power as a function of hydronic return temperature for Unit 01 and 02. The plot
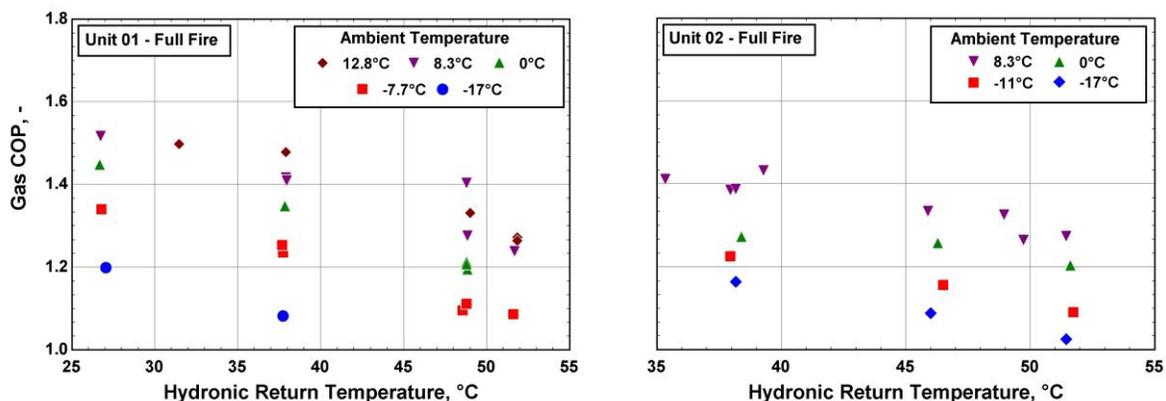

Figure 4: Unit 01 and 02 Gas COP versus ambient and hydronic return temperatures
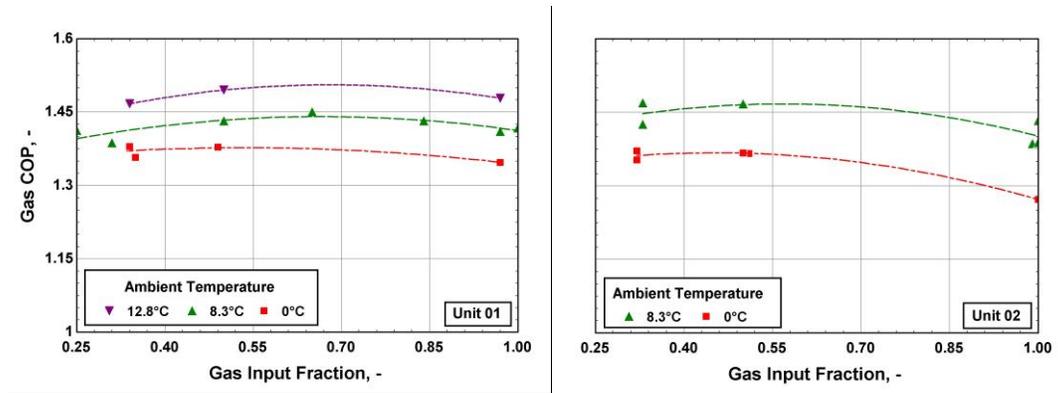
Figure 5: Gas COP as a function of desorber firing rate

shows that parasitic power is reduced with reduced hydronic return temperature. This is because the required pumping power decreases as the high to low side pressure difference decreases. The vertical scatter in several locations is a result of investigating system performance with varying evaporator fan speeds. Parasitic power for Unit 02 is roughly 50 to 100 watts lower than Unit 01 for any given case. This is a result of design changes that occurred between fabrication of the two units

Performance of Unit 01 was investigated by Gas Technology Institute using the ANSI Z21.40.4 test method to estimate the Annualized Fuel Utilization Efficiency (AFUE) of these gas heat pump units. The ANSI Z21.40.4 requires a series of steady state tests performed at full and partial loading to calculate the AFUE. The AFUE is the ratio of the useful heat delivered by a system over a complete heating season to the gas consumed to drive the unit. It should be noted that the AFUE does not include electricity consumption in the denominator and that testing for this AFUE was performed separate from the data reported above. Data used in the ANSI bin method calculation is presented in Table 1 for climate region IV, corresponding to an outdoor design temperature of -15°C and 5643 bin hours. This resulted in a predicted AFUE of 136% with a seasonal output and consumption of 37,543 and 27,637 kWh, respectively. The annual estimated electricity consumption from the procedure is 5,274 kWh, which combined with fuel consumption yield a Heating Season Performance Factor of 9.45 on a source energy basis. Additional testing of Unit 01 demonstrated a COP_{Gas} of 1.2 with -25°C ambient temperature, at full fire with a 35°C return water temperature.
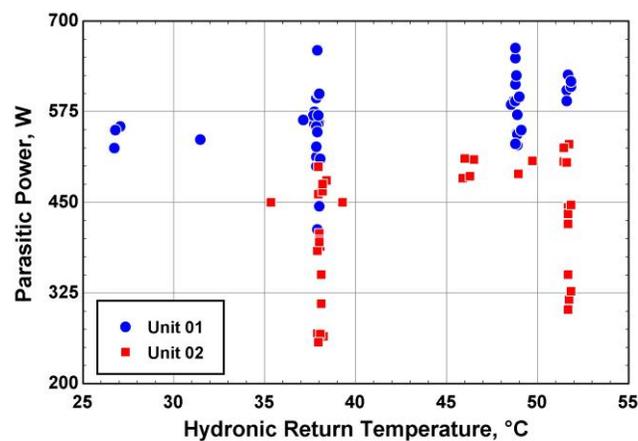
Figure 6: Parasitic power as a function of hydronic return temperature

Table 1: Input and output data used for ANSI Rating Points

Rating Point	Ambient Temperature, °C	Firing Rate, kW	Heat Output, kW	COP$_{Gas}$	Electric Power Input, kW
1	8.2	4.8	7.5	1.54	0.55
2	1.6	4.8	7.0	1.45	0.56
3	-8.4	4.7	6.4	1.35	0.52
4	-8.4	9.0	12.7	1.41	0.58
5	1.6	16.2	23.4	1.44	0.63
6	-8.4	15.4	21.1	1.37	0.63
7	-14.0	14.7	18.4	1.26	0.59

## 6.0 COMPARISON WITH COMMERCIALLY AVAILABLE SYSTEMS

The availability of residential capacity gas absorption heat pumps is significantly limited. To the knowledge of the authors there are only a few companies currently manufacturing these gas heat pump systems, the Italian company Robur is one, and they use a GAX Absorption cycle as their core technology. Published Robur data (Toppi *et al*. 2014; Robur 2013) and data collected as part of this study are compared in Figure 7. All of the performance data is reported using the Gas Utilization Efficiency (GUE) which is similar to the Gas COP but uses the Lower Heating Valve (LHV) for the gas instead of the HHV. This was done because the Robur performance data is presented in GUE. The figure shows that Unit 01 and 02 performed at or above the reported performance of the Robur units for the ambient temperature range and hydronic supply temperatures reported. This is significant because the Robur units use the GAX absorption cycle, which is inherently more complex and costly than the single-effect cycle used in Units 01 and 02.

Performance was then compared to a commercially available electric heat pump (EHP) system that was specifically designed for cold ambient operation (Space Pak, 2015) and two cold ambient EHPs under development (Shen *et al*. 2016). To allow for proper comparison between the gas and electric heat pumps, the Primary Energy COP was calculated for both systems (Equations 7 and 8).

$$COP_{PE,EHP} = COP_{EHP} \times 3.15 \tag{7}$$

$$COP_{PE,GAHP} = Q_{Heating}/(Q_{Gas} + P_{Electric} \times 3.15) \tag{8}$$

The 3.15 adjustment factor was provided by the U. S. Department of Energy (2015). It should be noted that it is unclear from either of the electric heat pump data sets whether the non-compressor electric power is factored into the COP$_{EHP}$. If it is not, accounting for this would reduce the EHP COP values. Figure 8 presents a plot of Primary Energy COP
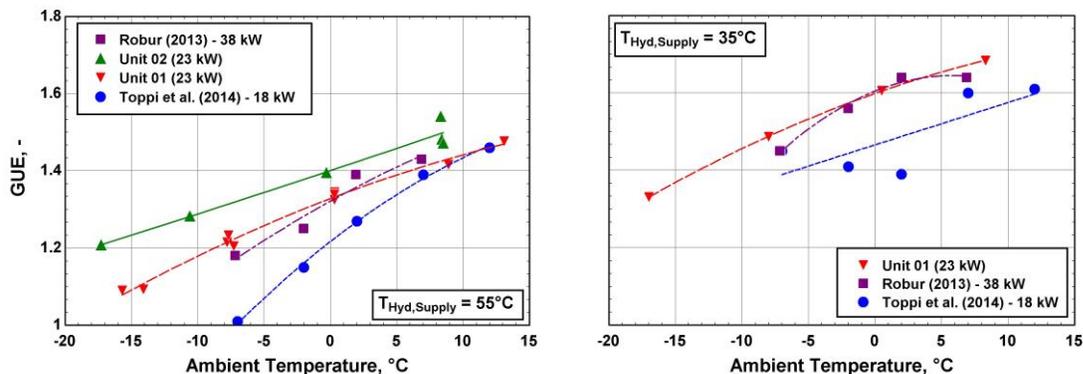
Figure 7: GUE comparison at 55 and 35°C hydronic supply temperatures

for the EHP systems, and GAHP Unit 01 and 02. The plot shows that the gas heat pumps outperform the Space Pak (2015) electric heat pump for the entire range of ambient temperatures and the units presented by Shen *et al.* (2016) for the majority of the ambient temperature range (below 0°C). A condensing furnace would outperform all of the EHP systems at ambient temperatures less than -5°C. This plot shows that even cold ambient EHP systems are not ideal for cold ambient conditions and that the gas heat pump is more appropriate for cold climate heating. Comparison with other residential capacity GAHP and cold ambient EHP systems shows that the units under investigation have the potential to be successful from a performance standpoint in heating dominated climate regions.
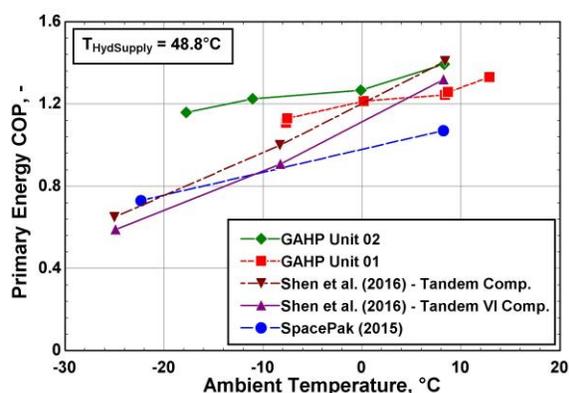

Figure 8: Primary Energy COP comparison

In order for the units under investigation to achieve widespread adoption, they not only need to outperform current technologies but must also allow for reasonable payback periods when compared to less efficient alternatives. Typical non-condensing and condensing gas furnaces have AFUE values around 80 and 95%, respectively. The non-condensing furnace will use minimal electricity while the condensing furnace is expected to have a parasitic electrical load of 4% of the gas input. The GAHP has an AFUE of 136% and is expected to have a parasitic electrical load of 6% of the gas input. Based on these assumptions the GAHP has the potential to save 18,890 and 11880 kWh of energy annually when compared to the standard and condensing furnaces (for the climate region IV), respectively. Assuming a 0.042 $/kWh cost of natural gas (EIA.gov, 2016) and a 0.1181 $/kWh of electricity, the GAHP will save $765 and $500 annually when compared to a typical furnace and condensing furnace, respectively. This means that for a 3 to 4 year payback the difference in installed cost between the standard furnace and the GAHP must be between $2,295 and $3,060. For the condensing furnace the difference in installed cost must be between $1,500 and $2,000.

For the GAHP to be adopted readily, unit cost must be low. This becomes a challenge because heat pumps are inherently more complex than standard furnaces and boilers. The units investigated above try to address this concern in several ways. The first is that the single-effect heat pump is one of the more basic absorption cycles. Limiting the complexity of the system will limit cost through fewer heat exchangers and parts. All of the components within the units are designed using similar parts and raw materials which allows for fabrication with minimal tooling variation. The current projected cost of the GAHP systems investigated (after typical distribution channel mark-ups) is 40 to 50% that of commercially available GAHP systems, which should make them competitive with standard heating systems.

7.0 CONCLUSION

Two prototype single-effect ammonia-water absorption heat pump systems designed to provide 23.5 kW of heating at a cycle COP of 1.65 were investigated. Both units operated within 6% of their target cycle COP and heating duty. The units maintained high coefficients of performance for the range of ambient and hydronic return temperatures investigated. The units showed further versatility in their ability to achieve 4:1 modulation for a range of operating conditions. Parasitic power was significantly reduced between fabrication of Unit 01 and 02 and will continue to be a focus as additional prototype units are fabricated. AFUE evaluation in climate region IV was determined to be 136% which is significantly higher than standard furnace and boilers.

Comparison with a commercially available GAHP showed that the units have similar performance. The biggest difference is that the Robur units use the GAX cycle which is significantly more complex and costly than the single-effect cycle used in Unit 01 and 02. Comparison with a commercially available low ambient EHP showed that the GAHP units outperform the electric units. Annual energy and operating cost savings of the GAHP were calculated against standard and condensing furnaces and found to be significant. These savings are important because they are needed to reduce the payback and improve the likelihood of adoption when in production. Low cost component

designs and production methods are projected to bring the installed cost of the units under investigation to 40-50% of the current installed cost of a Robur GAHP and bring absorption heat pumps in line with the 3-4 year payback.

NOMENCLATURE

AFUE	Annualized Fuel Utilization Efficiency		GUE	Gas Utilization Efficiency
ANSI	American National Standards Institute		HHV	Higher Heating Value
CE	Combustion Efficiency, %		Hyd	Hydronic
CHX	Condensing Flue Gas Heat Exchanger		LHV	Lower Heating Value
COP	Coefficient of Performance, -		P	Electric Power, kW
Cp	Specific Heat, kJ/kg-K		PE	Primary Energy
EHP	Electric Heat Pump		ṁ	Mass Flow Rate, kg/s
GAHP	Gas Absorption Heat Pump		Q	Heat Duty, kW
GAX	Generator-Absorber heat eXchange		T	Temperature, °C

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