Experimental Investigation of a Gas Driven Absorption Heat Pump and In-Situ Monitoring

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Abstract

This work describes the methodology used to realize a performance analysis of an ammonia-water condensing gas absorption heat pump. This heat pump shows a nominal heating output of 18,9 kW for outdoor temperature of 7°C and delivery temperature of 35°C, and it is designed for domestic hot water and heating production. The experimental results obtained in the laboratory are contrasted with those obtained from the monitoring of two residential facilities in the northern part of Belgium. The experimental tests were carried out in a climatic chamber to simulate different outside climatic conditions regarding temperature and humidity; different tests conditions were imposed based on a combination of the EN 12309 requirements and typical Belgium weather data. Measures of gas consumption, electrical consumption, water flows and temperatures were collected to compute performance indicators. On the other hand, the monitoring data was analyzed and contrasted with the experimental results to determine the effect of different variables over the system performance. The differences found are described and discussed.

Keywords: Gas Heat Pump, Absorption, Experimental, Monitoring.

Introduction/Background

International commitments related to energy use, environmental impact and decarbonization goals are increasingly restrictive and ambitious. The COP21 objectives signed in 2015 in Paris to limit global warming to 2 K above pre-industrial levels have encourage commitments at both national and regional levels. Without going any further, in Belgium at the end of 2020 the Walloon Region has legally acted that the reduction of its territorial greenhouse gas emissions should reach at least 95% compared to the 1990 levels by the year 2050 [1].

To achieve these goals, a more detailed analysis in terms of energy consumption and final energy use is necessary in order to focalize the efforts. Is in this line that the building sector has been pointed as one of the key areas in the matter; in 2017, the household sector represented 30% of the final use of energy consumption in the European Union (EU), only being surpassed by the industrial sector [2]. Furthermore, 80% of the energy used in the residential sector was destinated for domestic hot water (DHW) and space heating (SH) production.

It is here where heat pumps represent an interesting topic. Studies have shown that heat pumps are a good alternative to reduce the energy consumption and CO2 emissions, of which a significant part is destinated to buildings in Europe [3-5]. Between 2005 and 2018, the use of heat pumps in the heating sector in the EU represented an increase in energy consumption of 8.3 Mtoe, surpassed only by the use of solid biomass [6]. Related to this and according to 2016 data, the energy consumption in dwellings in Belgium destinated just to space heating and water heating represented 1.52 Mtoe [7], where the consumption of natural gas represented a 45.6% of the total energy consumption followed by electricity consumption (29.7%) [8].

An attractive alternative to traditional appliances is gas absorption heap pumps (GAHP) since thanks to the competitive price of gas, it offers substantial cost and energy savings compared to conventional commercially available systems for water heating [9]. However, the correct integration, sizing, and control of the system is of vital importance to not negatively affect the COP [10].

In this work, an experimental analysis of a gas driven absorption heat pump was conducted. Different outdoor ambient conditions regarding temperature and humidity were emulated in the laboratory to characterize its behavior and to estimate performance indicators. Besides, the system has been installed and monitored quite exhaustively in two residential houses in the northern part of Belgium for the whole year 2020. The results obtained in the laboratory and in the field are compared, finding differences in the behavior of the systems.

Description of the system

Designed for space heating and domestic hot water (DHW) for residential applications, the tested gas absorption heat pump (GAHP) has a nominal heating capacity of 18.9 kW. The system is based on the Water-Ammonia absorption cycle using outdoor air as renewable energy source (low-temperature heat source) and natural gas combustion as high-temperature heat source; the delivered hot water is the medium-temperature heat sink. The working principle of the system is represented in the diagram shown in Figure 1.

To heat the absorbent-refrigerant solution in the Generator (GEN), a Burner (BRN) driven by natural gas is used. The heat delivered to the GEN causes the separation of the two components of the solution by desorption. The desorbed ammonia vapor leaves the GEN and passes through the Rectifier (REC) to remove the last parts of water that could remain. Then it continues to the Condenser (COND), transferring the heat of the refrigerant to the water destinated to the Heating Circuit (HC) e.g., radiators, floor heating or others. The water is previously Pre-Heated in a heat exchanger (PH) by the combustion gases and is impulsed by the Water Circulation Pump (WP).

To reduce its pressure, the refrigerant leaving the COND is throttled by means of a restrictor valve and cooled down inside the Pipe in Pipe heat exchanger (PiPHx); then, by means of a second restrictor valve, is brought to the ideal pressure and temperature conditions before entering the Evaporator (EVAP) where the liquid refrigerant is evaporated by taking heat from the surrounding air. Then, the low-pressure vapor ammonia is overheated in the PiPHx before been send to the Solution Cooled Absorber (SCA), where it meets the poor refrigerant solution coming from the GEN. The pressure of the incoming solution is reduced by a third restrictor valve.

Since the absorption process it is an exothermic reaction, the solution is sent to the Water Cooled Absorber (WCA) where a considerable amount of thermal energy is transferred to the water of the heating circuit. Once the absorption is completed, the solution is pumped back to the GEN using a Solution Pump (SP).

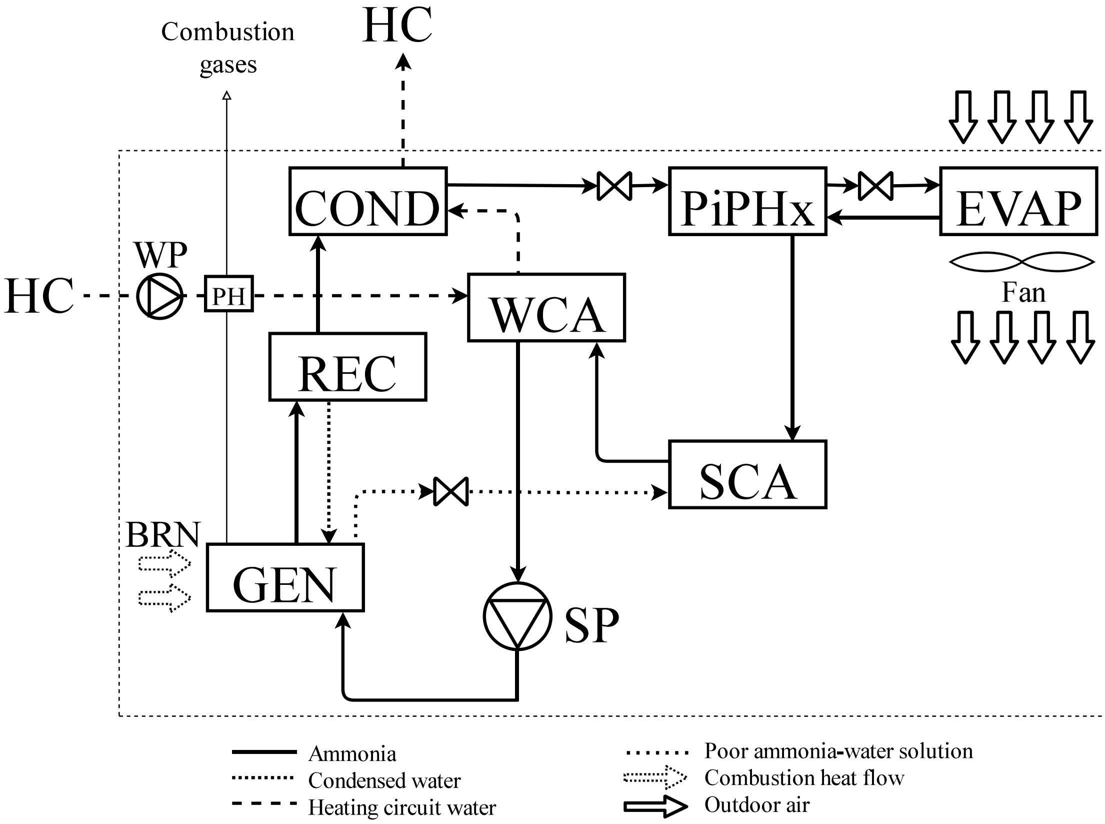

Figure 1. Gas absorption heat pump schematic

Description of the test bench

The system is an outdoor unit, thus, it is installed and the tests are performed in a climatic chamber to vary and control the temperature and humidity conditions. The test bench facilities are shown in Figure 2.

The appliance needs to be supplied by electricity and natural gas, consumptions that are measured. To emulate a heat demand of a house, a heat exchanger is placed in the room adjacent to the climate chamber where the load is regulated by controlling the chilled-water flow rate through the exchanger. The products derived from the operation of the system such as combustion gases, condensate and hot water are removed from the test bench.

The room temperature is decreased by means of an outdoor air-to-water heat pump unit located inside the chamber. The humidity of the room is reduced by water condensation in the evaporators of both units and drawn off of the chamber. Once the temperature and humidity setpoints are reached, a steady state is maintained by means of an electrical heater and a humidifier. These latter are connected to an acquisition system and controlled by a PI controller which receives the signal of temperature and humidity sensors placed at the entrance of the evaporator.

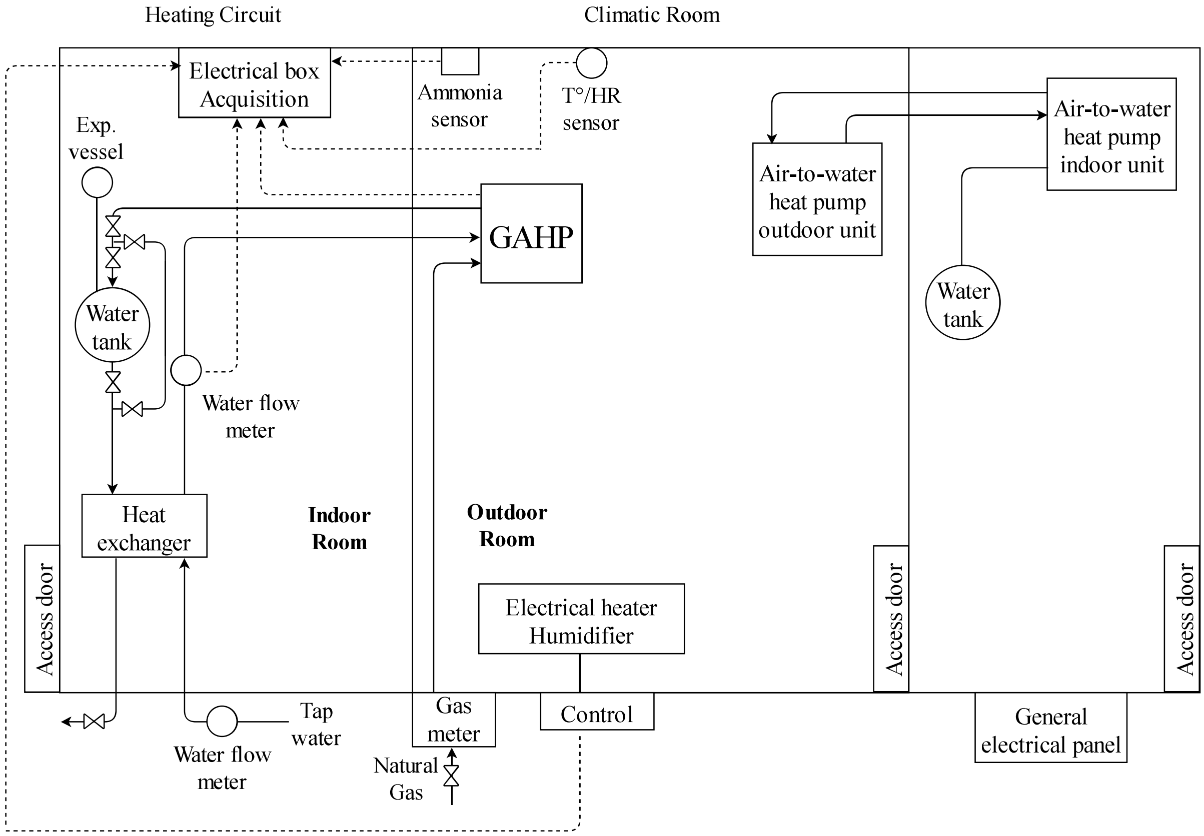

Figure 2. Schematic of the test bench used to characterize the absorption heat pump

In terms of measuring devices, inside the heat pump only surface thermocouples were installed on the different pipes between the components. These thermocouples were placed on an electro-insulating and thermo-conductive sheet, fixed with plastic clamps and insulated at each measurement point to ensure thermal contact and correctly measure the fluid temperature. On the rest of the test bench, in-pipe thermocouples were used. In the cases where the temperature of a large cross-section had to be measured, a grill of thermocouples was used; more precisely, 4 equidistant thermocouples were installed at the fan exhaust and 9 at the evaporator supply. Measurements of gas consumption, water consumption, electrical consumption, room temperature and humidity are also collected.

For caution and since the unit works with an ammonia-water solution that is harmful for health, an ammonia sensor was installed close to the unit to detect leaks and release pipe was installed to extract the ammonia out of the room if necessary. The measuring devices and their characteristics are summarized in Table 1.

Table 1. Measuring devices

Sensor	Type	Accuracy	Number of measure points
Thermocouples	T	± 0.3 K	45
Humidity	Capacitive - wettable	± 2 %	2
Water meter	Volumetric	± 2 % Q_n ; ± 5% Q_{min}	1
	Magnetic	± 0.5% from 0.3 to 11.89 m/s	1

Gas meter	Diaphragm	± 0.5 %	1
Power meter	Multifunctional	± 0.5 %	1
Ammonia sensor	Electrochemical	± 5 ppm	1

Testing conditions

The gas absorption heat pump has certain operating parameters that are supplied by the manufacturer and some of these are modifiable. A display board gives access to different menus and to facilitate the characterization of the system, some of them are changed as described hereunder.

First, it is sought to maintain a constant water temperature difference between the delivery and the inlet of the appliance. To achieve this, the modulation of the circulation pump is activated and the water delta T° is set to 10 K.

Second, it is necessary to set the permissible delivery and return water temperature range of the appliance to not restrict the system's behavior. In other words, a wide enough water temperature range allows to not operate, for example, at partial load. Therefore, the delivery water temperature range is set between 30°C and 75°C, while the return range goes between 20°C and 30°C.

Third, the control method of the delivery water temperature should be set. This can be done by a variable water setpoint which depends on the outdoor temperature (weather compensated control) or by means of a fixed setpoint. The latter method is used, coinciding with the maximum delivery water temperature set (75°C) and having the option of modifying it if necessary.

Finally, it is possible to establish a power output control of the system allowing the modulation of the burner or based on a "On/Off" behavior. The first option is chosen, having as a consequence a modulation of the gas flow on the burner side, while in the absorption cycle it is reflected in variations in the fan and water circulation pump drive voltage.

The described adjustable parameters configuration is shown in Table 2.

Table 2. Adjustable parameters configuration

Description	Setting
Modulation of circulation pump	Active
Heating circuit water $\Delta T°$ setpoint	10 K
Power modulation	Active
Delivery water temperature range	From 30 K to 75 K
Delivery water temperature setpoint	From 45K to 75 K
Return water temperature range	From 20 K to 30 K

The performed test matrix is shown in Table 3. the test campaign is based on the EN 12309 [11] regarding the test conditions at full load refer to the type of appliance (e.g., air-to-water, water-to-water), its application (e.g., low/medium/high temperature), the outdoor heat exchanger conditions referring to dry-wet bulb temperatures and the classification of the climate (e.g., medium, warm, or cold).

To consider the weather conditions to which the appliances are subjected in the field in terms of temperature and humidity, a weather data analysis was made for the cold season from October 2018 to March 2019 based on two local weather stations close to systems [12].

Based on these two aspects, the performed test matrix is shown in Table 3. Here, five outdoor air-dry bulb temperatures and four water delivery temperatures are tested. This base matrix is performed for a relative humidity of 75% since it is the most frequent value obtained from the weather data analysis. Every test is performed at full load on steady state for a period of 20 minutes. The test conditions are monitored throughout the test with a smartphone connected to the appliance besides the test bench data acquisition system.

Table 3. Gas absorption heat pump test matrix

		Water delivery Temperature [°C]			
		35	45	55	65
Outdoor dry bulb Temp.[°C]	12	75%			
	7				
	2				
	-7				
	-10				

Monitoring

The system is installed in two residential houses in the northern part of Belgium. The two houses are considered to be in the same climatical region. These locations have sensors that provide information equivalent to the one obtained in the laboratory to analyze the system's inputs and outputs, allowing to estimate efficiencies and utilization costs among others. The data collected is daily sent to the Cloud for later analysis.

The sites named Brasschaat and Brecht are equally monitored. The used sensors are identical and are placed at the same spots, as can be seen in the installation schemes shown in Figure 3 and Figure 4, respectively.

Both installations count with sensors to measure indoor and outdoor ambient conditions, as well as gas and electric meters to measure the consumptions of the system. A heat meter is installed between the inlet and outlet pipes of the machine to measure the heating energy delivered by the system based on the measurement of the water flow that circulates through the circuit and its respective inlet and outlet temperatures.

The monitored houses count with a water tank for domestic hot water and heat storage. In both sites, the space heating is based on the use of radiators. Additionally, Brasschaat's site has thermal solar panels and an extra buffer for DHW storage, adding complexity to the installation. The heat produced by gas absorption heat pump is directed towards one or the other tank depending on whether the demand is for space heating or DHW.

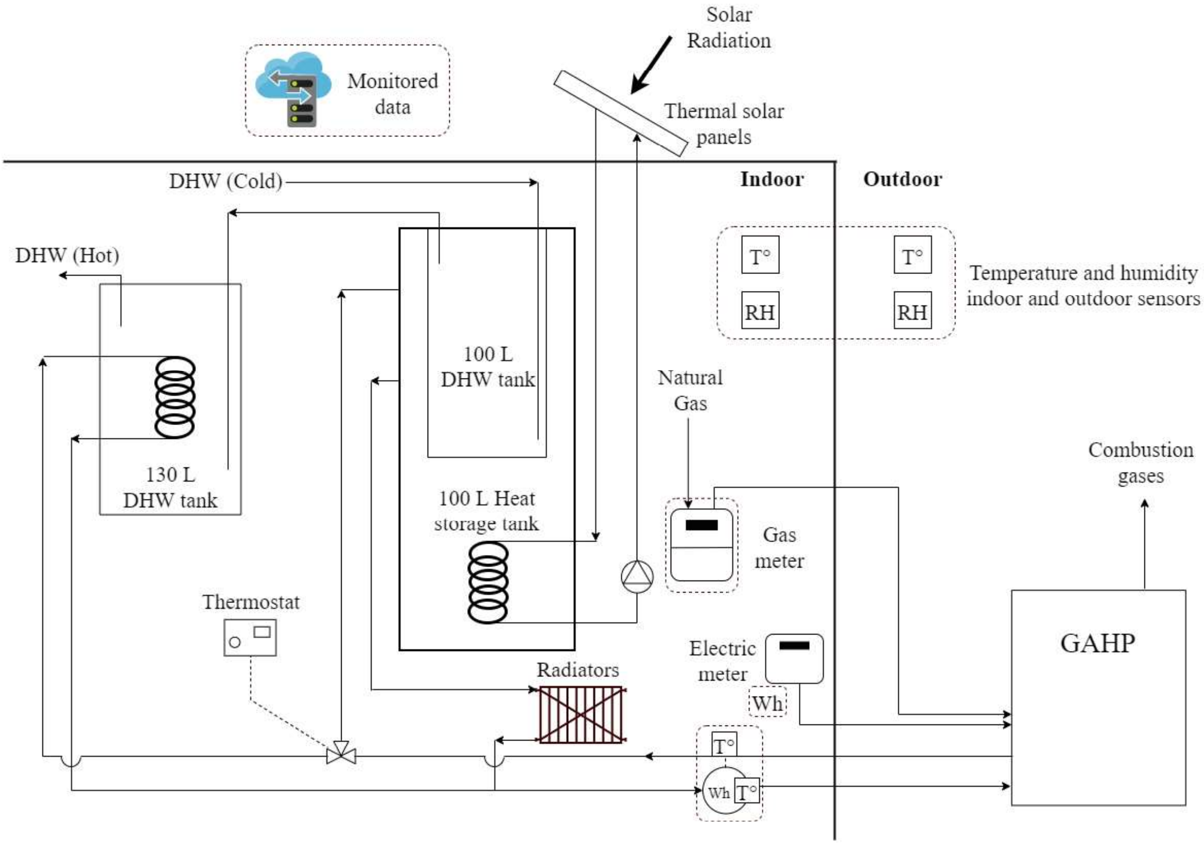

Figure 3. Installation scheme of Brasschaat monitoring site

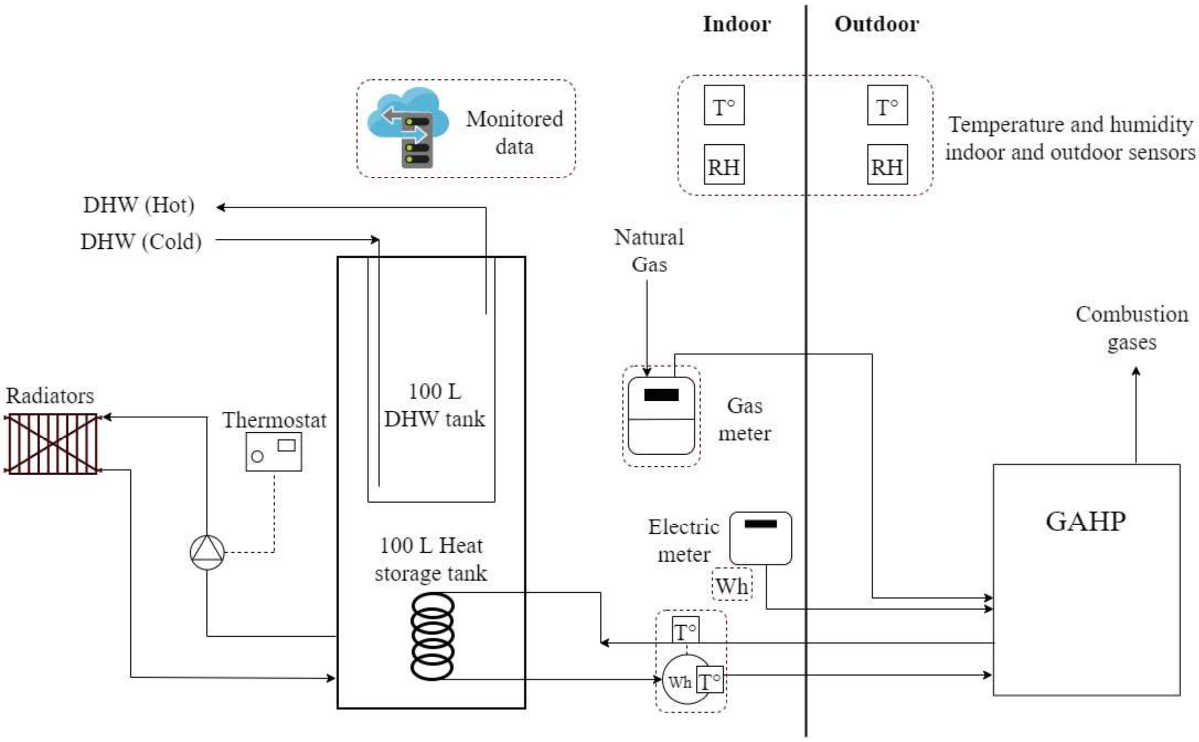

Figure 4. Installation scheme of Brecht monitoring site

The sensors references, their precision and resolution of the acquired data are presented in Table 4.

Table 4. Sensors used at monitored sites

Sensor	**Reference**	**Resolution***	**Precision**
External temperature and humidity	Weptech Munia	0,1 K 0,1 %	± 0,3 K ± 2 %
Internal temperature and humidity	Weptech Munia	0,1 K 0,1 %	± 0,3 K ± 2 %
Heat counter	Qalcosonic E1	1 kWh 1 L 0,1 K	Accuracy Class 2 [13]
Machine electrical energy counter	Iskraemeco ME162	1 Wh	Accuracy Class 1 [14]
Gas volume counter	Elster BK-G4T	10 L	<1%
Data logger (cloud connection)	Viltrus MX-9	-	-

** Data logger included*

It is worth mentioning that some control and internal parameters of the systems such as power modulation or temperature setpoint are not remotely controlled or monitored. This means that changes or modifications made by the user or installer could not be communicated, being difficult or impossible to identify only with the data analysis. A constant monitoring is carried out, without guaranteeing that no omissions ocured that could potentially affect the monitoring data and its subsequent analysis.

Results

- **Laboratory**

A valid data collection period is defined on the European standard based on the coefficient of change shown in Equation (1). If this coefficient remains within 2.5% during the data collection period, then the test can be considered as steady state. This coefficient is the difference between the outlet and the inlet temperatures of the heat transfer medium at the indoor room heat exchanger and should be calculated every 5 minutes starting at the end of the previous period ($\tau = 0$).

$$\%\Delta T = \frac{\Delta T_{i(\tau=0)} - \Delta T_{i(\tau)}}{\Delta T_{i(\tau=0)}} * 100 \tag{1}$$

Where $\%\Delta T$ is the coefficient of change, in %; $\Delta T_{i(\tau=0)}$ is the average difference between the outlet and the inlet temperatures for the first 5 min. period; $\Delta T_{i(\tau)}$ is the average difference between the outlet and the inlet temperatures for other 5 min. period than the first 5 min.

In addition, allowable deviation values from the set values are established. This corresponds to ± 0.3K for room temperature, ± 2% for room mean humidity and ± 1K from the setpoint for the depart water temperature.

The COP (also called *efficiency* in the monitoring section) for each test was estimated as the ratio between the thermal power output to heat and electric power input as defined in Equation (2).

$$COP = \frac{\dot{Q}_{HC}}{\dot{Q}_{gas} + \dot{W}_{in}} \tag{2}$$

The thermal power output corresponds to that given to the heating circuit $\dot{Q}_{HC}$ while the inputs are the thermal heat obtained from the natural gas combustion $\dot{Q}_{gas}$ and the electric input to the appliance $\dot{W}_{\mathrm{in}}$. The thermal power transferred to the water is defined in Equation (3).

$$\dot{Q}_{HC} = \dot{Q}_{WCA} + \dot{Q}_{cond} + \dot{Q}_{gases} \tag{3}$$

Where $\dot{Q}_{WCA}$, $\dot{Q}_{cond}$ and $\dot{Q}_{gases}$ are the thermal powers obtained from the water cooled absorber, the condenser, and the combustion gases, respectively.

Since the internal configuration of the system makes it difficult to install sensors between components that allows to measure the previously defined heat inputs individually, it is decided to estimate the heat input transferred to the water as defined in Equation (4).

$$\dot{Q}_{HC} = \dot{m}_{HC,w} * c_{p,w} * (T_{out} - T_{in}) \tag{4}$$

Where $\dot{m}_{HC,w}$ heating circuit water flow, $c_{p,w}$ is the specific heat of water, T_{out} and T_{in} are the outlet and input water temperatures of the system. Similarly, the heat input is defined in Equation (5).

$$\dot{Q}_{gas} = \dot{V}_{gas} * HCV \tag{5}$$

Where $\dot{V}_{gas}$ is the consumed gas flow and HCV is the daily average high calorific value. The electric consumption of the appliance $\dot{W}_{in}$ is constantly registered and considered on the results, with maximum variations of 2% between tests and close to 0.35 kW. This consumption includes components such as the fan, oil pump, water circulation pump and sensors.

With these considerations, the results obtained for the test matrix are shown in Table 5. The results are computed meeting the requirements of Equation (1) and are based on the average values of the measurements carried out during a 20-minute test.

Table 5. COP and Thermal Capacity values at a relative humidity of 75%

COP		T° delivery			
		35	45	55	65
Outdoor T°	12	1.45	1.34	1.19	1.05
	7	1.38	1.29	1.13	1.04
	2	1.36	1.21	1.09	0.95
	-7	1.21	1.13	1.02	0.86
	-10	1.16	1.14	0.95	0.86

Th. Capacity [kW]		T° delivery			
		35	45	55	65
Outdoor T°	12	21.11	19.31	16.98	14.82
	7	19.55	18.57	16.30	14.92
	2	20.10	18.01	15.64	13.70
	-7	18.33	16.89	15.13	12.65
	-10	17.36	16.82	14.14	12.66

- **Monitoring**

Both sites were exhaustively monitored during 2020. Their monthly efficiencies for the whole year based on the high calorific value are shown in Figure 5. Unlike laboratory results, here the electrical consumption is not included; its effect, however, will only penalize the displayed values.

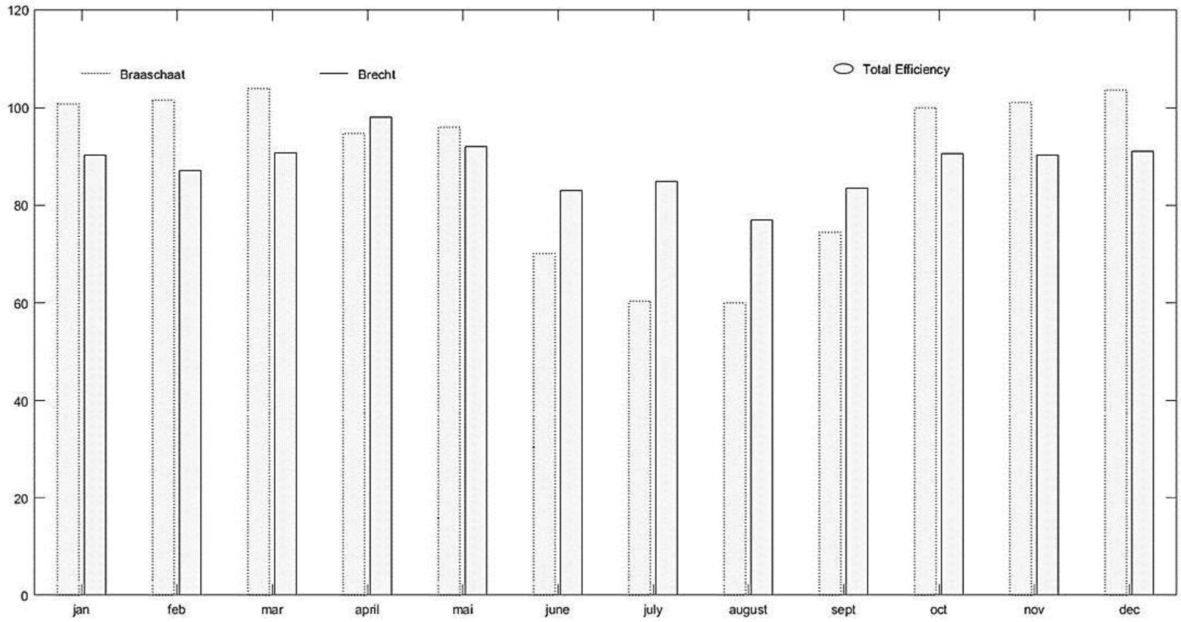

Figure 5. Monitored GAHP's monthly efficiencies

A clear seasonal effect can be observed, showing a penalty in the efficiency during summer that is related to the fact that the systems are less frequently used (no space heating request), generating more on/off cycles to supply only the production of DHW. In this sense, a greater impact is observed in Brasschaat site. This can be partially explained by the coupling of the thermal solar panels and their effect on the working temperature, inducing a change in the behavior of the system. However, these results are far from the ones expected and obtained in the laboratory, especially for winter conditions. Even more, unexpected large differences are observed between the performances of both machines.

To try to explain the differences, an in-depth analysis of the behavior of both systems was carried out. Figure 6 shows the daily thermal production of both sites in relation to their efficiency. Even though Brecht produces more thermal energy compared to Brasschaat, the system is less efficient.

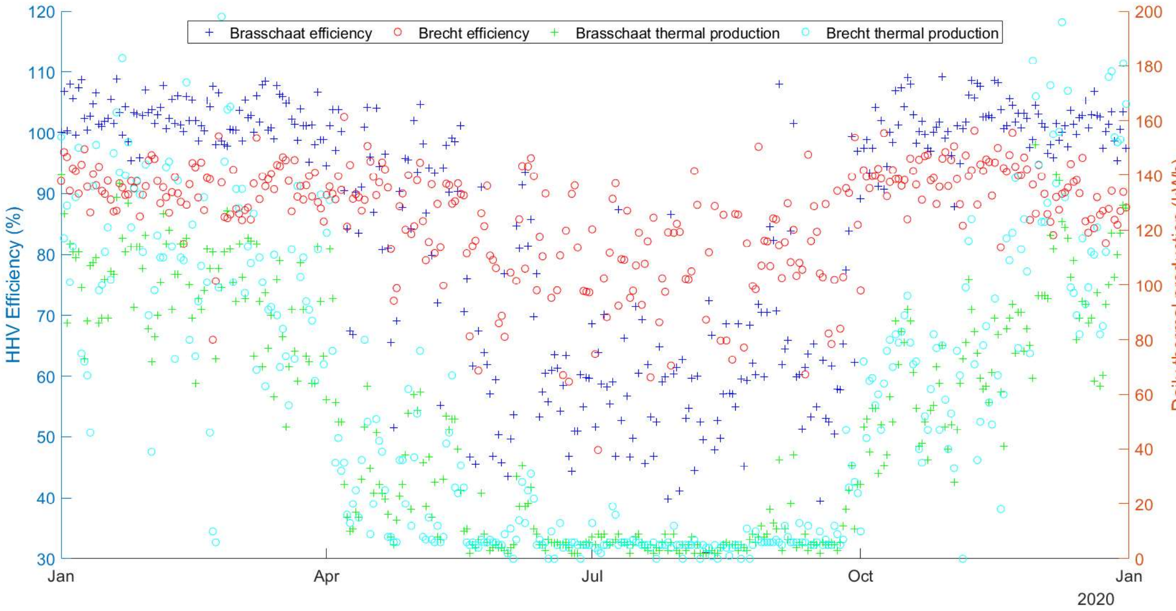

Figure 6. Monitored GAHP's daily thermal production

On the other hand, the daily thermal production is related to the way in which the production of the system is controlled (i.e., On/Off or modulation). Since this information is unknown and is not part of the data collected from the monitoring, a deeper look to try to establish a relationship between the smoothness of the behavior of the system and the electrical consumption is made in Figure 7. Here, Brecht has a higher electrical consumption, thus the machine is working for a longer amount of time which could be related to a smoother behavior; this information though is not conclusive to explain the differences found.

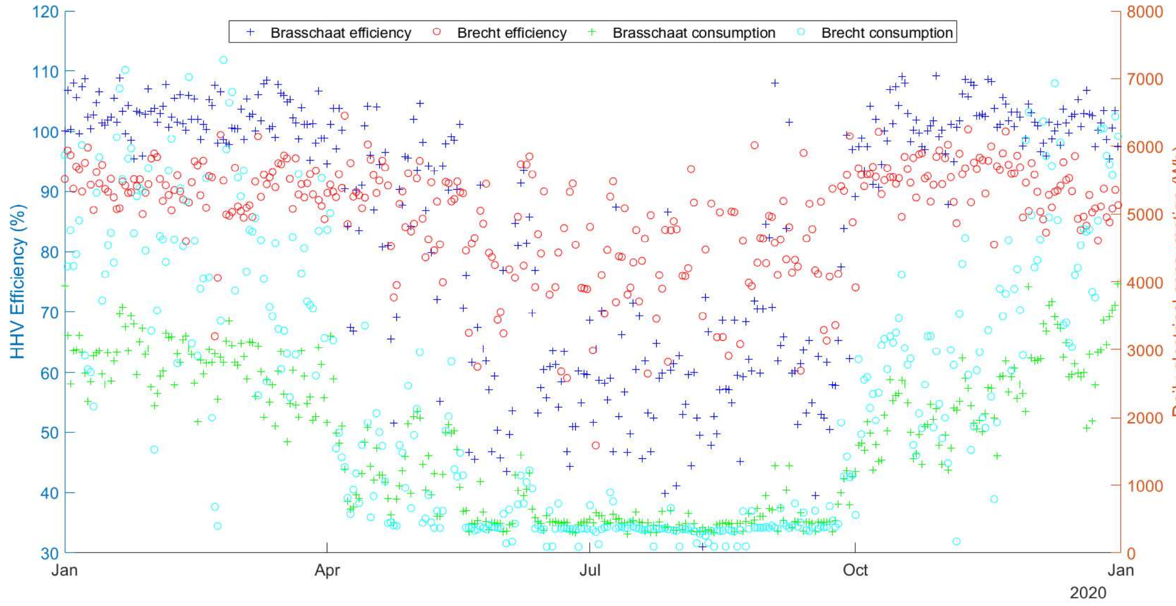

Figure 7. Monitored GAHP's daily electrical consumption

It is noticed that the working temperature of both systems is different as can be seen in Figure 8. Here, it is observed that Brasschaat site does not overpass 40°C of return temperature, while Brecht has a scattered behavior. It is expected that for the temperature range between 30°C and 40°C the systems will operate under similar conditions and therefore, similar efficiency results will be obtained. Despite this, a gap of approximately 10 percentage points is clearly visible.

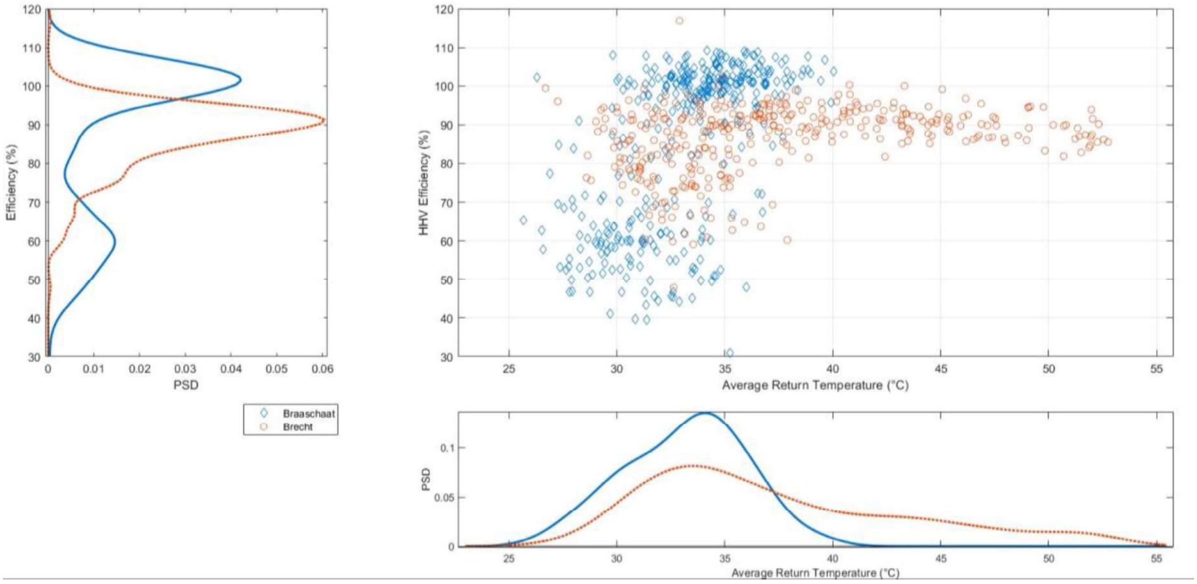

Figure 8. Monitored GAHP’s average return temperature

Conclusions

An experimental investigation of a gas absorption heat pump has been conducted where coefficients of performance have been calculated both in the laboratory and in the field, finding discrepancies between them being the latter lower than the former.

The results obtained in the laboratory confirm the expected trends, with an efficiency that increases as the ambient temperature increases and decreases if the water outlet temperature is higher. Besides, the orders of magnitude obtained correspond to those indicated by the manufacturer for the specified conditions. For the monitored systems, a seasonal effect is clearly observed with total efficiency drops during the summer, with both machines showing not negligible differences between them of at least 10 percentage points on their performance values.

Even though the number of machines tested in this study is far from being sufficient to be statistically representative, it is possible to cross-check valid information between laboratory results and on-site monitored data to make a comparison between the three available systems. However, the information obtained by the monitoring data does not allow to provide a conclusive explanation to the observed differences, being necessary to obtain more information regarding the different adjustable settings of the appliances and the quality of the installation.

Even though the conditions in the field are far from being stationary, an attempt has been made to find some small timeframes for which the machines were submitted to almost stationary conditions regarding external temperature, delivery and return temperature, power output and humidity. A comparison has been made by performing a double linear interpolation within the efficiency matrix obtained in the laboratory to fit the field test conditions, obtaining the results shown in Table 6.

Table 6. Steady state field test conditions and efficiency comparison

	Brasschaat	Brecht
Date and time	10/02/2021 – 16h	10/02/2021 – 14h
Duration of the timeframe of stationary conditions	85 min	140 min
Delivery temperature (°C)	51.25	57.77
Return temperature (°C)	39.1	50
Humidity	0.8	0.79
Outdoor temperature (°C)	-1.8	-1.2
Field test COP (HCV)	1.108	0.837
Double linear interpolation COP (HCV)	1.104	1.024

From here, it is possible to establish *a priori* a correlation between the Brasschaat site and the laboratory results for these specific conditions, but not for the Brecht site. Thus, a more detailed analysis of this facility is required to determine what is the cause of the observed discrepancies, highlighting the main role of the correct integration and control of the system in the performance of the latter.

Acknowledgements

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