13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Trends and Recent R&D Activities on Fuel Driven Sorption Heat Pumps

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Abstract

Over the last 4 years, the IEA-HPP Annex 43 has worked on Sorption Gas Heat Pumps (GHP). GHP have been identified as an efficient solution for space heating and sanitary hot water preparation. There was advance on several ongoing developments both for ad- and absorption technology. A water-ammonia absorption GHP based on plate heat exchangers (PHE) is under development and shows promising results both in terms of compactness and efficiency. An absorption GHP for the residential market is being developed. Another participant is working on the development of an adsorption gas heat pump with active carbon and ammonia as working fluid, using a promising new adsorber design. The development of a zeolite-water based GHP is pursued with a consortium of industry and research partners. The open source SorpPropLib materials database allows evaluation of materials for sorption heat pumps in SorpSim or other platforms. A common view on market requirements and potential was found for different markets.

Selection and/or peer-review under responsibility of the organizers of the 13th IEA Heat Pump Conference 2020.

Keywords: Gas Heat Pump;Sorption;Fuel Driven Heat Pump

1. Introduction

Over the last 4 years, the IEA-HPP Annex 43 has worked on Sorption Gas Heat Pumps (GHP). GHP have been identified as an efficient solution for space heating and sanitary hot water preparation, mainly in existing buildings. They are a complementary technology to electrical heat pumps with potential to reduce requirements on the electric grid and to balance the energy consumption in the future energy mix. Annex 43 had the aim to support the technology through cooperation between industry and academia. At present, due to a lack of competitive commercially available products, the market share of sorption heat pumps on the total heating market is marginal. However, it is expected that a potential exists to assist the transition from completely fossil fuel based heating technologies towards technologies, including environmental heat sources and thereby decreasing the demand on fossil fuels.

2. Results on Gas Heat Pump R&D

There was advance on several ongoing developments both for ad- and absorption technology. At Polimi (Italy), a water-ammonia absorption GHP based on plate heat exchangers (PHE) is under development and shows promising results both in terms of compactness and efficiency. Also an Italian company is working on an absorption GHP for the residential market. University of Warwick (UK) is working on the development of an adsorption gas heat pump with active carbon and ammonia as working fluid, using a promising new adsorber design. Fraunhofer ISE (Germany) works on the development of a zeolite-water based GHP with a consortium of industry partners. At ORNL, research is ongoing on a GHP with salts and ammonia as working pairs.

2.1. Water-Ammonia Absorption GHP based on plate heat exchangers

At Politecnico di Milano research is carried out with the objective of developing an air source gas-fired heat pump for space heating and DHW production for domestic applications. To assure a large potential for market penetration, the target of reducing specific costs and size compared to existing products is addressed. As an additional measure to ease the industrialization of the GHP, it has been decided to rely mainly on components derived from large series production, whose manufacturers actively collaborate to the project. In particular, all heat exchangers, except the desorber, are fusion-bonded plate heat exchangers.

The outcome of the development is a 7.5 kW GAHP prototype, whose diaphragm pump and desorber have been designed to reduce the appliance size to the dimensions of a standard domestic condensing boiler. The effectiveness of different configurations of the refrigerant circuit has been investigated, together with the potential benefits of controlling the flow rate of refrigerant and solution. The achieved performances, measured according to the European Standard EN 12309, are in line with the expectation: a sGUE based on the net calorific value ($sGUE_{NCV}$) of 1.5 has been reached for the average climate (design temperature of -10 °C) and for the high temperature application (supply temperature of 55 °C). However, a detailed analysis shows room for improvements on some of the component, which are expected to boost the $sGUE_{NCV}$ up to about 1.6.

2.2. Active Carbon – Ammonia Adsorption GHP

The overall objective of the research at Warwick was to develop a domestic air source gas-fired heat pump to replace standard condensing boilers cost-effectively. The working pair is ammonia (able to evaporate at sub-zero temperatures, as required for an air-source) and active carbon. A succession of sorption generators have been prototyped, culminating in the 'kebab' design in which monolithic carbon is compressed between aluminium fins on a steel tube containing pressurised water that either heats or cools the adsorbent in a two-bed cycle with heat and mass recovery. The 'kebabs' are illustrated in Figs. 1 and 2.

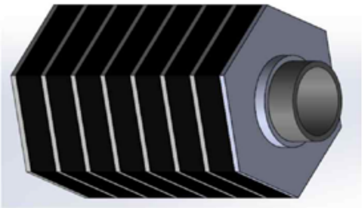

Figure 1: 'Kebab' schematic

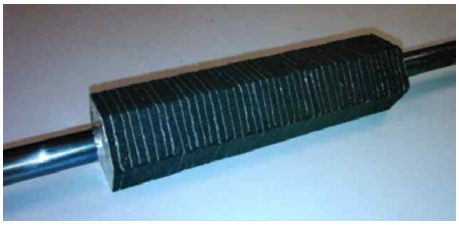

Figure 2: Sample 'kebab'

A 10 kW system was built and tested. Initial results were poor with Coefficient of Performance (COP) a little above 1. This was due to mass transfer resistance in adsorption being too high, due to an excessive binder fraction. A new formulation has been tested in a single 'kebab' and the results are consistent with an internal COP of 1.40 when delivering 10 kW at 50°C and evaporating at 0°C or 1.34 when delivering 20 kW. Simulation results are given in Fig. 3, illustrating how power may be traded off against efficiency. It is clear that the sensitivity of GUE to power output is significant but there is the prospect of achieving an average GUE of > 1.2 in UK climatic conditions. Whether this is commercially acceptable will depend crucially on the production cost. Previous 4-bed configurations with enhanced internal heat recovery [1] show a GUE of 1.4 to be possible but at the expense of greater complexity and cost. The aim here is to explore simpler, low cost options if at all possible.

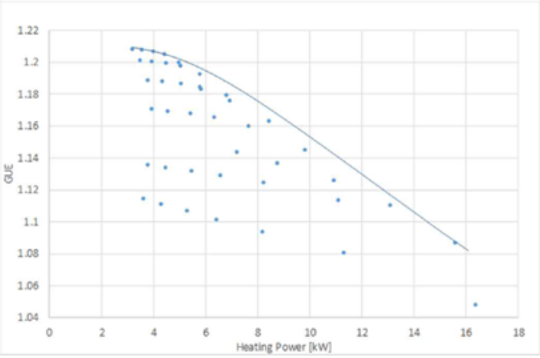

Figure 3: GUE(based on Gross Calorific Value) v. SCP for final design of 208C carbon + organic binder 'kebab'

2.3. Zeolite-water adsorption GHP

Two gas-fired adsorption heat pump products based on the working pair zeolite-water have been on the market by the companies Vaillant and Viessmann. Both are no longer market available, mainly due to high cost and not being able to sufficiently serve the retrofit market with higher needed supply temperatures at reasonable efficiency. Adsorption modules were based on a loose grain configuration and a binder based coating on stainless steel heat exchangers, respectively.

Promising developments with potentially much higher power densities have recently been made at Fraunhofer ISE together with the company Fahrenheit. The combination of an aluminium fibre structure and a direct crystallization coating of a thin zeolite layer on the extremely high surface of such a heat exchanger showed the feasibility of power densities which potentially allow for a wall hung GHP unit [2].

Activities on binder-based coated adsorbers are also being developed by CNR ITAE and University of Messina, mainly focusing on the intensification of heat and mass transfer efficiency with a low-cost and energy intensive manufacturing process [3].

There are yet unresolved issues concerning long-term stability, and proof has to be made that such adsorption modules can be manufactured in a cost-efficient way. One drawback of water as working fluid is the limitation to ambient source temperatures >0°C. A potentially feasible option is the use of exhaust air from a central ventilation unit. Compared to a compression heat pump, a gas heat pump needs only about a third of ambient source power. With a limitation of about 1 kW source power from exhaust air (typical ventilated apartment), a vapour compression heat pump with a COP of 4 could deliver a maximum power of about 1.3 kW, while a gas heat pump with a GUE of 1.3 could deliver about 4 kW.

2.4. Salt-Ammonia GHP

An ammonia-based triple-state sorption heat pump was developed and investigated by ORNL and SaltX to significantly improve the current gas heating efficiency in cold climates. The gas-fired heat pump extracts heat from cold ambient by absorbing ammonia onto salt held in a nano-coated matrix, and it supplies high-temperature heat from heat of adsorption and the heat of ammonia condensation when the salt is heated and desorbs ammonia. A simulation study identified the optimal heat pump sizing as 22-44% of peak heating load for the shortest payback under typical cold climate conditions in the U.S [4,5].

A laboratory prototype with design targets of delivering 54.4°C (130°F) hot water under ambient temperature of -20°C with GUE > 1.0 has been developed a Swedish company and ORNL and evaluated experimentally at ORNL. The prototype has a simple configuration including a salt-containing reactor and a salt-less combined condenser-evaporator. No pump or valves are needed in the fully hermetic ammonia system. The COP and capacity of the prototype progressed with insulation and improved controls in the shakedown tests, and a heating capacity of 4.4 kW at 55°C hot water supply with a cycle GUE of 1.02 was demonstrated in the laboratory with 8°C simulated ambient temperature. A dynamic model using finite-difference method has been developed for the salt-containing reactor and is now being validated with test results.

Another outcome of the Annex is the compilation of vapor pressure properties for sorption working pairs into the open source SorpPropLib materials database developed by ORNL and Purdue University. This allows evaluation of materials for sorption heat pumps in SorpSim or other platforms [6].

3. Performance potential study

A simulation study has been performed to provide performance numbers of gas fired sorption heat pumps in the residential sector in order to assess the impact of such systems with respect to environmental effects, compared to conventional heating systems.

3.1. Scope

A comparative approach is applied in this study: two different fuel driven sorption heat pump technologies based on currently developed technologies are compared with conventional heating technology, representing the exclusive use of a condensing gas boiler (reference system). The phrase 'current technology' in this context means one market available technology (ammonia-water absorption technology) as well as present laboratory test status of a water-zeolite adsorption technology. For these technologies, reliable data to execute the comparative calculations are available. Other technologies (e.g. ammonia-active carbon adsorption, ammonia – salt absorption, other ammonia-water absorption cycles) are still under development and may achieve promising performance results in the near future, see sections above.

To assess the potential of the heat pump systems, building loads from typical residential buildings are applied. The loads are generated through building simulation, but on base of well-defined building standards. The applied building models range from non-retrofitted multi-family houses (MFH) to new single family houses (SFH, present building standard). All calculations are executed for meteorological conditions of five European sites.

Economical aspects and life-cycle aspects are not topic of this study. An energetic and economic comparison of absorption and electrically driven compression heat pumps is e.g. shown in [7].

Thus, the performance figures and environmental savings presented in this study reflect the running system operation. The results are presented as annual values of performance (i.e., gas utilization efficiency) and environmental savings in comparison to the reference system (i.e., CO2 and primary energy savings and primary energy ratio).

3.2. Sites and thermal building loads

Climate data of five European sites (London, Potsdam, Paris, Strasbourg, Milano) were applied in the study, to determine the building heat loads. From a meteorological point of view, the sites correspond to the climate classification [8] of Cfb (warm temperate climate, fully humid, warm summer) with the exception of Milano, corresponding to Cfa (warm temperate, fully humid, hot summer) respectively.

Despite of identical or similar climate classification, the site dependent temperature conditions reveal large differences in heating demand for the buildings in the survey. For the calculation of the heat demand, hourly data of ambient temperature and humidity were generated for each site by use of the meteorological engineering software Meteonorm [9].

For four sites, the minimum ambient temperatures are still above -10°C and thus conform with the 'average climate‘, as classified in the European Standard EN12309, part 7 [9], whereas the Potsdam site normally fits to the 'cold climate‘ classification. Nevertheless, in the light of the very few hours of falling below -10°C at Potsdam site and for reasons of a better comparison of the results, the heating system temperature curve of the 'average climate‘ was applied in the calculations to all sites.

The meteorological data set of Strasbourg is additionally used for the performance calculation of a representative European site (EU), applying European conversion numbers for primary energy use and greenhouse gas emission instead of individual national conversion numbers.

In the building sector, multi-family houses (MFH) play an important role in greenhouse gas avoidance strategies, as their share on building stock and on living space area is high. e.g., in Germany, 31% of the living space accounts to small and medium size MFH with 3 to 12 apartments [10]. Another reason for the interest in MFH in the context with this study is that the market available gas fired sorption heat pump from the manufacturer Robur with its capacity of 18 kWth or above yet does not fit to small residential buildings.

For the assessment in this study in the context with a larger gas driven heat pump, an MFH model was applied, which was defined within the activities in the Low-Ex project group [11]. The building model images an MFH with 3 floors and 3 apartments on each floor. The building standard corresponds to the construction period of 1959-1978, as compiled by the Tabula/Episcope Projects (see: http://episcope.eu); the total number of occupants is 13. The building model setup and calculation of thermal loads was performed in the simulation environment of TRNSYS, version 17 [12].

Two versions of the building are applied:

1. MFH as representative for an average German non-retrofitted building (building stock);
2. MFH+ retrofitted in a conventional way according to Tabula/Episcope specifications for Germany, which resemble the requirements of the German EnEV 2014/2016 [13].

The load data are transferred to hourly data of each hour of a representative year of meteorological data for the sites previously specified. Additionally, thermal loads for preparing domestic hot water (DHW) for the buildings are included. The annual share of heat demand for DHW preparation on the total heat demand is shown in Figure 4, revealing the distinctly higher significance of hot water preparation in buildings with higher energy saving standards.

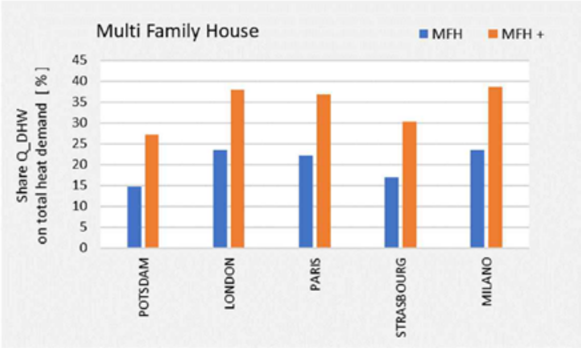

Figure 4: MFH: Share of heat demand for DHW preparation on the total heat demand.

For small capacity gas fired adsorption heat pumps, the market of single family houses (SFH) is of especial interest. Within this comparative study, two single family houses were modelled and heat loads for the sites given in Figure 2.1 have been determined:

1. SFH+ as representative for a retrofitted building with 120 m² living area;
2. SFH_{NEW} as representative of a new building with 150 m² living area.

The load calculations were carried out with a one-node building model according to DIN EN ISO 13790 [14]. The adopted U-values of the key building components are the averages of the published values of the respective countries.

The load data are determined as hourly data of each hour of a representative year of meteorological data for the sites previously specified. An overview on site dependent heating loads is given in Annex A1 of this study. The number of occupants in both buildings is 4; the DHW loads are calculated accordingly on base of the approaches, used for the MFH.

The annual share of heat demand for DHW preparation on the total heat demand is shown in Figure 5. In general, the set value of supply temperature in heating systems is expressed as a function of the ambient temperature. This heating system temperature is essential in the calculations, since the performance of sorption heat pumps as with all heat pumps is very sensitive to the supply temperature level.

In this study, the heating system temperature relations are derived from EN12309, part 7 [9]. The High Temperature curve (max. 55°C) requires moderate effort in exchange of e.g. appropriate radiators and is applied in the calculations of the multifamily buildings (stock and retrofit) in combination with the gas driven ammonia-water heat pump.

The Medium Temperature curve (max. 45°C) requires more ambition in the heating distribution system and is applied in the MFH+ and additionally in the calculations of the single family houses, where adsorption heat pumps are considered.

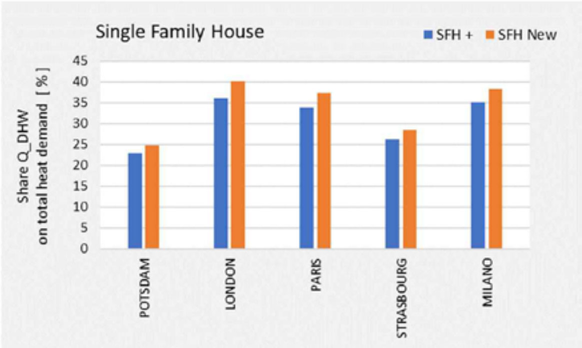

Figure 5: SFH: Share of heat demand for DHW preparation on the total heat demand.

3.3. Thermally driven heat pump models

Ammonia-Water absorption heat pump

The model is based on the gas fired absorption heat pump from Robur, model K18. The machine uses the fluid pair ammonia and water and requires ambient air as low-temperature source. Since the evaporator is integrated into the machine, the heat pump is designed for external installation. The K18 model provides a heating capacity of 18 kWth (some basic data are given in [3.1/1]). Due to the ability to deliver hot water of up to 60°C, DHW can be prepared beside space heating. The simulation model of the Robur K18 heat pump was developed by POLIMI [15] and has been applied in other comparative studies as well, such as [16, 7].

The simulation of the K18 heat pump system reflects a system setup where either the DHW buffer storage is heated or the space heating is served. In the latter case, a backup gas boiler is implemented to cover peak loads on demand. This is especially required in applications with a high exploitation of the heat pump and at colder sites (e.g., Potsdam, Strasbourg).

Water-zeolite adsorption heat pump

The adsorption heat pump model is based on experimental laboratory tests at Fahrenheit GmbH and modelling based on these results by Fraunhofer ISE; the machine is not market available yet. In the experimental setup, the working pair water with the zeo-type material SAPO-34 as adsorbent is applied. The adsorption module consists of two similar heat exchangers, one acting as combined evaporator/condenser (EC) and the other as adsorption heat exchanger (AdHX). The AdHX is coated with SAPO-34 with the partial support transformation technique as by Bauer et al. [17]. The experimental results and the component data were published by Wittstadt et al. [2].

A detailed numerical model of the adsorption module was developed at Fraunhofer ISE and validated with the experimental data. The model allows the variation of geometric key parameters of the components in order to optimize the adsorption module for a given application [18]. The data presented here are obtained with geometrically optimized components for the heating application. One important difference between the experimentally tested module and the optimized module is the size of the EC. The size of the EC was reduced significantly in order to improve the efficiency without worsening the overall dynamics of the module. The model takes into account important loss mechanisms such as condensation of the working fluid on the housing and heat flux from AdHX to EC.

The heat pump for this study is considered to be connected to a ground tube as low temperature source, as low temperatures < 5°C until now cannot efficiently be used with water as working fluid due to freezing in the evaporator.

The following operation boundaries were included in the model:

- Low temperature source temperature: 5°C - 9°C;
- Medium temperature (inlet into AdHP): 25°C – 43°C;
- Desorption temperature (driving heat from gas boiler): 80 °C – 120 °C

The source temperature is determined as a function of the ambient temperature in accordance with VDI 4650, which provides corresponding values for heating operation [19]. The maximum heating capacity of the

AdHP research unit is approx. 7 kWth. However, in the comparative study, the capacity is site dependently adjusted to the building load with the target to maximize the annual overall sGUE (heating and DHW, including gas boiler performance). Thus, the maximum capacity in calculations ranges from 7 to 11 kWth.

To emphasize a special advantage of adsorption modules, the cycling period of the sorption process can be controlled in a variable way. In the model, this period is varied between 75 s (high power output, but moderate to low GUE values) to 500 s, resulting in low power output in part-load situations, but performing at distinctively higher GUE values.

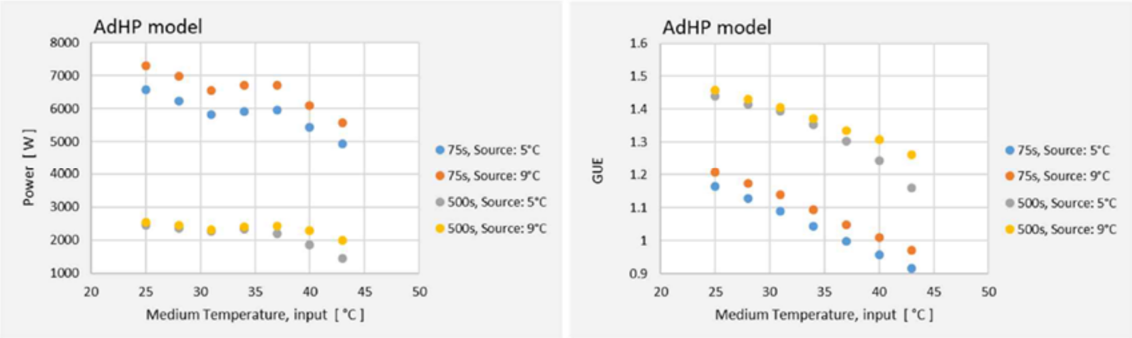

Figure 6: Performance of the AdHP versus the medium temperature input. Displayed for the minimum and maximum cycling period (75s and 500s resp.) and for the low temperature bounderies 5°C and 9°C. The lowest GUE values occur at medium temperatures close the upper limit and at lowest source temperature (5°C) and at short cycling period. In this operation mode, the efficiency is comparative to the gas boiler efficiency.

For the determination of the actual GUE in the simulation, the gas boiler runs in desorption with fixed efficiency of 85%, but additional heat recovery in the flue gas heat exchanger increases the heating capacity and thus the GUE. This is considered through an increase in overall boiler efficiency, using the relation between hot water temperature (Medium temperature) and efficiency as described.

To illustrate the scope of the AdHP performance, Figure 6 shows examples on modelled performance for the minimum and maximum low temperature source and for the minimum cycling period (high capacity) and maximum cycling period (low capacity, high GUE).

In the comparative study, a gas boiler, foreseen to be integrated into the AdHP and actually turning it into a hybrid heat pump being able to run in direct or heat pump mode, serves as high temperature source for desorption. Moreover, the boiler is used as peak-load and backup boiler (e.g., heating to the set point, in case the output temperature of the sorption unit is not matching the set value, given by the heating temperature curve). The boiler additionally covers all of the DHW heat demand, since the inlet temperature range into the heating circuit of the sorption unit is below the temperature levels of the DHW buffer: the lowest temperature level in the DHW buffer in the simulation is 45°C; this corresponds well with field monitoring results, gained in the German ‘WP Monitor’ project [20].

The system integration, applied in the comparative study for the AdHP development, is shown in figure 7.

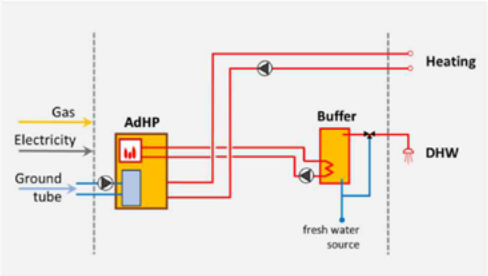

Figure 7: Sketch of the heating system with the Adsorption heat pump (AdHP).

Condensing gas boiler

The GAHP model returns the GUE for each time step; the model is based on test data. Thus, the internal boiler efficiency for heating and DHW preparation with the sorption module is indirectly included. For the external peak load boiler in the GAHP and for the gas boiler in the AdHP system (Figure 7), the efficiency (base: gross calorific value GCV) is simply calculated as function of the hot water input temperature into the boiler. The function is shown in Figure 3.6 and is derived from Haller et al. [21].

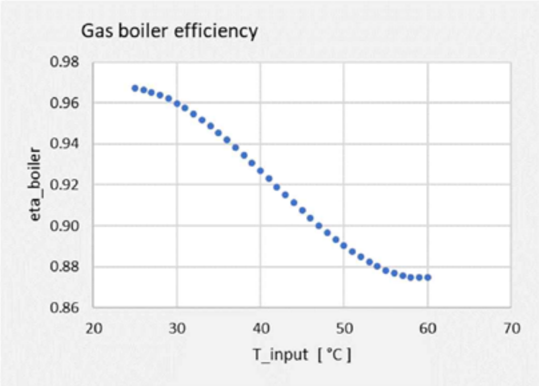

Figure 8: Efficiency model of the gas boiler (peak load use and DHW heating in the AdWP system).

3.4. Results

In the following, annual results from the simulations are depicted for the sites, buildings and heat pump systems as described. For the five sites, national conversion factors for primary energy use and CO_2 emissions were used to determine the environmental performance figures.

For each site and building, a reference calculation is carried out, considering a system without heat pump but with a gas condensing boiler as only heat source for heating and domestic hot water (DHW) preparation. Focus is on the performance (seasonal Gas Utilization Efficiency, sGUE) and on environmental benefits such as CO_2 and primary energy savings (relative to the expenditures in the reference system) and on the primary energy ratio PER. The total annual $sGUE_{total}$ is calculated by including all gas input into the heat pump and peak load boiler for both heating and DHW preparation.

The calculation of environmental benefits includes beside natural gas consumption the electricity consumption in the low temperature sources (fan of air source unit, pump of ground tube circuit respectively) and auxiliary electricity demands, e.g. for the gas boiler fan. Electricity demand for heat distribution in the building is not considered, as no substantial deviations from the reference system for this purpose are expected.

Table 1 summarizes the results by order of the building types. The range of the results expresses site dependent differences.

The results are interpreted in the following way:

Absorption heat pump system (ammonia-water):

- Highest performance is achieved at applications with a high degree of utilization (high workloads), as the heat pump performs more favorable in this operation mode. This is especially the case in the non-retrofitted MFH;
- The performance in combination with MFH+ is comparatively low due to unfavorable part-load operation of the heat pump, since the machine is oversized for this building loads (since the market available Robur 18 kW_{th} is modelled, the capacity is not varied in the simulations). Thus, in an additional calculation two buildings are served by one heat pump in order to achieve more appropriate workloads (case: MFH+, 2 units). This leads to increased performance, comparative to the results obtained in the MFH;
- If in the retrofitted MFH+ the heat distribution systems are additionally replaced by low-temperature distribution systems, allowing the Medium Temperature heating system curve. In this combination,

the highest system performance and environmental benefits are achieved (MFH+, 2 units; Medium heating temperature);

- In the most favorable applications, the sGUE (GCV) exceeds 1.35 and annual CO_2 savings up to 30 % are obtained;
- The high performance in nearly all applications is supported by the ability of the ammonia-water heat pump to cover the DHW demand as well. This is especially important in retrofitted buildings, which show a high share of DHW on the overall heat demand.

Table 1. Summary of the results for the two different heat pump systems, sorted by building types. The range of the results is due to site dependent differences. The most favorable applications are highlighted in blue.
The capacity factor indicates the adjustment of the heat pump capacity, in order to achieve an adequate heat pump operation. The factor is applied to the nominal capacity of the adsorption unit (7 kWth). The absorption heat pump model was not adjusted, as this unit is market available.

	Heating Curve	$sGUE_{total}$	Relative CO2 savings	Relative PE savings	PER / PER_{Ref}	Capacity factor
		-	%	%	%	-
Absorption: Ammonia-Water						
MFH	High	**1.30 – 1.36**	**22.9 – 28.8**	**21.5 – 26.0**	**27.4 – 35.1**	**1**
MFH⁺	High	1.22 – 1.30	19.2 – 26.3	19.5 – 24.0	21.3 – 31.5	1
MFH⁺ , 2 units	High	1.29 – 1.35	23.0 – 29.2	21.6 – 26.5	27.6 – 36.0	1
MFH⁺ , 2 units	Medium	**1.32 – 1.37**	**24.7 – 30.0**	**23.1 – 27.2**	**30.1 – 37.3**	**1**
Adsorption: Water-Zeolite						
SFH⁺	High	1.13 – 1.16	16.5 – 18.7	16.4 – 18.0	19.7 – 22.0	1
SFH^{NEW}	High	1.12 – 1.13	15.9 – 17.5	15.7 – 16.7	18.6 – 20.0	1
SFH⁺	Medium	**1.17 – 1.21**	**18.6 – 21.3**	**18.5 – 20.4**	**22.7 – 25.6**	**1**
SFH^{NEW}	Medium	**1.15 – 1.20**	**17.5 – 20.5**	**17.4 – 19.8**	**21.1 – 24.7**	**1**
MFH	High	1.07 – 1.12	9.8 – 14.6	9.8 – 14.5	10.9 – 16.9	1.5
MFH⁺	High	1.06 – 1.13	11.0 – 15.8	11.0 – 15.7	12.4 – 18.6	1.5
MFH⁺	Medium	1.12 – 1.15	14.9 – 17.7	14.9 – 17.1	17.3 – 20.6	1.5

Adsorption heat pump system (water-zeolite):

- The performance is lower than in the ammonia-water systems in some operation modes. However, in part-load operation modes, the adsorption system benefits from the possibility to increase the performance switching to higher cycle periods and thus showing in such operation modes an inverse behaviour than the ammonia-water heat pump. An appropriate layout and control of the adsorption system is therefore essential;
- The performance is affected due to the fact, that DHW demand is not supported by the heat pump, but completely served through the gas boiler. The latter fact is important, since in retrofitted or new buildings the DHW share on the total heat demand increases;
- The heating system temperature curve is more important in the application of this heat pump than in case of the ammonia-water heat pump. Thus, the highest performance is achieved in buildings, allowing the medium heating temperature curve;
- In the most favorable applications, the sGUE is in the range of 1.2 and annual CO_2 savings up to 21% are obtained.
- It needs to be kept in mind that a very simple configuration of an adsorption GHP has been modelled, which does not allow for any kind of heat recovery. Also, the limitations of the zeolite-water working

pair reflect in the fact that the device cannot be run in heat pump mode for LT source temperatures below 0°C due to freezing in the evaporator. Both issues might be overcome by recent technological developments e.g. with Active Carbon – Ammonia as working pair or by making use of an LT heat source >0°C, see above.

Table 2 presents the results by order of the sites. The range thus reflects the influence of building types and applied heating temperature curves.

Table 2. Summary of the results for the two heat pump systems and different buildings and heating system curves, ordered by sites. EU denotes the representative European site, using climate data of Strasbourg and default European conversion factors (primary energy use and CO_2 emissions in electricity consumption).

	Building, Heating Curve	$sGUE_{total}$	Relative CO2 savings	Relative PE savings	PER / PER_{Ref}	Capacity factor
		-	%	%	%	-
			Absorption: Ammonia-Water			
Potsdam	all	1.22 – 1.32	19.2 – 24.7	19.5 – 24.9	24.4 – 33.3	1
London	all	1.30 – 1.37	24.3 – 27.6	24.0 – 27.2	31.5 – 37.3	1
Paris	all	1.28 – 1.36	26.3 – 30.0	20.7 – 24.8	26.1 – 33.0	1
Strasbourg	all	1.23 – 1.33	23.4 – 28.1	17.6 – 23.1	21.3 – 30.1	1
Milano	all	1.27 – 1.36	22.4 – 27.1	22.6 – 27.0	29.2 – 37.0	1
EU	all	1.23 – 1.33	20.7 – 25.8	20.4 – 25.6	25.6 – 34.3	1
			Adsorption: Water-Zeolite			
Potsdam	all	1.06 – 1.21	9.8 – 20.3	9.8 – 20.4	10.9 – 25.6	1 – 1.5
London	all	1.12 -1.18	14.6 – 18.9	14.5 – 18.8	16.9 – 23.1	1 – 1.5
Paris	all	1.11 -1.18	14.1 – 20.2	12.6 – 18.5	14.4 – 22.7	1 – 1.5
Strasbourg	all	1.07 – 1.20	11.6 – 21.3	10.1 – 19.4	11.2 – 24.1	1 – 1.5
Milano	all	1.08 – 1.17	11.8 – 18.6	11.7 – 18.6	13.3 – 22.8	1 – 1.5
EU	all	1.07 – 1.20	10.9 – 20.4	10.8 – 20.3	12.1 – 25.5	1 – 1.5

Considering the two heat pump systems (absorption and adsorption), a difference occurs at the 'colder' sites Potsdam and Strasbourg: In the ammonia-water heat pump system, the performance at Potsdam and Strasbourg is below the performance at the other sites. This is due to the fact that higher heating supply temperatures in general affect the performance. In principle, this is true as well in the water-zeolite system, but the effect can be superposed by the DHW preparation: due to the high heating loads at these sites, the share of heat demand for DHW is smaller than at other sites. For this reason, the influence of the low-performance DHW preparation done by the gas boiler is smaller as well. Consequently, the overall performance achieves comparatively high values in some applications. In the ammonia-water system this effect is not appearing, since hot water is prepared by the sorption heat pump as well.

4. Summary, Discussion and Future Perspective

The results underline the capability of gas fired heat pumps to distinctly decrease environmental loads in terms of CO_2 emissions and primary energy demand. In currently available applications, savings of 30 % (CO_2)

and an improvement in PER of > 35 % can be obtained. This is a significant increase in efficiency of the overall heat supply in residential buildings.

The highest sGUE value close to 1.4, achieved in the GAHP system at London site in the MFH, corresponds very well to the simulation results of 1.37-1.38, published in the UK summary report on Annex43 [22] for UK houses.

Considering the EU site with default EU conversion factors, highest performance is achieved in the GAHP system, serving two units of the MFH+, and resulting in an annual sGUE of 1.33 and close to 26 % of CO_2 savings (Medium heating temperature).

However, differences between the analyzed technologies, i.e., ammonia-water absorption and water-zeolite adsorption, are obvious. Performance results for the AdHP are throughout below the performances of the GAHP system. The main reason for this difference is the necessity in the AdHP system to use the gas boiler for DHW preparation. This requirement, resulting from present laboratory tests with water-zeolite adsorption technology, lowers the efficiency considerably, as e.g. the share of heat demand for DHW preparation in well retrofitted or new single familiy houses is high. In the mid-term, the focus in the development of adsorption heat pump thus should allow to use the sorption unit for DHW preparation at adequate temperatures as well. It can be seen from the simulations, that the sGUE's for space heating only in the AdWP system are very promising and approaching to annual values of 1.4.

Likewise in many heating systems, an appropriate layout of the heating components is essential. As an outcome of this comparative approach, the different part-load behaviour of the heat pump technologies leads to oppositional performances: whereas the GAHP (the market available Robur K18) obviously performs better at high utilization and an oversizing therefore has to be avoided, the AdHP (test bench model) performs much better in part-load situation through the unique possibility of cycle variation in adsorption modules. Thus, undersizing of the AdHP decreases the annual performance.

In general, lower requirements on the heating temperature, e.g., application of the medium heating system temperature curve, improves the performance. This is especially true for the zeolite-water AdHP, which shows advantages in new or retrofitted buildings with fewer requirements on high heating temperatures.

Although the performance figures of the sorption heat pump technologies, analyzed in the context of residential building heating in this study are promising, many steps towards a higher share of market penetration have still to be done. With respect to the adsorption technology, a challenge remains in enabling domestic hot water preparation, i.e., to increase the supply temperature level, and further to allow the use of a more widely available low temperature source, in the best case ambient air or building exhaust air. Identifying proper materials and heat pump design allowing for this, will make the technology complementary to present absorption (i.e., ammonia-water) technologies in the residential sector.

Other obstacles in market penetration are connected with cost, awareness of building planners and building service companies and system integration. These topics are not touched in this study. However, gas fired sorption heat pump systems are still a new technology and demonstrate great potential to decrease the gas consumption considerably on the one hand without stressing the public electricity grids on the other hand. Thus, the technology can assist European and national efforts towards a low-carbon energy supply system transformation.

Gas (natural gas, biogas, hydrogen etc.) heat pumps for domestic use are potentially a huge market if they can become the successor technology to condensing boilers whose worldwide production exceeds 13 million/year. Sorption technology can reduce gas consumption for domestic heating by almost 40% (existing products) and might increase the saving to 60% with corresponding benefits in GHG emissions.

Acknowledgements

The work of Warwick University presented here has been supported by RCUK grant EP/K011847/1, Interdisciplinary Centre for Storage, Transformation and Upgrading of Thermal Energy (i-STUTE) and Department for Business, Energy and Industrial Strategy, BEIS Low Carbon Heating Technology Innovation Fund grant 'Adsorption gas heat pump'.

The work presented by Fraunhofer ISE and Fahrenheit has been supported by the German federal ministry of Economic affairs and energy (BMWI) under grant number FKZ 03ET1554 and FKZ 03ET1127.

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