Development of a compact ammonia-water Gas Absorption Heat Pump

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Abstract:
Costs and size reduction is crucial to assure a large market penetration of Gas Absorption Heat Pumps (GHP) and the resulting cut in CO2 emissions. Such target has driven this work, focused on the development of a small rated ammonia-water GHP, mainly built of 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 is an 8 kW GHP prototype, whose diaphragm pump and generator have been specifically designed to reduce the appliance size to the dimensions of a domestic condensing boiler.
We investigated the effectiveness of different configurations of the refrigerant circuit, and the benefits of adapting the flow rate of refrigerant and solution to different operating conditions.
We achieved a remarkable Seasonal Gas Utilization Efficiency (SGUE) of 1.58 on a net calorific value basis, according to standard EN 12309-6:2014.

1 Introduction

Gas Absorption Heat Pumps (GHP) can play a major role in reducing the CO2 emissions for space heating and domestic hot water production in existing buildings: they can replace gas boilers, while operating efficiently even with a high-temperature heat distribution system (radiators) and if air sourced [1]. Moreover, running on natural gas, they can handle the peaks of the demand exploiting the large capacity of existing gas and future hydrogen networks, without impacting on the electrical grid.
Absorption is a mature technology, but not in the heating sector and, more specifically, not in the residential field. Just one manufacturer of ammonia-water heat pumps is on the market, an Italian company which has demonstrated their feasibility and reliability by means of thousands "light commercial" installations. On the other hand, such market area does not have a suitable scale to boost GHPs industrialization and achieve the required cost reduction. Ammonia itself has been inherently a further limit to industrialization, as it requires steel components and rules out most of the available products normally applied in the refrigeration, which are either made of copper alloys or have unsuitable sizes being intended for industrial plants. As a result, the heat exchangers of the ammonia circuit have been so far realized in-house by the few manufacturers engaged in the development of this technology.
The scientific community can support the industry by focusing the research on practical features actually needed for absorption heat pumps large deployment, i.e. operational flexibility, long term reliability, low cost and small footprint.
In this perspective the present project aims at developing a reliable, compact, cost effective air-source ammonia-water GHP with a large modulation range. This research started from a modelling and simulation activity as the base of components sizing and design process, alternate with an extensive experimental work, until the present version of GHP prototype, which meets the project targets. In this paper we present (where not prevented by IP protection issues) the specific features of such prototype and how the final design has been selected. Then the energy performances of the prototype, measured by an accredited laboratory in accordance to the relevant international standard are reported.

2 Experimental Set-up

The subject of our development is an 8 kW air-source heat pump, with an intermediate water-glycol solution circuit between the evaporator and the outdoor heat exchanger. Despite the need of an additional heat exchanger, which may slightly reduce the efficiency, such layout has several advantages. At first it is more flexible since it enables different defrosting modes and simplifies the manufacturing of the air-side heat exchanger, allowing for the use of standard components (e.g. copper tubes). Moreover, a separate air-to-brine heat exchanger can be installed outdoor, while keeping the rest of the GHP indoor, with benefits in terms of heat loss reduction. The results presented in this work refer to the development of the sealed circuit, with a controlled brine flow used as heat source.

Our prototype is based on a single effect absorption refrigeration cycle and comprises variable expansion valves, both on the solution and refrigerant side. These are shown in the outline of prototype's circuit in Figure 1 (EV1 and EV2), together with the main components of the GHP: CONdenser, EVAporator, ABSorber, GENerator, RECtifier, Solution Pump (PSO), Ammonia Storage Vessel (ASV, shown in different points of the circuit), Flue gas heat recovery unit (FHX), Solution Heat Exchanger (SHX), Refrigerant Heat Exchanger (RHX).

Single effect cycle requires the smallest number of heat exchangers and is less affected than more advanced cycles as the GAX cycle [2] by part load and high temperature lift operation, both frequent conditions for heating applications. Moreover, the lower efficiency of single effect cycle has been compensated designing a very effective Solution Heat Exchanger (SHX).

The high effectiveness and compactness of the SHX and all the heat exchangers (except the generator) is achieved by using Plate Heat Exchangers (PHEs). Indeed, a quite recent manufacturing process - the fusion–bonding technology - makes it possible to produce 100% stainless steel PHEs, ensuring corrosion resistance and pressure-temperature ratings suitable for GHPs. Moreover, this novel method of brazing the plates can boost the industrialization of GHPs. The identification of optimal design of PHEs as components of compact GHPs is critical, since very long thermal lengths are needed to maximize the performances, and the large difference in flow rate between ammonia-water solution and heating water (or water-glycol solution) requires asymmetric PHEs. Such features can be achieved by a specific development either of plates design or of the heat exchanger as a whole, as done by previous research activities [3]. Our approach has been different, aiming at finding a suitable compromise between standard components (i.e. the plates already developed by PHE manufacturer) and custom channels configurations, which maximize series flow in most critical units (SHX and ABS) with neglectable effects of the co-current flow along the turning plates, and allows a strongly asymmetrical flow in the two sides.

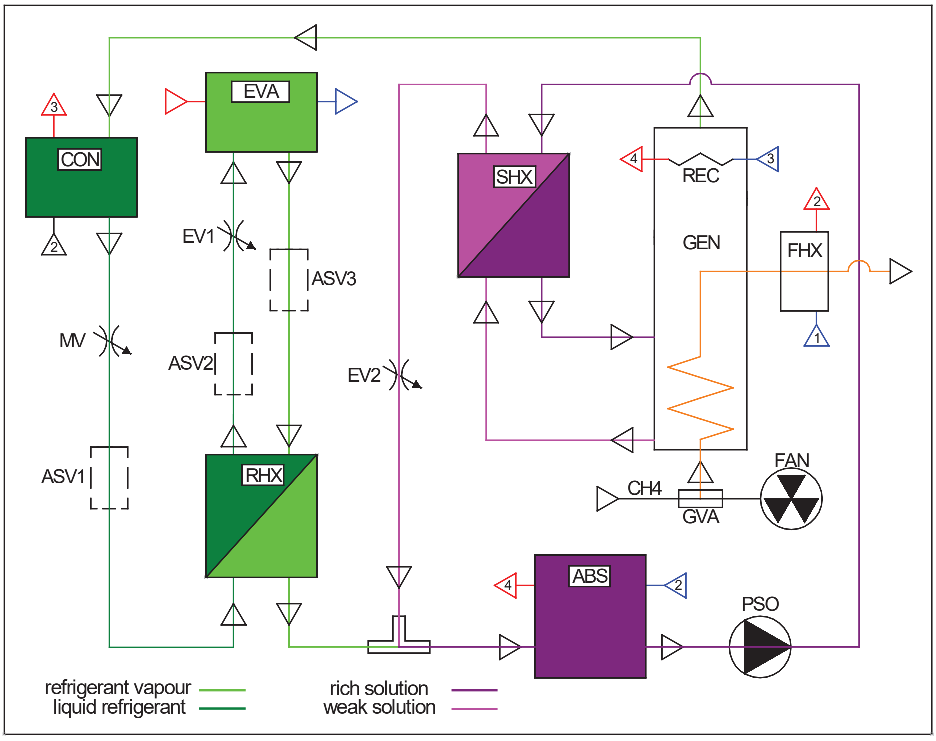

Figure 1 - Outline of GHP circuitry implementing the single effect absorption cycle.
Heating water first crosses the Flue gas heat recovery unit (FHX), then it is splitted in two equivalent parallel streams, one crossing in series the CONdenser and RECtifier, the second through the ABSorber.

We have been supplied with, and could investigate, heat exchanger prototypes, not commercially available and customized on the basis of our findings and requirements. This is an added value of the present work compared to previous research on the use of PHE in ammonia-water absorption [4-5].

The use of variable expansion valves on the solution side of the circuit, poor solution between the SHX and ABS, makes it possible to adapt the thermodynamic cycle to the operating conditions, which results in high performances over the entire range of modulation and thermal lift.

Additionally, it allows the reduction of the generator temperature at nominal power (by increasing the solution flow rate), so extending the capacity range and the durability of the GHP. Crucial is the control strategy and the choice of the control parameters, since the response time of certain physical quantities to changes in flow rate is up to some minutes. We have provided also for the use of an electronic variable expansion valve in the refrigerant circuit, to investigate different configurations of such circuit - with three different positions of the ammonia storage vessel - as well as to further optimize the AHP operation in different working conditions.

3 Results

The main findings of this work can be summarized as follows:

- The last prototype results very compact, as can be appreciated in Figure 2: the dimensions of the sealed circuit of the GHP, i.e. except for the air to brine heat exchanger, are comparable to those of a standard domestic condensing boiler. In particular, the height of nearly 850 mm is a remarkable outcome, achieved thanks to a brand-new design of generator's boiler and water cooled rectifier, for which patent applications are pending. The ammonia charge is well below 2 kg.
- Three different configurations of refrigerant circuit have been explored and compared: one is the state of the art, currently implemented in commercial GHPs, and based on fixed orifice restrictors and a passive concentration control system, placed downstream the evaporator (ASV3 in Figure 1). ASV3 is equipped with a calibrated liquid drain, whose flow rate depends on the head of liquid refrigerant, so the amount of stored ammonia in ASV3 depends on a dynamic equilibrium between inlet and outlet of liquid refrigerant. For example, stored ammonia increases in case of flooded evaporator, up to a new thermodynamic equilibrium related to the reduction of solution concentration, which promotes evaporation and thus the reduction of liquid feed from the evaporator.

  The other configurations are based on a variable electronic expansion valve (we successfully tested both a solenoid valve and a proportional needle valve), similarly to most recent ammonia-water prototypes [4-6].

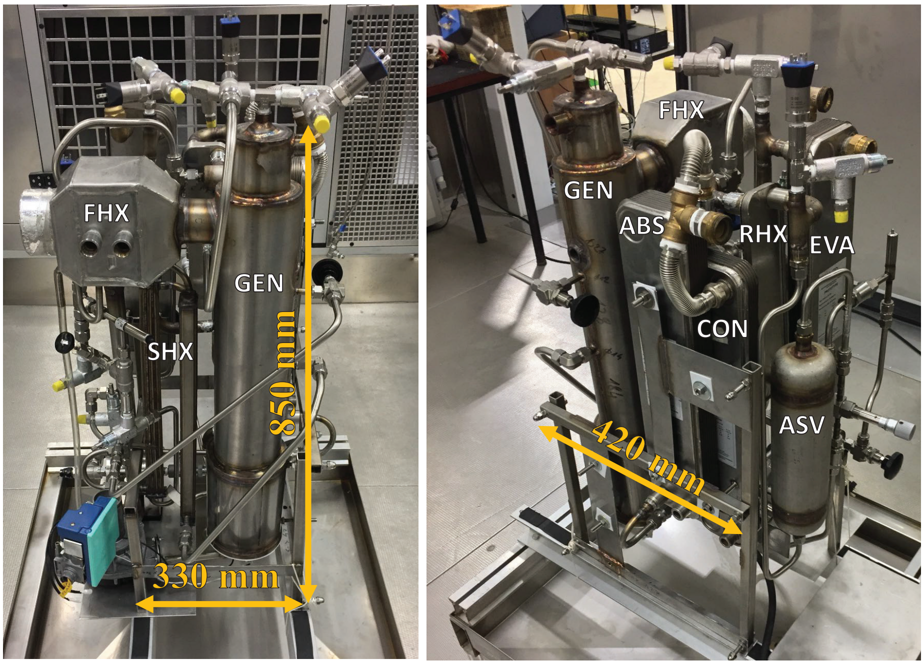

Figure 2 – View of two sides of GHP sealed circuit, showing its main components and overall dimensions

We investigated the effectiveness of placing the ammonia storage vessel just upstream or downstream the RHX (ASV1 and ASV2 in Figure 1), at an intermediate pressure in the cycle. The ASV, at least under most operating conditions, is partially filled by a two-phase solution (mostly refrigerant). As saturated liquid is drawn from the bottom of ASV, the first configuration provides the maximum efficiency, since the pressure in ASV rises until it nullifies the flash in the first restrictor (MV), so heat recovery in the RHX is maximum. The second configuration provides better valve control, since the liquid refrigerant entering the variable valve (EV1) is kept nearly at saturation. Despite the cost of variable valves, their use allows greater flexibility in sealed circuit layout, which is crucial to reduce the overall dimensions.

- The prototype, with the "efficient" configuration of the refrigerant circuit, i.e. the ASV in position 1 upstream the RHX, has been tested in the working conditions defined by the EN 12309-6:2014 [7] for high temperature application and average heating season. The results of the testing campaign, carried out in an accredited laboratory, are reported in Table 1 and provides us with the third and main outcome of our work.
  It is pointed out that the prototype has been tested with a water-glycol flow temperature lower than the required air temperature, to simulate the effect of the indirect water-glycol circuit:
  water-glycol Tin = air Dry Bulb Temp – 2 K.
  The Seasonal Gas Utilization Efficiency (SGUE) resulting from the testing campaign and calculated in compliance to EN 12309-6:2014, is 1.58 on a net calorific value basis. This is a very satisfactory result, which is mainly due to the high effectiveness of SHX, the optimized operation of refrigerant circuit, and the possibility of reducing the solution flow rate in part load conditions.

Table 1 – Gas Utilization Efficiency of GHP prototype in working conditions as per EN 12309-6:2014 - high temperature application and average heating season. Experimental data are reported in italics.

Load	**Heating Power**		**Air DBT**	**Water-glycol Tin**	**Water Tin**		**Water Tout**		**Gas Power (lhv)**	**GUE***
	kW		°C	°C	°C	°C	°C	°C	kW	
100%	8.00	*7.96*	-10	*-12.1*	42	*42.0*	55	*54.8*	*6.112*	***1.30***
88%	7.04	*7.19*	-7	*-9.1*	40	*40.0*	52	*52.3*	*5.137*	***1.40***
54%	4.32	*4.33*	2	*-0.1*	33	*33.0*	42	*41.9*	*2.714*	***1.60***
35%	2.80	*2.70*	7	*5.1*	29	*29.0*	36	*36.2*	*1.636*	***1.65***
15%	1.20	*1.21*	12	*10.0*	25	*25.0*	30	*29.8*	*0.734*	***1.65***

* based on lower heating value of methane

4 Conclusions

A five year-long numerical and experimental activity has led to the realization of a compact 8 kW rated ammonia-water Gas Absorption Heat Pump prototype. The development has been based on the wide use of custom multipass stainless steel plate heat exchangers and variable expansion valves, both in the refrigerant and solution circuits.
Flow control has led to remarkable prototype performances, as the Seasonal Gas Utilization Efficiency of 1.58 for high temperature application in average climate.
Thanks to a novel design of the direct fired desorber and a water cooled rectifier, which are the subject of patent applications, the generator height has been shortened and the overall dimensions of the sealed circuit are comparable to those of a standard domestic condensing boiler.
The reliability of expansion valves has been ascertained, while the next developments concern the implementation of the indirect water-glycol circuit, the automatic control of GHP and a further reduction in the size of solution pump and all the heat exchangers.

5 List of References

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