Experimental Evaluation and Concept Demonstration of a Novel Modular Gas-Driven Sorption Heat Pump

Corey Blackman[a,b,c]*, Chris Bales[b], Eva Thorin[c]

[a]SaltX Technology AB, Hägersten, 12653 Stockholm, Sweden
[b]Dalarna University, Falun, 79188, Sweden
[c]Mälardalens University, Högskoleplan 1, Västerås, 72123, Sweden

Abstract

Gas-driven sorption heat pumps (GDSHPs) exhibit possibilities in the reduction of energy use and environmental impact of heating systems that utilise natural gas. By utilising renewable thermal energy from the environment, that is, air, ground or water sources, significant reduction of primary energy use can be achieved. However, high cost, low coefficient of performance (COP) and large volume per unit thermal power produced have limited the proliferation of GDSHPs. In this work, exploiting the benefits of reversible chemical reactions in sorption systems, with no internal moving parts, noise, vibration and maintenance-free reactor design, two novel modular prototype sorption components were developed and evaluated experimentally. They were designed to operate as part of an intermittent cycle GDSHP to deliver heat directly to a load or to a stratified hot water store. Prototype 1 was an ammonia-salt basic sorption unit while prototype 2 was an ammonia-salt resorption unit both employing proprietary composite sorbent materials. Test results showed that the prototype 2 reactor produced a specific heating capacity of 46 W/litre at a temperature lift of 50°C yielding a COP of 1.38. Prototype 1 demonstrated higher heating capacity of 73 W/litre at a temperature lift of 70°C but exhibited lower COP of 1.10. Given its higher COP but lower temperature lift, prototype 2 could be employed in a GDSHP designed for moderate heating demands or where a ground source heat exchanger is employed as the low temperature heat source. In the case where a higher temperature lift is required, for example, for an air-source GDSHP unit then the prototype 1 design would be more applicable.

Keywords: Gas-driven sorption heat pump; sorption module; advanced sorption cycle; resorption; absorption;

* Corresponding author. Tel.: +46 0733167042
E-mail address: corey.blackman@saltxtechnology.com

Nomenclature

$\dot{m}$ – average mass flow rate of heat transfer fluid (kg/s)
COP_{heat} – heating coefficient of performance
c_p – specific heat capacity of heat transfer fluid (J/kg-°C)
E_{el} – electricity input to heater (Wh)
E_{heat} – heating energy during absorption phase (Wh)
$E_{re-cool}$ – heating energy during desorption phase (condensation energy dissipated) (Wh)
$\dot{Q}_{heat}$ – average heating power during absorption phase (W)
$\dot{Q}_{re-cool}$ – average heating power during desorption phase (condensation power dissipated) (W)
t – phase time (hours)
T_{amb} – average ambient temperature (°C)
T_{co} – condensation temperature (°C)
T_{cxi} – average inlet temperature to condenser/evaporator heat exchanger (°C)
T_{cxo} – average outlet temperature from condenser/evaporator heat exchanger (°C)
T_{rxi} – average inlet temperature to hybrid thermosyphon heating unit heat exchanger (°C)
T_{rxo} – average outlet temperature from hybrid thermosyphon heeating unit heat exchanger (°C)
ΔT – average temperature lift (°C)

1. Introduction

Substantial energy savings can be made by enhancing condensing boilers to a boiler with sorption capabilities [1]. This allows for renewable thermal energy from ambient air, ground or water sources to be used for space heating and domestic hot water (DHW) preparation purposes. Sorption heat pumps exploit the principle of reversible chemical reactions, that is, chemisorption to drive a process where thermal energy can be extracted from a source of low temperature and delivered to one of higher temperature (i.e. heat pumping process) using high exergy thermal energy as the driving source. Utilising this otherwise untapped low temperature (i.e. exergy) thermal energy as a complement to high exergy thermal energy to provide useful heating, gas-driven sorption heat pumps (GDSHP) produce savings on gas utilisation compared to conventional gas boilers [2]. However, this increased coefficient of performance (COP) of a sorption heat pump often comes at the penalty of increased complexity, cost and reliability [3,4]. In the case of monovalent GDSHPs, that is, GDSHPs designed without a backup burner, there's a marked decline in performance as temperature lift (i.e. temperature difference between low temperature heat source and heat delivery temperature) increases [5]. Therefore, to meet the design point conditions at the coldest part of the year the GDSHP must be adequately dimensioned often leading to it being substantially oversized compared to the heating demand for most of the year [3]. Additionally, there are often deleterious effects on GDSHP efficiency at low part load operation [4].

To avoid the aforementioned limitations of monovalent GDSHPs a bivalent (also known as hybrid) GDSHP which integrates a backup burner was considered for this study. Bivalent GDSHPs can be dimensioned in such a way that the heating capacity of the gas burner meets that of the system design point or that the heating capacity of the sorption heat pump unit and the backup burner combined meet the full heating capacity required at design point. Given that, in general, the design point conditions only occur for a relatively short part of the year, the sorption component, which is typically the more costly component compared to a gas burner, should be dimensioned to match the average heating demand during the year. This is to avoid it being oversized compared to the required capacity for a large part of the year. Additionally, this would reduce the need for the sorption module to operate at low part loads for an appreciable part of the year thus reducing part load inefficiencies and increasing seasonal efficiency of the GDSHP. To ensure that the sorption module can be adequately dimensioned a modular sorption component has been designed. A bivalent GDSHP unit has be conceptualised and modular sorption heat pump components developed. These modular sorption heat pumps were experimentally evaluated in this study to determine their performance and give insight into their potential application areas.

2. Modular Sorption Components for a Gas-Driven Sorption Heat Pump

2.1. Basic Sorption Module (Prototype 1)

The basic sorption module (Prototype 1) is a sorption heat pump module that comprises two cylindrical vessels, the reactor (R) and the combined condenser-evaporator (CE). Within each vessel there's a heat exchanger made up of disc-shaped stainless steel plates engineered in such a way as to allow a heat transfer fluid to flow within the discs. The heat exchanger of the reactor vessel is used to provide thermal energy to, or remove thermal energy from, a proprietary matrix material infused with a salt (alkali halide) capable of absorbing and desorbing ammonia. The matrix is housed in the spaces between the heat exchanger discs in thermal contact with said discs (see Figure 1). The CE vessel is identical to the R with the exception that the matrix material between the discs does not contain salt. Both the R and CE vessels have an opening at the top which allows ammonia to flow back and forth between them via a connecting pipe.

The basic sorption module functions under a batch process with two main phases; absorption and desorption (also known as regeneration) [6]. During the process of absorption, the difference in vapour pressure between the salt and the ammonia causes ammonia to evaporate from the CE (acting as an evaporator in this case) and form a salt ammoniate in the reactor. The reaction between salt and ammonia creates heat which can be harnessed for space and/or domestic water heating purposes. After the absorption phase is complete, the component can then be regenerated by heating the reactor forcing the desorption of ammonia from the reactor matrix where it condenses in the CE with condensation heat being removed via a heat transfer medium. This condensation heat can also be used for space and/or domestic water heating purposes. This regeneration phase is aptly called desorption.
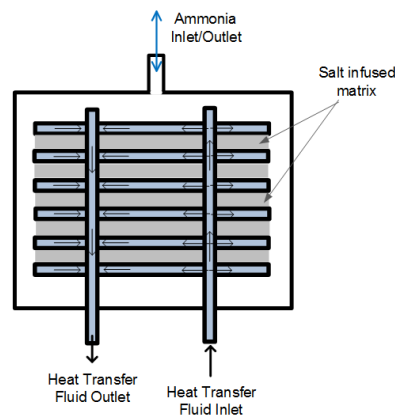

Figure 1 - Illustration of a heat exchanger vessel of a sorption heat pump module

2.2. Resorption Module (Prototype 2)

A resorption cycle uses two different salts (alkali halides), having different chemical affinities for a given refrigerant which in this case is ammonia. The salt with the higher affinity is referred to as the high temperature salt (HTS) while that with the lower affinity is referred to as the low temperature salt (LTS). During the desorption process, a high temperature (i.e. high exergy) heat source is used to incite the flow of ammonia from the HTS to the LTS. The reverse occurs during absorption in which the refrigerant flows from the LTS to the HTS, where the LTS can absorb low temperature (below ambient temperature) thermal energy, while the HTS rejects heat at a medium temperature (above ambient temperature) [7].
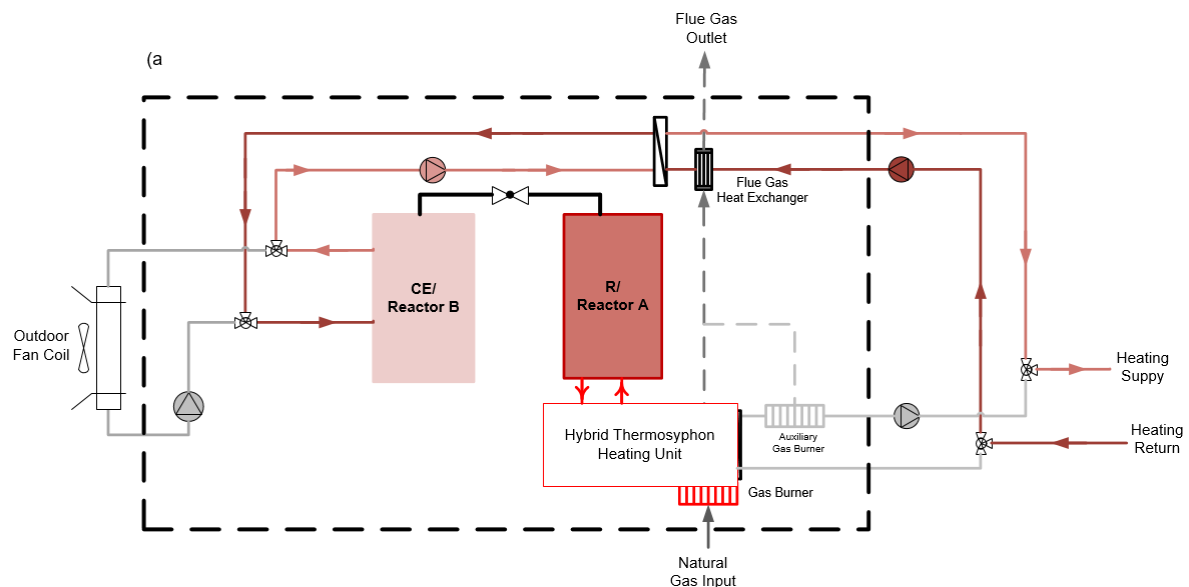
The resorption module prototype (Prototype 2) was designed to operate under the same principle as the basic sorption component with the exception that the matrix of the CE is also infused with a salt, in this case a LTS. Due to this, the second vessel is no longer denominated as CE but as a reactor. Therefore, the resorption prototype essentially has two reactors; Reactor A (RA) which houses the HTS and reactor B (RB) which houses the LTS. Similar to Prototype 1, the resorption prototype is operated to provide useful heating during both desorption and absorption phases.

3. System Concept

The sorption heat pump modules are designed for implementation in a gas-driven sorption heat pump appliance as shown in Figure 2. The sorption heat pump modules are thus designed to be desorbed with natural gas where the evolving heat from the natural gas burner is used to desorb ammonia from the R (Prototype 1) or RA (Prototype 2) to the CE (Prototype 1) or RB (Prototype 2). The resulting condensation (prototype 1) or reaction heat (prototype 2) can then be harnessed for space heating and/or DHW purposes (Figure 2a). The desorption phase is therefore characterised by heat rejection/delivery from the CE or RB. When the R or RA is fully desorbed, that is, all ammonia (possible to be desorbed under the conditions) has been transferred from the R or RA to the CE or RB, the unit is switched to the absorption phase.

During the absorption operation phase, the gas burner shuts off and heat is recovered and rejected from the hot R or RA. The CE or RB is connected to an outdoor fan coil where low temperature thermal energy is absorbed from outdoor air inciting the transfer of ammonia to the R or RA. Heat is thus delivered from the module via the R or RA (see Figure 2b) in the absorption phase.

In the current studies, a bivalent GDSHP has been conceptualised to produce useful heating during both desorption and absorption phases. Based on the salts employed, the R or RA requires a high temperature heat source of 140°C to 250°C in the desorption phase followed by medium temperature heat rejection (40°C to 80°C) in the absorption phase. For this purpose, a proprietary integrated hybrid thermosyphon heating unit (HTHU) has been developed. The HTHU is a thermosyphon designed to allow for heating of the R or RA units with saturated steam during desorption and water re-cooling via a pumped water flow during absorption. Rejected heat is extracted directly from the HTHU via a pumped flow of heat transfer fluid. By virtue of its design, steam generation in the HTHU can be done with a gas burner, electric heater or any heat source with a temperature high enough to create steam to activate the desorption phase. During desorption, the heat delivery temperature from the unit is pre-determined by the needs of the heating load (i.e. space heating temperature or DHW temperature). Heating temperatures required for the R or RA are therefore modulated by the required heat delivery temperature given that the heating temperature of the R or RA is directly proportional to the heat delivery temperature from the CE or RB [8,9]. Correspondingly, on the CE or RB side of the module, switching between outdoor air heat absorption (absorption phase) and heat rejection to the heating load (desorption phase) is done by 3-way valves. Additionally, heat is also recovered from the flue gases of the burner via a flue gas heat exchanger in order to improve the overall efficiency of the GDSHP. The system also contains an auxiliary burner which allows for direct heat delivery to the load (i.e. bypassing the sorption component) if the sorption component is unable to fulfil the full heating demand at any given point. Additionally, the sorption component is fully modular where the number of discs and thus the amount of substance within each vessel can be varied as necessary when dimensioning the component. This allows for the sorption unit to be adequately dimensioned to meet heating demand under most of the year without having to meet peak demand, thus reducing overall cost of the GDSHP [3]. Given that the absorption process tends to be limiting phase in terms of heating capacity of the module, module design and dimensioning would be based on average heating capacity during the absorption phase.
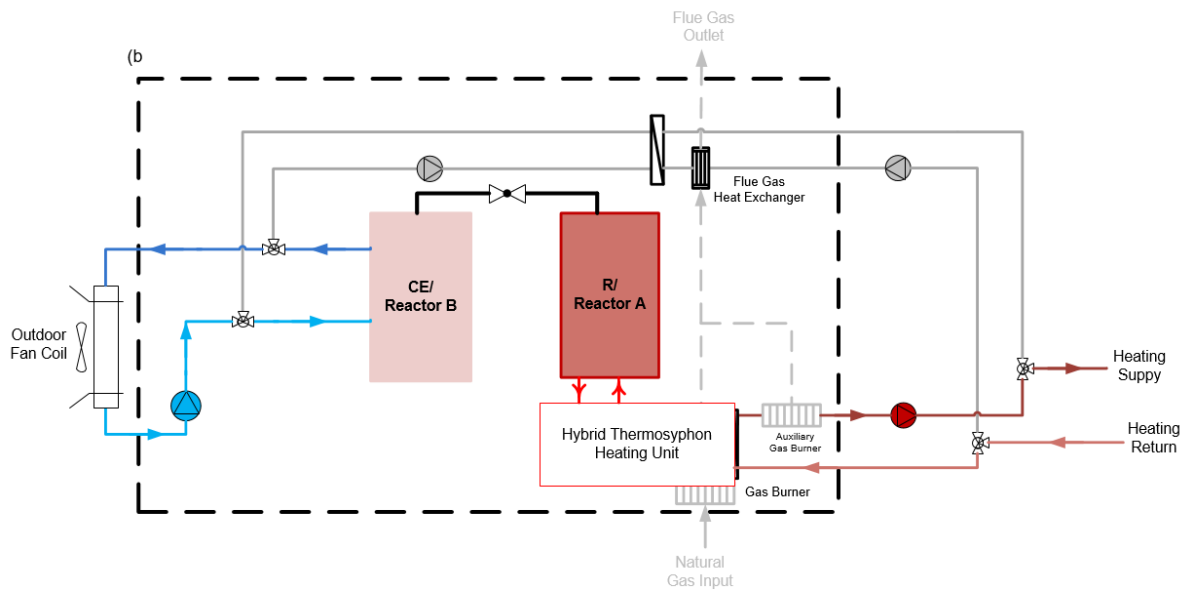
Figure 2 – Modular gas-driven sorption heat pump concept. Desorption phase (a), absorption phase (b).

4. Experimental Evaluation

Tests for both heat pump components were carried out in a test rig developed to provide controllable heat rejection and desorption temperatures (see Figure 3). The sorption component was connected to two hydraulic circuits; circuit 1 connected to the R or RA and circuit 2 connected to the CE or RB. Circuit 1 was connected to the R or RA via the HTHU. The HTHU, developed for saturated steam heating of the Reactor or RA units during desorption and water re-cooling via a pumped flow during absorption employed a 4-kW electric heater for the experimental evaluations in this study. The use of a retrofitted electric heater as opposed to a gas burner as described in the system concept (section 3) was due to cost and convenience factors involved in the measurement of the heat input during desorption in the laboratory tests.

Circuit 1 comprised a pump (P1) an electrically actuated mixing valve (MV1) and a plate heat exchanger (HEX1) connected to a ground-source heat rejection loop. The ground-source heat rejection loop had a temperature between 12°C and 15°C. With this setup, it was possible to heat and/or reject heat from the R or RA with the HTHU controlling both heating and heat rejection temperatures. Therefore, the test setup was used to emulate the desorption and absorption temperature and flow rate parameters expected during operation of the heat pump components to produce space heating and/or domestic hot water.

Circuit 2, connected to the CE or RB, consisted of a plate heat exchanger (HEX2) also connected in parallel to the same ground-source heat rejection loop as circuit 1. Circuit 2 also contained a pump (P2), an electrically actuated mixing valve (MV2) and a 2-kW heater (Heater 2). Circuit 2 thus allowed for heat rejection from the CE or RB as well a low temperature heat load to be applied with Heater B.

During tests, employing the HTHU, Heater 2 and the mixing valves MV1 and MV2, a constant temperature control strategy can be employed to provide constant heat rejection fluid (simulated space heating/DHW load) and low temperature fluid (i.e. simulated heat transfer fluid from an outdoor fan coil) inlet temperatures to evaluate the performance of the prototypes. In each hydraulic circuit heat transfer fluid inlet and outlet temperatures (Trxi, Trxo Tcxi, Tcxo) were measured with K-Type thermocouples fixed to the surface of copper piping with aluminium tape. Grundfos VFS 1-12 flow sensors (FM1, FM2) were used in each circuit to measure heat transfer fluid flow.

Tests were run in two phases; desorption immediately followed by absorption which constituted one operation cycle of the sorption heat pump component.
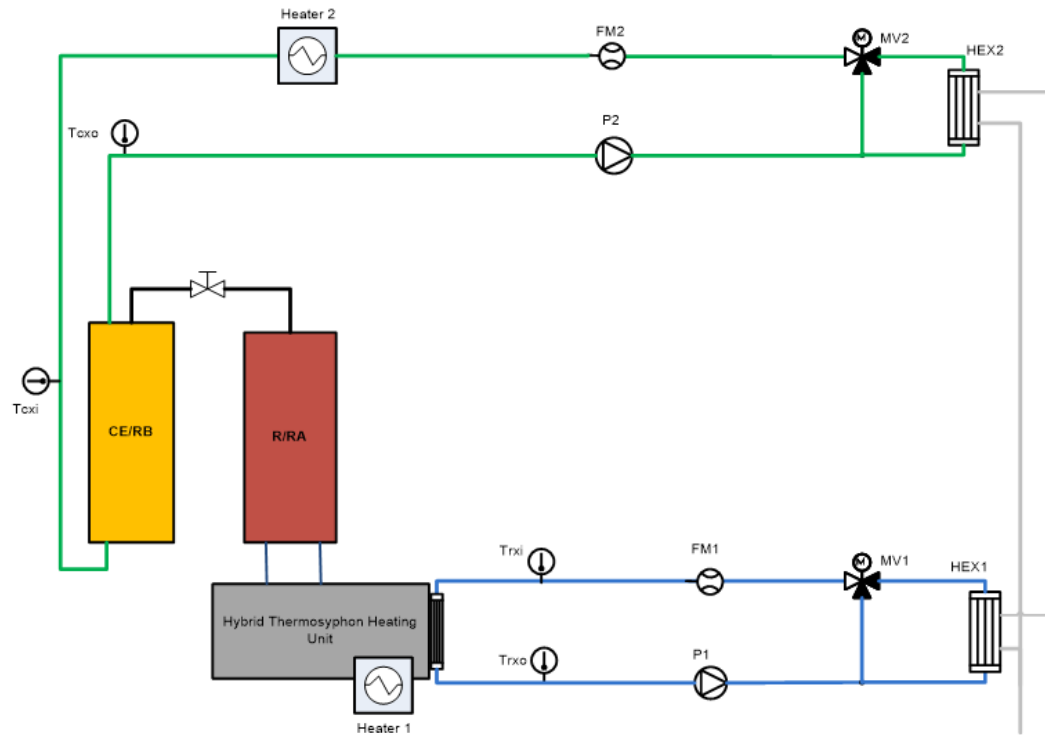
Figure 3 - Schematic diagram of laboratory setup [circuit 1 (blue), circuit 2 (green), ground source loop (grey)]

Figure 4: Photograph of the laboratory test rig.

4.1. Test Sequences

For a GDSHP operating with an outdoor air source unit and heat delivery at temperatures typically required for space and/or domestic water heating, the sorption modules would operate at various temperature lifts. According to the European Union regulations ecodesign requirements for space and combination heaters, under standard rating conditions, a delivery temperature of 55°C is required and reference design temperature 2°C for an average European climate [10]. Therefore, for an average European climate, the maximum temperature lift for a bivalent

GDSHP is expected to be 53°C. Estimating, a temperature drop of 15°C between outdoor air temperature and circulating heat transfer fluid in the outdoor fan coil, then the sorption component would need to operate at a maximum temperature lift of 67°C.

Various test sequences were thus carried out with each prototype with temperature lifts up to 70°C during the absorption phase to determine their performance sensitivity to temperature lift. All absorption phases were carried out immediately after a full desorption phase. At least 40 cycles were run for each prototype to ensure repeatability of the measurement results.

4.1.1. Performance Indicators
Table 1 summarises the equations used to calculate the performance indicators of the heat pump module prototypes.

Table 1 - Equations used to calculate performance indicators of the sorption module prototypes

Performance Equations	Units	Equation no
$\dot{Q}_{heat} = c_p \dot{m}(T_{rxo} - T_{rxi})$	W	(1)
$\dot{Q}_{re-cool} = c_p \dot{m}(T_{cxi} - T_{cxo})$	W	(2)
$E_{heat} = \int_0^t \dot{Q}_{heat}$	Wh	(3)
$E_{re-cool} = \int_0^t \dot{Q}_{re-cool}$	Wh	(4)
$COP_{heat} = (E_{heat} + E_{re-cool})/E_{el}$	-	(5)
$Specific\ Capacity_{heat} = \dot{Q}_{heat}/(Physical\ Volume\ of\ Module)$	W/litre	(6)
$\Delta T = (T_{rxo} - T_{cxo})$	°C	(7)

4.1.2. Desorption
In desorption phase, the HTHU heater heated the Reactor or RA to between 160°C and 180°C with heat rejection fluid temperatures of 30°C to 40°C from CE or RB. Maximum Reactor and RA temperatures and thus maximum heat rejection temperatures were limited by maximum pressure tolerance of the laboratory heater employed in the HTHU. Fluid was circulated in circuit 2 allowing for heat to be rejected from the CE or RB and ejected to the ground-source heat exchanger via HEX2. The desorption phase continued until heat rejection power fell below 100 W. For the prototypes tested, desorption phases lasted between 30 and 60 minutes.

4.1.3. Absorption
During the absorption phase the heater of the HTHU was turned off and its integrated pump started so heat is rejected. Heat rejection temperatures from the HTHU were between 30°C and 70°C depending on the test sequence carried out and the prototype involved. Fluid was circulated in circuit 2 with Heater B regulating fluid temperature into the CE or RB was 10±2°C. Absorption phases lasted for between 19 and 24 minutes for prototype 1 and between 23 and 30 minutes for prototype 2. For both prototypes the reduction of heat rejection power from the R or RB to below 100 W signalled the end of the absorption phase.

Table 2 – Test sequence parameters for Prototype 1

Test Sequence	Desorption		Absorption	
	R Inlet Set point (°C)	CE Inlet Set point (°C)	R Inlet Set point (°C)	CE Inlet Set point (°C)
1	180	40	45	10
2	180	40	50	10
3	180	40	55	10
4	180	40	60	10
5	180	40	65	10
6	180	40	70	10
7	180	40	80	10

Table 3 - Test sequence parameters for Prototype 2

Test Sequence	Desorption		Absorption	
	RA Inlet Set point (°C)	RB Inlet Set point (°C)	RA Inlet Set point (°C)	RB Inlet Set point (°C)
1	160	30	30	10
2	160	30	35	10
3	160	30	40	10
4	160	30	45	10
5	160	30	50	10
6	160	30	60	10
7	160	30	70	10

5. Results

Average heating powers during absorption were measured for both prototypes at various temperature lifts (see Figure 5). For the both heat pump component prototypes, it was observed that the average heating power during absorption was inversely proportional to the temperature lift. The results showed that for every degree increase in temperature lift there's a 1.4% and 3.4% reduction in heating capacity for prototypes 1 and 2 respectively.
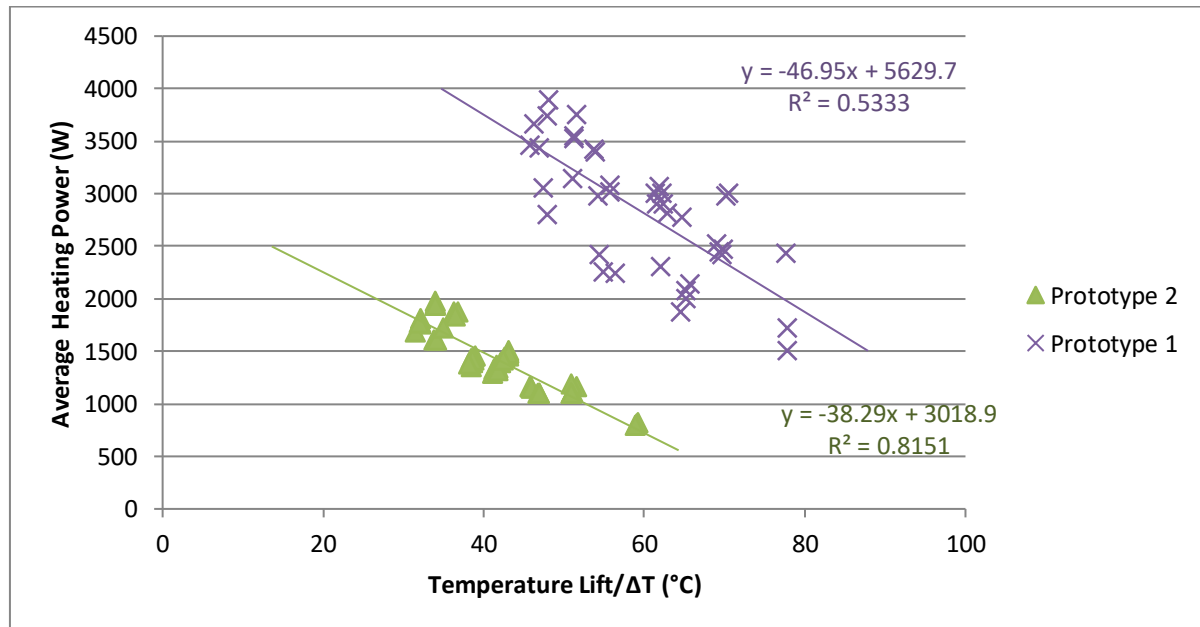

Figure 5: Heating power versus temperature lift for prototypes 1 and 2

For Prototype 1 the heating power was 3280 W at a temperature lift of 50 °C and 2343 W at a temperature lift of 70°C. While for Prototype 2 the average heating power was 1105 W at a temperature lift of 50 °C. At temperatures, above 60°C Prototype 2 performed relatively poorly and unstably thus these higher temperature operating points were not considered.

COP values for both prototypes were determined as a function of temperature lift (see Table 4).

Table 4 - Coefficient of performance of prototypes 1 and 2 with respect to temperature lift

Temperature Lift (°C)	COP Prototype 1	COP Prototype 2
50	1.28	1.38
55	1.21	1.26

| 60 | 1.16 | 1.15 |
| 70 | 1.10 | - |

For Prototype 1, the R and CE had a total volume of 32 litres. Therefore, at temperature lifts of 50°C and 70°C it demonstrated specific heating capacities of 102 W/litre and 73 W/litre respectively. In the case of Prototype 2, its specific heating capacity was 46 W/litre at 50°C temperature lift with a corresponding total volume of 24 litres.

6. Discussion

Prototype 1 performed stably with over 40 cycles carried out for each prototype at varying temperature lifts while Prototype 2 performed stably at temperature lifts up to 60°C. It was observed that for both prototypes the heating capacity is inversely proportional to temperature lift. This corresponds well with sorption theory where increased temperature lift reduces the vapour pressure difference between the Reactor or RA and CE or RB vessels which in turn reduces the rate at which ammonia flows between them and thus heating power [8]. Prototype 1 however exhibits lower sensitivity to temperature lift compared to Prototype 2 which renders it a better option for GDSHPs that require high heat delivery temperatures at low ambient temperatures. Prototype 2, even though being more susceptible to increases in temperature lift, exhibits higher COP when operating at comparable temperature lifts to Prototype 1. The use of a retrofitted electric heater in the HTHU had an impact on the results of the analysis since it was found that the electric heating unit had an overall efficiency (i.e. ratio of electricity input to heat output) of 72% due to elevated losses from the heater unit. This efficiency is considered somewhat lower than that of a well-designed gas burner which can reach over 90% in some cases [11]. Therefore, it is expected that with a well-integrated gas burner into the HTHU that COP values for the sorption heat pump modules should be higher than those shown in this study.

These findings have significant implications on the applicability of each prototype in the field. A GDSHP employing a Prototype 1 type sorption module would be best suited to applications that have high temperature lift requirements (>60°C) and high heat demand for an extended part of the year. However, in the case of Prototype 2, applications which allow for moderate temperature lifts (< 60°C) for the majority of the year would be more appropriate. Especially considering the energy saving benefits due to the higher COP of Prototype 2 compared to Prototype 1 at lower temperature lifts. However, a full understanding of applicability would require further analysis including the cost of the sorption heat pump modules which relates to their relative sizes and expected annual energy cost savings based on their COPs.

7. Conclusions

This paper presents a concept for a bivalent gas-driven sorption heat pump (GDSHP) which incorporates novel sorption heat pump modules. Additionally, experimental evaluations of two prototypes of the sorption heat pump modules designed for integration into a GDSHP are presented. Prototype 1 was developed as a basic sorption component, and exhibited a heating capacity of 3280 W at a temperature lift of 50 °C and 2343 W at a temperature lift of 70°C. Prototype 2, a sorption module based on the resorption cycle, had lower heating capacity of 1105 W at 50 °C. The coefficient of performance for each prototype was determined, where Prototype 1 though able to operate at higher temperature lifts than Prototype 2, exhibited lower coefficients of performance (COP). COP values for the prototypes operating at an average temperature lift of 50 °C were 1.28 and 1.38 for Prototype 1 and Prototype 2, respectively. The findings of the study give insight into the applicability of the prototypes based on temperature lift requirements. Prototype 1, by virtue of its salt and refrigerant combination allowing operation at high temperature lifts, would be best suited to GDSHP applications that have high temperature lift requirements (up to 70°C) for a large part of the year while still providing COPs greater than 1. For Prototype 2, applications which allow for moderate temperature lifts (< 60°C) for the majority of the year would be more appropriate.

The studies carried out show that the sorption module prototypes operating in a similar manner to the proposed concept could be employed in a GDSHP. This warrants further analysis including the cost of the sorption heat pump modules as it relates to their relative sizes and expected annual energy cost savings based on their COPs.

Acknowledgements

References

[1]   Qu M, Abdelaziz O, Yin H. New configurations of a heat recovery absorption heat pump integrated with a natural gas boiler for boiler efficiency improvement. *Energy Convers Manag* [Internet]. 2014 Nov [cited 2016 Nov 16];87:175–84. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0196890414006086

[2]   Wu W, Wang B, Shi W, Li X. Absorption heating technologies: A review and perspective. Applied Energy. 2014. p. 51–71.

[3]   Wu W, Wang B, Shi W, Li X. Techno-economic analysis of air source absorption heat pump: Improving economy from a design perspective. *Energy Build*. 2014;81:200–10.

[4]   Aprile M, Scoccia R, Toppi T, Guerra M, Motta M. Modelling and experimental analysis of a GAX NH3-H2O gas-driven absorption heat pump. *Int J Refrig*. 2016;66:145–55.

[5]   Wu W, Shi W, Wang B, Li X. A new heating system based on coupled air source absorption heat pump for cold regions: Energy saving analysis. *Energy Convers Manag*. 2013;76:811–7.

[6]   Rosato a., Sibilio S. Preliminary experimental characterization of a three-phase absorption heat pump. *Int J Refrig* [Internet]. 2013;36(3):717–29. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0140700712003234

[7]   Spoelstra S, Haije WG, Dijkstra JW. Techno-economic feasibility of high-temperature high-lift chemical heat pumps for upgrading industrial waste heat. *Appl Therm Eng*. 2002;22(14):1619–30.

[8]   Wang R, Wang L, Wu J. Adsorption Refrigeration Technology: Theory and Application. Adsorption Refrigeration Technology: Theory and Application. 2014. 1-494 p.

[9]   Villeneuve A De. Modelling of gas-solid reaction—Coupling of heat and mass transfer with chemical reaction. *Chem Eng Sci*. 1996;51(15).

[10]   European Council. Commission Regulation (EU) No 813/2013 of 2 August 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for space heaters and combination heaters. *Off J Eur Union* [Internet]. 2013;56. Available from: http://data.europa.eu/eli/reg/2013/813/oj

[11]   Barcellos WM, Souza LCEO, Saveliev A V., Kennedy LA. Ultra-low-emission steam boiler constituted of reciprocal flow porous burner. *Exp Therm Fluid Sci* [Internet]. 2011 Apr [cited 2016 Nov 16];35(3):570–80. Available from: http://linkinghub.elsevier.com/retrieve/pii/S0894177710002190