DEVELOPMENT OF A DOMESTIC ADSORPTION HEAT PUMP

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Abstract: This paper presents both experimental and predicted model performance of a gas fired adsorption heat pump demonstration unit for domestic hot water production and space heating. The heat pump uses two compact high efficiency carbon-ammonia generators operating out of phase in a regenerative cycle. The full laboratory prototype is designed to deliver hot water at a maximum flow rate of 10 l/min with a temperature rise of 30°C and a nominal space heating power of 7 kW (conditions suitable for the majority of homes in UK). The gas burner is simulated by a modulated electrical heater rated to 10 kW. This demonstration unit has produced heating powers ranging from 7 kW to 11 kW (COP of 1.42 to 1.61) with a driving temperature of 120°C and water flow rate range of 5 l/min to 10 l/min. The typical ambient temperature during testing was about 10°C. The performance obtained matched with the model predictions within 11% or better.

Key Words: heat pumps, adsorption, activated carbon, ammonia, COP

1. INTRODUCTION

The development of compact sorption generators aimed at high power density and COP for both cooling and heating systems has been the focal point of adsorption refrigeration R&D at Warwick University in the past two decades. The patented concept of a plate heat exchanger applied to sorption generators for cooling and heat pump applications (Critoph 2008) was investigated initially through computational modelling and has proven to be interesting: a specific cooling power (SCP, the cooling power per unit mass of adsorbent) from 1 kW kg^{-1} carbon up to 6.5 kW kg^{-1} carbon with cooling COP varying between 0.5 and 1.2 are achievable with only two beds operating out phase (Critoph and Metcalf 2004; Metcalf 2006). Furthermore, two demonstration cooling machines using compact high efficiency carbon-ammonia generators have already been tested successfully: a car air conditioning system driven by waste heat from the engine coolant water (at 90°C) has produced an average cooling power of 1.6 kW (with about 2 kW peaks) and a COP of about 0.23 under the EU typical normal conditions (33°C and 20°C for condensing and evaporating temperatures respectively) (Tamainot-Telto et al 2009; Critoph et al 2010); a solar powered mobile container for food conservation designed to produce 3 kW cooling with 10 m^2 of solar thermal collector operating in a desert environment (40°C and -10°C for condensing and evaporating temperatures respectively) was also tested (Critoph et al 2010). The domestic gas fired adsorption heat pump application is also an area that could benefit from this novel compact generator: the systems target COP of 1.4 represents substantial fuel savings and emissions reductions over a conventional boiler. In 2008, during the last IEA-Heat Pump Conference in Zurich, we presented the description of a laboratory prototype gas-fired air-source adsorption heat pump that could replace a domestic gas combination boiler (Metcalf et al 2008). For demonstration purposes, the heat input to the adsorption machine is to be simulated with electric cartridge heating elements. The heat pump is designed to provide a hot water flow rate of 10 l min^{-1} with a 30°C temperature rise and a nominal space heating power of 7 kW.
The aim of this paper is to present both experimental and predicted model performance of that gas fired adsorption heat pump demonstration unit for domestic hot water production and space heating applications and also to outline the progress on the development of an alpha version of a commercial prototype.

2. DOMESTIC ADSORPTION HEAT PUMP DEMONSTRATION UNIT

The schematic diagram of the gas-fired adsorption heat pump is shown in Figure 1. Five main components are highlighted: a pair of sorption beds (carbon-ammonia), the cooler (water to water heat exchanger), the condenser (water to ammonia), the expansion valve and the evaporator (air to ammonia). There are two distinct loops: the ammonia loop and the pressurised water loop. The hot water is supplied by an electric heater (simulating the gas burner) in order to provide the driving heat for the cycle. The heat pump is an air-source machine with a finned tube fan coil as an evaporator over which ambient air is passed. The heating water and hot water are heated firstly in the condenser and then in a water-to-water heat exchanger (cooler) by the heat rejected from the beds during the adsorption phase. This strategy lowers the condensing temperature and increases the efficiency of the heat pump. Both the condenser and the water-to-water heat exchanger are plate heat exchangers.

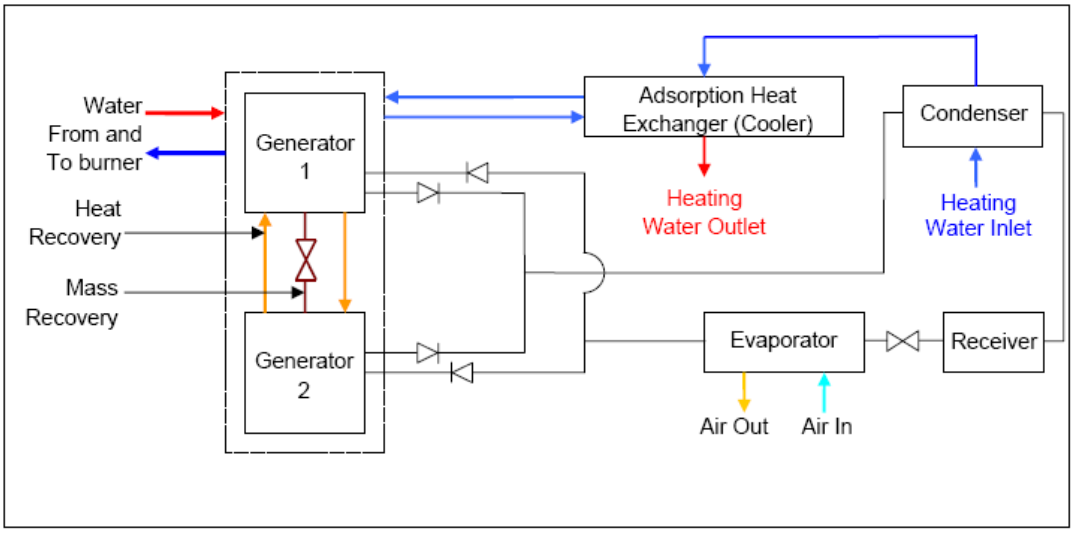


Figure 1: Schematic diagram of the gas-fired heat pump

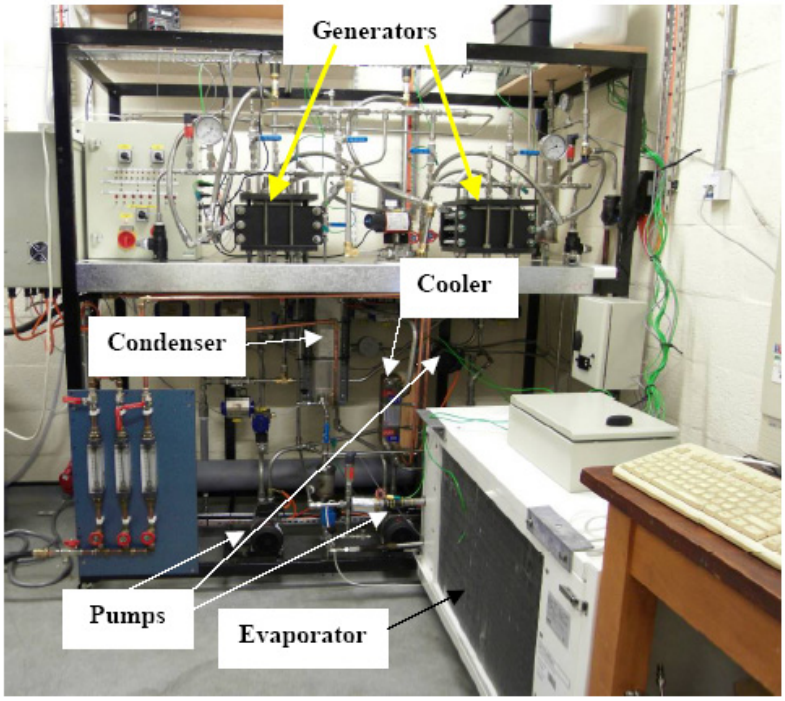


Figure 2: Photographic view: demonstration unit of domestic gas-fired adsorption heat pump

3. MAIN COMPONENTS SPECIFICATIONS

3.1 Heat exchanger generator (reactor)

It is a nickel brazed stainless steel design with 29 layers of active carbon adsorbent each 4 mm thick. By incorporating the carbon adsorbent in thin layers, conduction path lengths through the material are reduced and the area for fluid heat transfer is increased which enables rapid temperature cycling and thereby a high specific heating or cooling power. The separating stainless steel plates are constructed from chemically etched shims with 0.5 mm square water flow channels on a 1 mm pitch. These channels give a high heat transfer coefficient and a large heat transfer area, further improving heat transfer performance. The maximum operating pressure is 20 bar with a maximum temperature of 200^{o}C. The generator specifications are summarised in Table 1.

Table 1: Heat exchanger generator specifications

Type of carbon	Chemviron SRD1352/3 (compacted)
Filter	Stainless Steel Mesh (Mesh grade 180)
Thermal enhancement additives	None
Sorbent density	435 kg m^{-3}
Mass of carbon	1 kg
Maximum ammonia concentration	0.37 kg ammonia/kg carbon
Total weight of reactor)	9 kg
Maximum operating temperature	200°C
Maximum operating pressure	20 bar
Operating cycle time	60 seconds
UA value in water channels	4300 W K^{-1}
UA value in carbon-ammonia bed	420 W K^{-1}
Effective bed thermal conductivity	0.42 W $m^{-1}K^{-1}$
Overall bed UA value	380 W K^{-1}

3.2 Condenser and cooler

The condenser is an Alfa Laval AlfaNova HP52-20H fusion bonded stainless steel plate heat exchanger: it is rated to operate at up to 20 bar with a maximum temperature of 75^{o}C. The cooler is a stainless steel copper-brazed plate heat exchanger 'SL23-BR25-40-TL-LIQUID' from UK Exchangers Ltd: its maximum operating pressure is 10 bar at 200^{o}C. Both cooler and condenser specifications are summarised in Table 2.

Table 2: Condenser and cooler specifications

Parameter	**Condenser**	**Cooler**
Model reference	AlfaNova HP52-20H	SL23-BR25-40-TL-LIQUID
Maximum pressure	20 bar	10 bar
Maximum temperature	75	200
Number of plates	20	40
Heat transfer surface area	0.90 m^2	0.92 m^2
Overall bed UA value	2500 W K^{-1}	2630 W K^{-1}

3.3 Receiver

The receiver collects the condensed ammonia liquid to ensure an adequate supply of liquid is maintained to the expansion valve and is a small stainless steel vessel with a capacity of 1 litre. It is designed to operate up to 30 bar pressure with a maximum temperature of 50^{o}C.

3.4 Expansion valve

The expansion valve is an electronically controlled valve manufactured for ammonia refrigerant by Danfoss, model AKV10. It is an on-off solenoid valve controlled by a PID controller.

3.5 Evaporator

The evaporator is a bespoke fan coil with aluminium finned stainless steel tubes (16mm Outer Diameter and 0.8 mm thickness) and was designed and manufactured by Searle. The evaporator main specifications are summarised in Table 3.

Table 3: Evaporator specifications

Parameter	**Value**
Part number	SPEC/82842
Case volume	375 litres
Fan electrical power	280 W
Air flow rate	3600 $m^3 h^{-1}$
Number of tubes	60
Overall UA value	1500 W K^{-1}

3.6 Mass recovery valves

The mass recovery is implemented using two Danfoss solenoid valves under the reference EVRA3. These valves are connected in series and opposite directions between the two generators. Two valves are required since the solenoid valves only seal in one direction.

3.7 Check valves

The check valves (four in total: a pair on each generator) are from Parker Instrumentation under the reference 07YP 8Z (A)-C8L-1/3-T-SS. These are poppet type check valves with PTFE seals and stainless steel bodies. The cracking pressure is 1/3 psi (20mbar) and its maximum operating temperature is 200°C.

4. EXPERIMENTAL PERFORMANCE AND MODEL PREDICTIONS

Four tests were carried out under the conditions given in Table 4 and the results are given in Table 5. Table 5 also compares the model prediction to the experimental results and shows that the maximum difference between the model and experiment is only 9% for the COP and 11% for the heating power. Figure 3 compares the adsorbent temperature cycle from the experiment and the model and Figure 4 the pressure, and it can be seen that the agreement is good. More detailed results and analysis could be found in Metcalf 2009.

Table 4: Test conditions

Parameter	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Generator heating water set temperature	120°C	120°C	120°C	120°C
Generator maximum carbon temperature, T_3	110°C	100°C	100°C	110°C
Generator heat recovery approach temperature difference	10°C	10°C	10°C	10°C
Generator heating water flow rate	0.32 kg s^{-1}	0.32 kg s^{-1}	0.32 kg s^{-1}	0.32 kg s^{-1}
Generator heat recovery water flow rate	0.3 kg s^{-1}	0.3 kg s^{-1}	0.3 kg s^{-1}	0.3 kg s^{-1}
Generator cooling water flow rate	0.34 kg s^{-1}	0.34 kg s^{-1}	0.34 kg s^{-1}	0.34 kg s^{-1}
Condenser/cooler water flow rate	10 l min^{-1}	10 l min^{-1}	5 l min^{-1}	5 l min^{-1}
Condenser water inlet temperature	9.7°C	9.7°C	10.3°C	10.7°C
Evaporator air inlet temperature	13°C	12.5°C	12.3°C	13°C

Table 5: Experimental performance vs. Model predictions

Parameter	Test 1	Test 2	Test 3	Test 4
Supply water flow rate (l/min)	10	10	5	5
Complete cycle time (seconds)	311	146	102	250
COP Model	1.52	1.42	1.35	1.50
COP Experiment	1.42	1.43	1.49	1.61
Difference	+7%	-1%	-9%	-7%
Heating power Model (kW)	7.31	11.80	11.16	7.81
Heating power Experiment (kW)	7.05	10.61	11.04	8.04
Difference	+4%	+11%	+1%	-3%

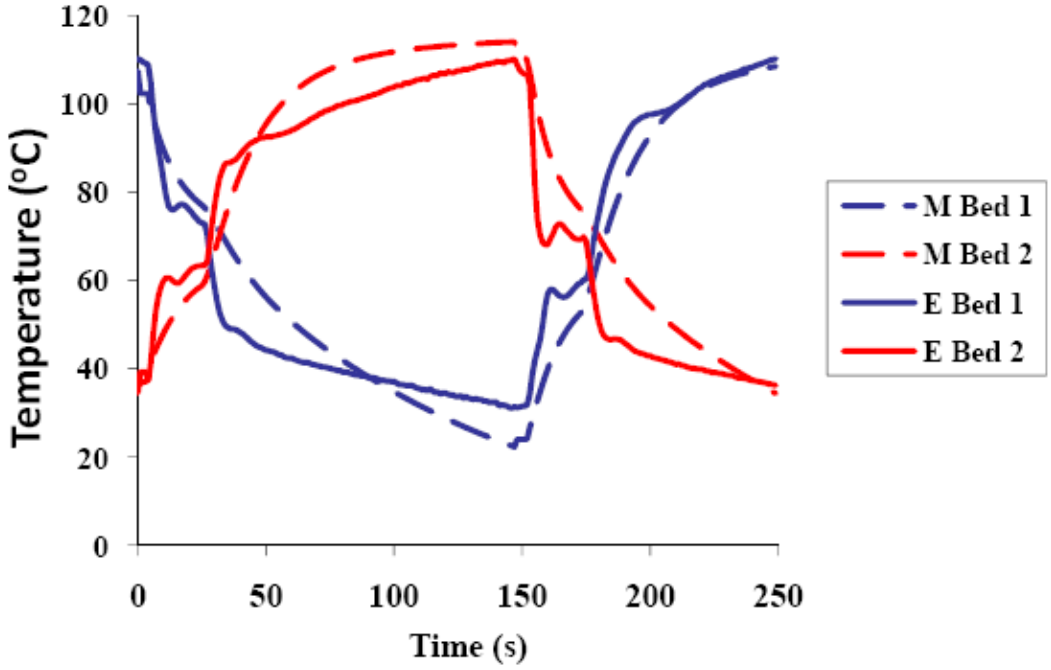


Figure 3: Comparison of adsorbent temperature cycles between the model and experiment for Test 4 (M=Model, E=Experiment)

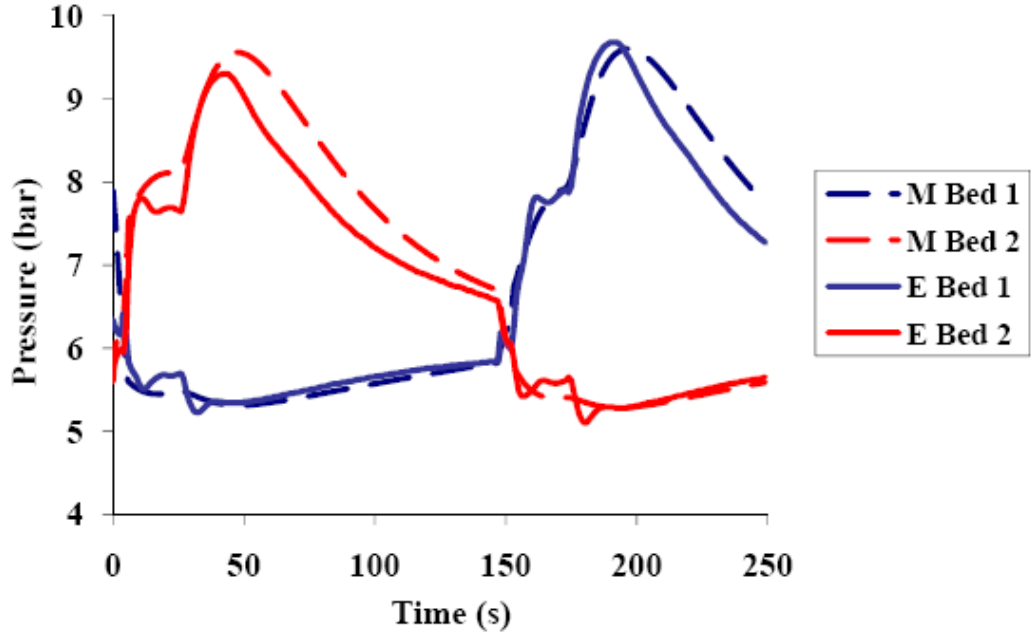


Figure 4: Pressure cycles comparison for Test 4 (M=Model, E=Experiment)

5. DEVELOPMENT OF A COMMERCIAL PROTOTYPE

Following this work, a prototype gas-fired air-source heat pump is currently under development as shown in Figure 5. It uses a four bed cycle with heat and mass recovery in order to increase the COP and is designed to replace a domestic condensing boiler. It is designed for a nominal heating power of 7 kW and has a predicted seasonal COP of 1.3.

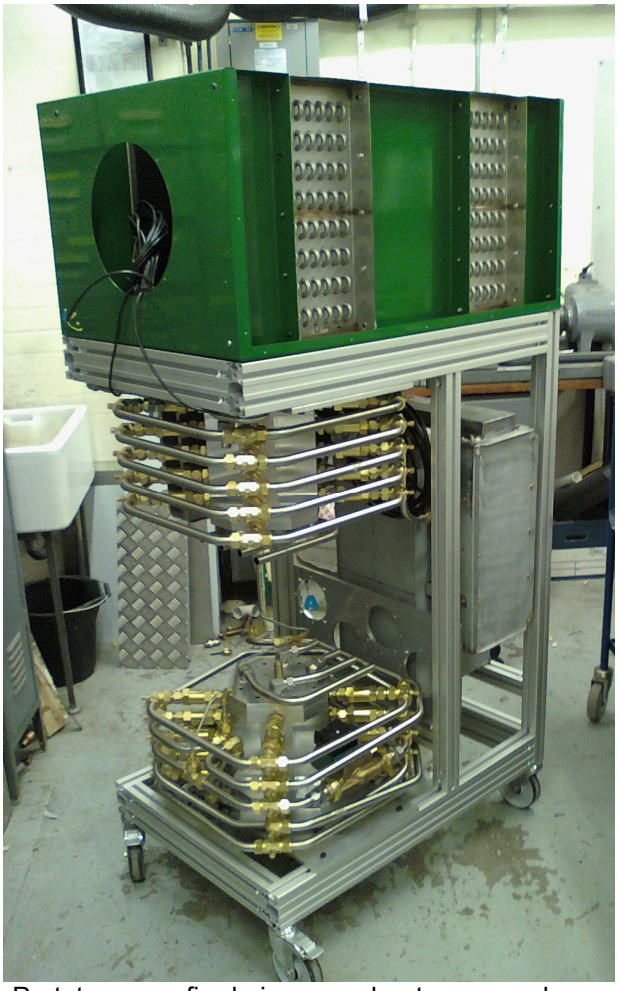


Figure 5: Prototype gas-fired air-source heat pump under construction

6. CONCLUSIONS

A proof concept prototype of gas-fired adsorption heat pump using activated carbon-ammonia pair has demonstrated satisfactory performance: it has produced heating powers ranging from 7 kW to 11 kW (COP of 1.42 to 1.61) with a driving temperature of 120°C and water flow rate range of 5 l/min to 10 l/min. Those performances are well in line with the model predictions within 11% or better. The development of a commercial version rated for a nominal heating power of 7 kW and a seasonal COP of 1.3 is currently ongoing.

7. ACKNOWLEDGEMENTS

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