DEVELOPMENT OF A DOMESTIC ADSORPTION GAS-FIRED HEAT PUMP

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Abstract: A gas-fired heat pump system intended to replace conventional condensing boilers is under development. The machine uses four sorption generators with heat recovery between all beds plus mass recovery and has a nominal heat output of 7 kW. Predicted annual average heating COP (Heat output / gas energy input based on gross calorific value) is 1.35 in a UK application with low temperature radiators. The system is described together with the simulation model, the test facilities and procedures.

Key Words: gas heat pump, adsorption, four bed cycle, activated carbon, ammonia

1 PROJECT BACKGROUND

Previous work at the University of Warwick has concentrated on the use of carbon-ammonia adsorption systems. The rationale for ammonia is fairly straightforward. We would like to develop gas heat pump systems for domestic use in the UK and elsewhere in the EU with the maximum possible market. This implies that they should be air source machines that are capable of replacing condensing boilers in retrofit applications. Approximately one million condensing boilers are installed each year in the UK as replacements for old irreparable systems. Whilst ground and water sources are desirable, air is a ubiquitous source and is the lowest capital cost option. If air is the heat source and the heat pump is to provide a significant proportion of the load it is necessary to evaporate at less than 0°C for much of the time, thereby ruling out water as a refrigerant, despite its excellent latent heat and other desirable characteristics. Methanol or ethanol are feasible regarding evaporating pressure but not sufficiently stable at higher temperatures if we want to take advantage of the higher COP offered by high driving temperatures. Ammonia is stable to temperatures of at least 200°C and so is selected despite the increased demands of system safety compared to other refrigerants.

A number of novel cycles have been investigated at Warwick in the past, including the Convective Thermal Wave (Critoph 1999), fixed bed or moving bed modular systems (Critoph 2005, Critoph 2001), and finally a 4-bed isothermal cycle with heat and mass recovery (Metcalf 2009).

The work described here, based on the 4-bed isothermal cycle has been carried out by the University of Warwick as part of a project called CALEBRE (Consumer Appealing Low Energy Technology for Building Retrofit) funded by EPSRC and EON and is the subject of further development by Sorption Energy Ltd, a university spin-out company. The concept is an affordable air source sorption heat pump that can replace a conventional gas-fired boiler and reduce gas consumption by over one third.

1.1 Choice of Cycle

There are a large number of possible cycles, ranging from Shelton's original thermal wave (Shelton 1986), through variations proposed by Critoph (1999) to isothermal beds with heat recovery (Meunier 1985). Metcalf (2009) carried out modelling to determine the advantages of various cycle types in an objective way. Specifically, he compared a 2-bed cycle with heat and mass transfer between beds, a 4-bed cycle with 3 stages of regenerative heating/cooling between beds and a modular thermal wave cycle from Critoph (2005). These results are shown in Figure 1. Each line for a system shows the best combination of COP and Specific Heating Power (SHP in Watts per unit mass of adsorbent) that can be obtained when using the optimum cycle time. The conditions used were 200°C input from the gas heat exchanger, 40°C condensing and adsorber inlet water, 5°C evaporating temperature.

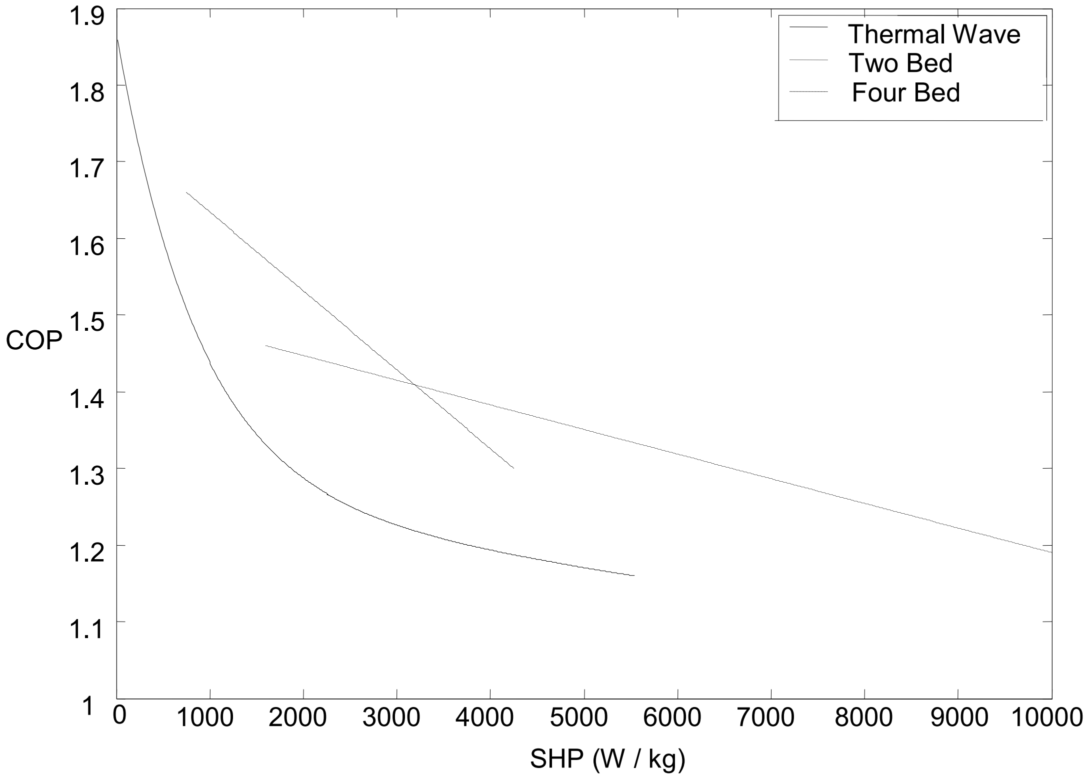


Figure 1: Cycle comparison in a heat pump application.

It can be seen that whilst the thermal wave can deliver very high heating COP's it has a correspondingly very low SHP which would imply a very large and costly machine (per unit of heating power). At the other extreme a simple two bed system with heat recovery and mass recovery between beds has much higher SHP's although lower COP's.

This leads to consideration of a four bed cycle. The four bed performance envelope is superior to that of the thermal wave for COP's less than 1.66 (SHP about 750 W/kg) and gives way to the two bed system for COP's less than 1.4 (SHP about 3200 W/kg). It was decided not to look at even larger numbers of beds since the mechanical complexity of valves and pumps would be excessive.

Similar comparisons can be made for different operating conditions but the conclusion made was that a four bed cycle was most suitable for a domestic heat pump system. It requires complex valves and extra pumps but in the range of interest the COP is about 25% higher than that of a two bed design.

1.2 Description of four bed cycle

The operation of a four bed system is described in more detail in Figure 2. The six parts of the figure show progress through half the cycle. In the first part (a) Bed 1 has reached the maximum temperature. Mass recovery is carried out by opening a valve to Bed 4, resulting in further desorption from 1 and adsorption in 4. In (b) to (c) high temperature heat recovery is carried out between 1 and 2 and low temperature heat recovery between 3 and 4. From (c) to (d) high temperature (driving) heat goes to Bed 2, heat is rejected from Bed 3 and medium temperature heat recovery occurs between Beds 1 and 4. In (d) mass recovery is carried out between 2 and 3. In (e) to (f) high temperature heat recovery is carried out between 2 and 4 and low temperature heat recovery between 1 and 3. Finally in (f) high temperature (driving) heat goes to Bed 4, heat is rejected from Bed 1 and medium temperature heat recovery occurs between Beds 2 and 3. This is half the cycle in which Bed 1 has gone from maximum to minimum temperature and Bed 4 has gone from minimum to maximum temperature. The second half continues in similar fashion to complete the cycle. Such an arrangement demands five pumps: one each for the source and sink and three for heat recovery. Obviously their electricity consumption must be minimised but in principle the pumping power can be very low.

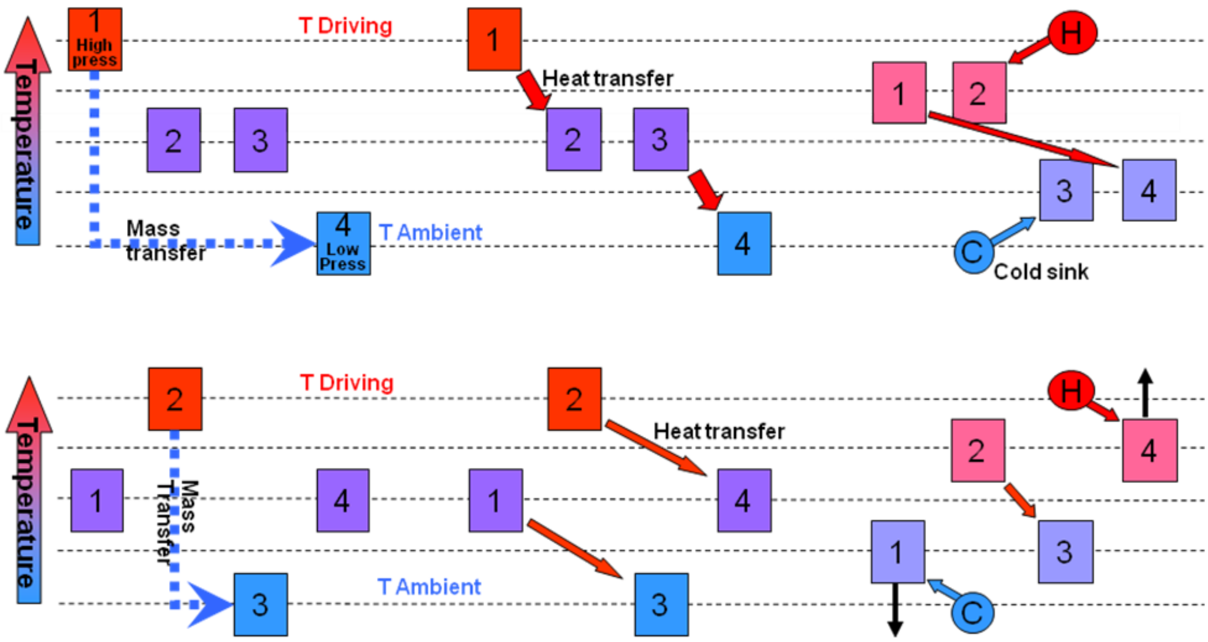


Figure 2: Processes in a four bed cycle.

2 MODELLING AND DESIGN

2.1 Modelling

A simulation model of a four bed system has been validated by Metcalf (2009) and used to generate the predicted performance data of Figure 3.

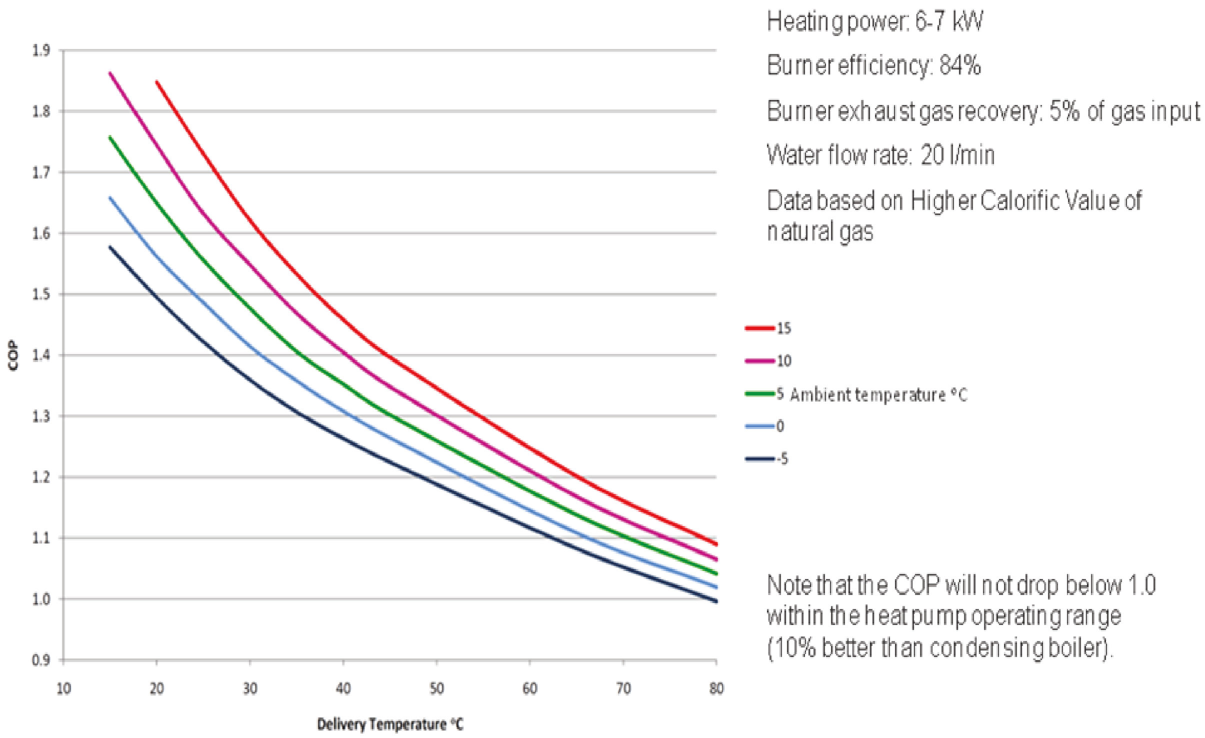


Figure 3: Predicted COP.

The machine was designed around a specification for a typical UK house that had been retrofitted with good insulation to the point that the heat pump needed to deliver 7 kW of heat. Assuming the UK climate and heat delivery at 50°C to low temperature radiators the calculated mean annual COP based on the higher calorific value of gas burnt would be 1.35. Running costs (2010 UK prices) comparative to an electric heat pump and a condensing boiler are given in Figure 4 and CO_2 emissions in Figure 5.

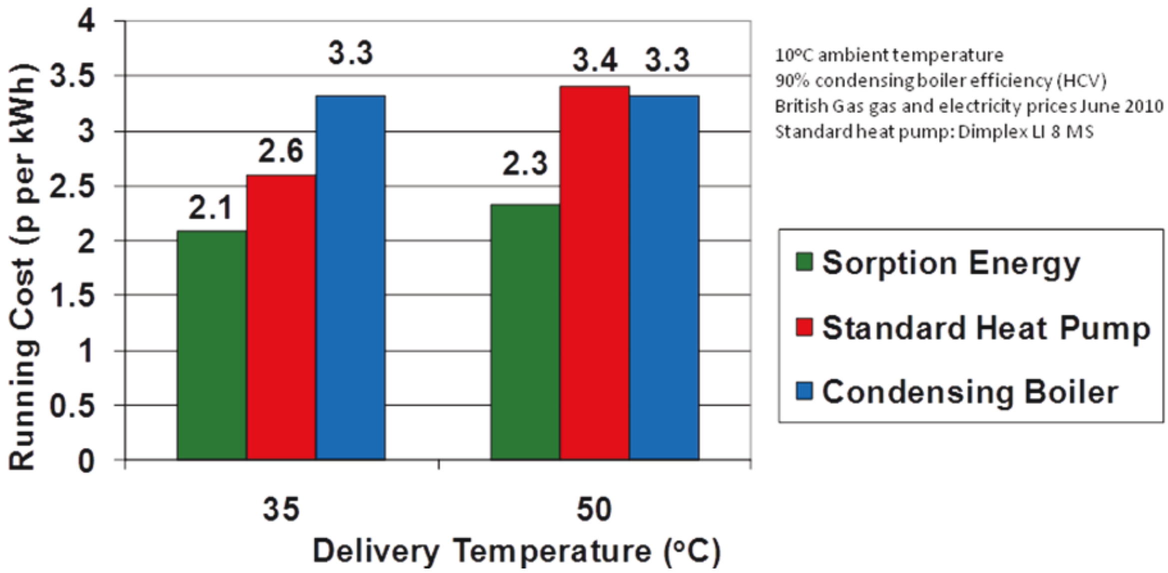
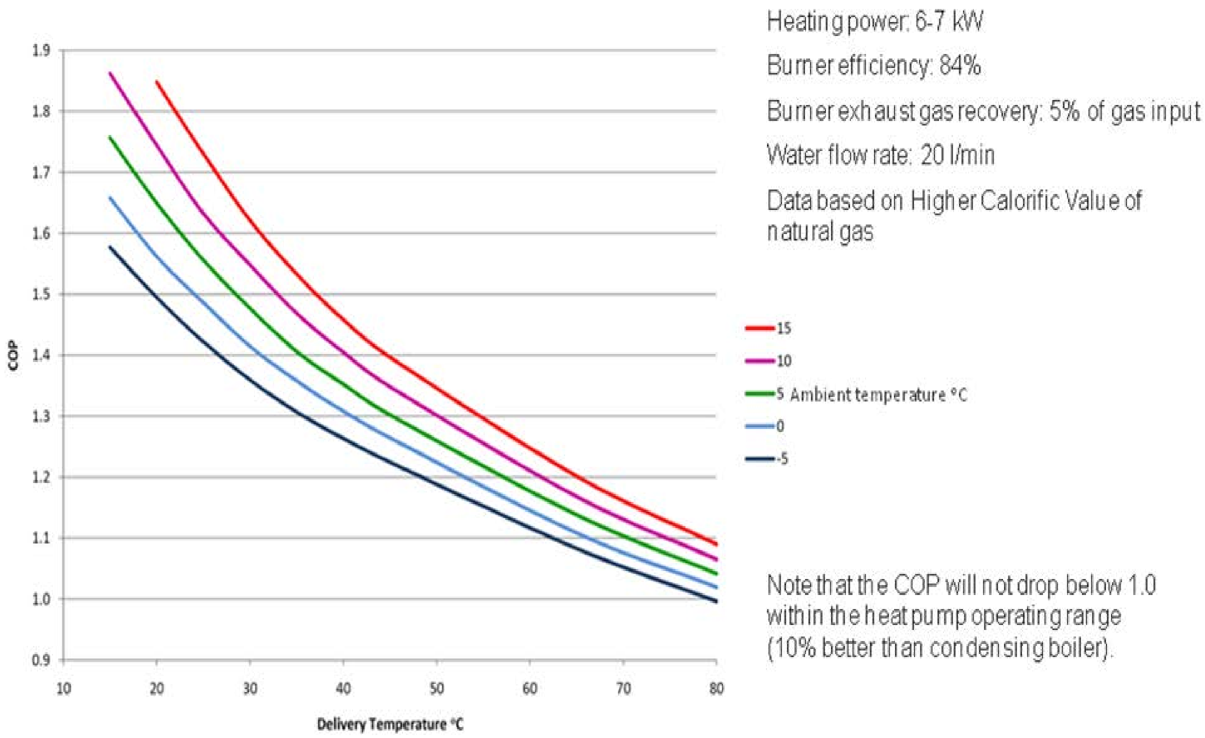


Figure 4: Comparison of Heating Costs (UK)



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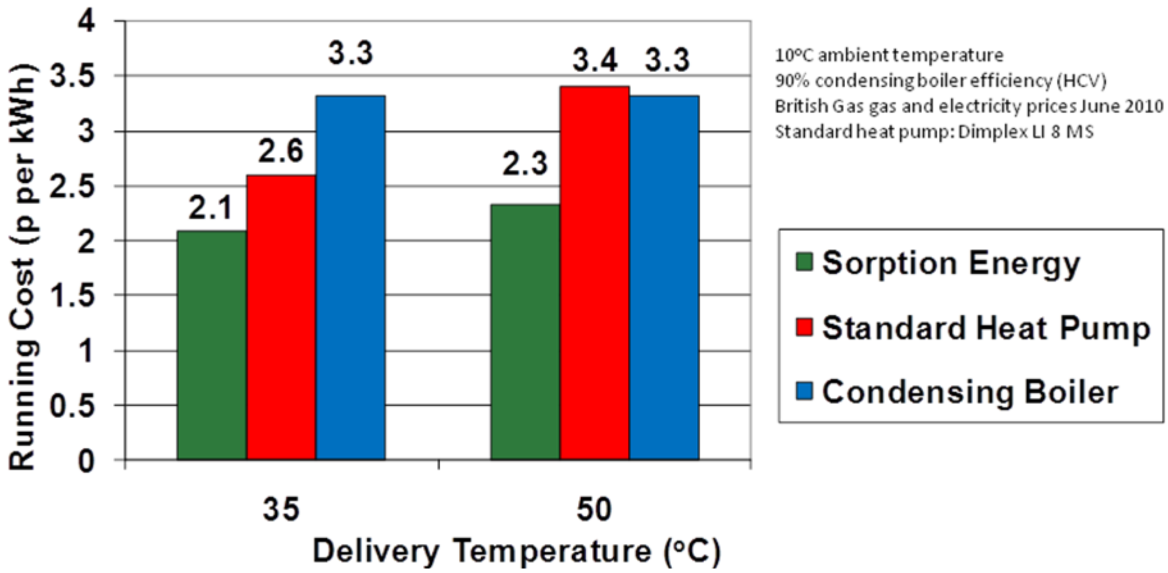

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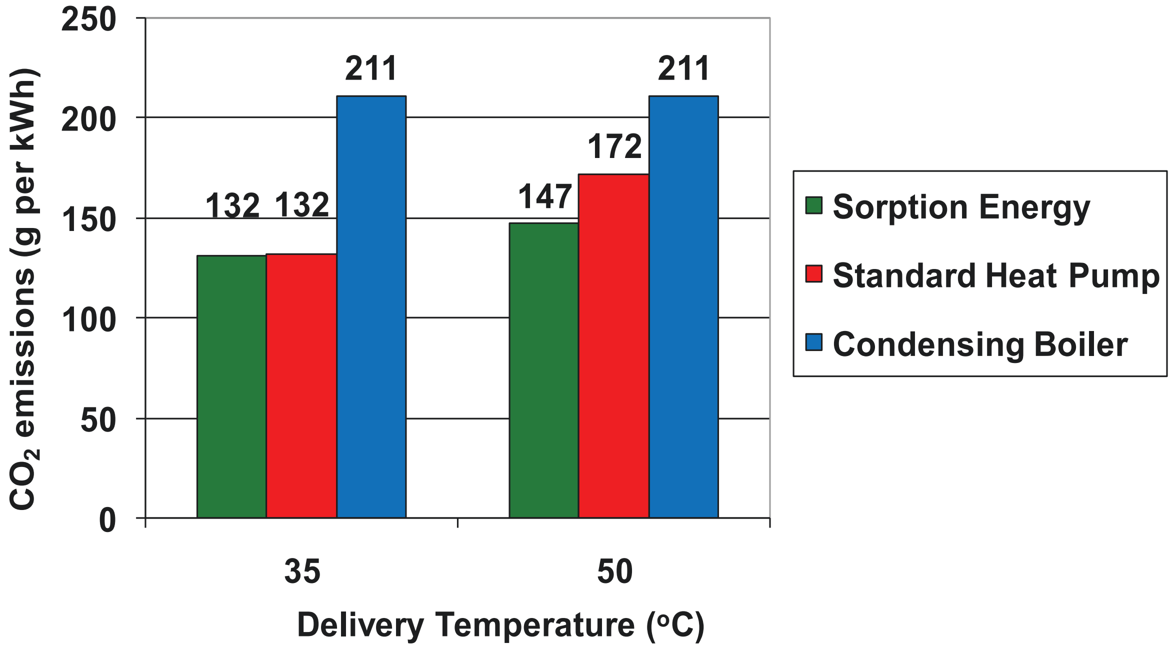

Figure 5: Comparison of CO_2 emissions (UK)

2.2 Component design

Previous sorption generators (Critoph et al. 2009) have used plate shim designs but theoretical modelling suggests that a shell and micro-tube construction could have less thermal mass and equivalent heat transfer. The core of such a heat exchanger is shown in Figure 6 and fully assembled in Figure 7.

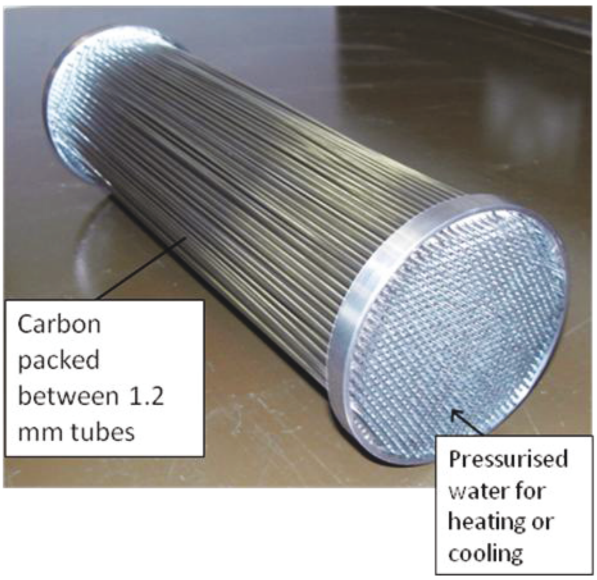

Figure 6: Generator core.

Figure 7: Complete generator.

The four generators form a sub-assembly as shown in the drawing of Figure 8. The module consists of the generators, ammonia check valves that connect to the evaporator and condenser and the mass recovery solenoid valves.

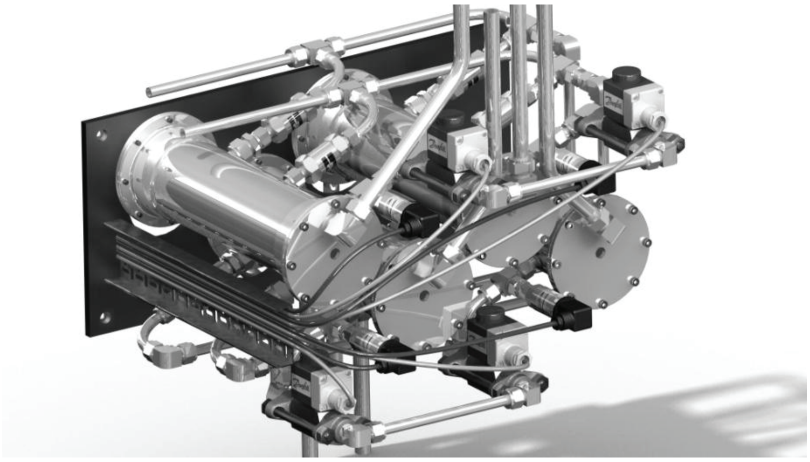

Figure 8: Generator module in Solidworks™.

Figure 9 shows the complete unit but without insulation. It is designed as a single unit to be installed outside the house with water, gas and electrical connections being made through the wall.

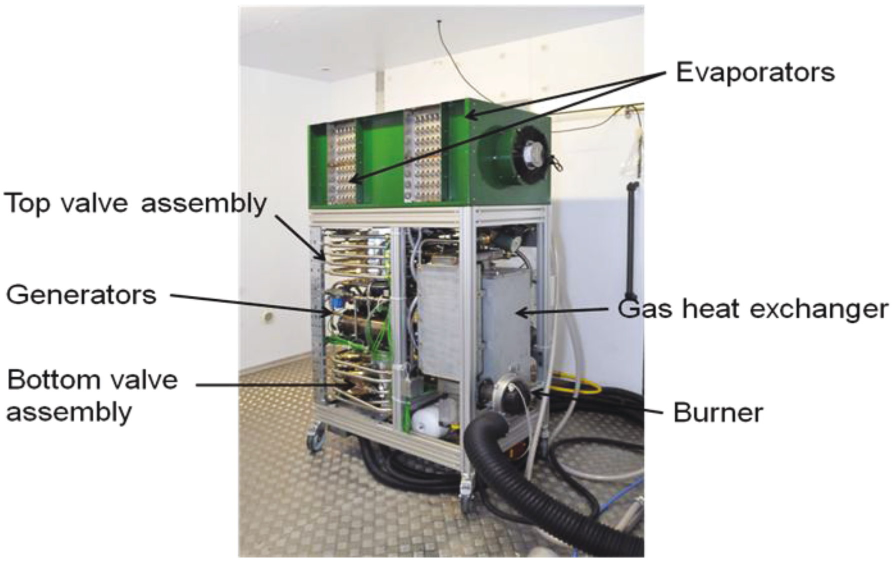

Figure 9: Prototype heat pump.

The gas burner and heat exchanger have been developed especially for this project and can modulate from 3 to 11 kW heat output at 170°C with a gross efficiency exceeding 80%. The unit has been tested outside the heat pump and performs well. It delivers pressurised water supplied to any of the four beds via the water valve assemblies. The water valve assemblies were very complex. Each was the equivalent of a 4-pole 5-way switch. They had 8 positions during a complete cycle and individual poppet valves were actuated by push rods driven by a cam shaft. This was intended to be a comparatively risk free design but not suitable for production.

3 DEVELOPMENT

The prototype was first tested in May 2011. Whilst the machine functioned as a heat pump and delivered hot water at up to 60°C internal leakage in the water valve assemblies meant that performance was unacceptably low and further testing would not be beneficial until the water valves were re-designed. After two iterations of development bespoke ceramic disc valves in a polymeric shell were manufactured and successfully tested. The new valve bodies were only 75 mm in diameter and 120 mm long and had negligible leakage of water and heat loss.

New system tests in April 2012 revealed a different challenge, related to generator heat transfer. The overall thermal resistance between the water in the generators and the bulk of the carbon was approximately twice the predicted figure which was based on measured data from a previous design (Critoph et al. 2009). The output power of the machine (at a given COP) is roughly inversely proportional to the thermal resistance and so a solution is needed to achieve a realistic power output sufficient for domestic heating.

Two approaches are being followed in parallel. The first (short term) approach is to build and install larger generators with the same basic design (150 mm nominal diameter and 400 mm long). Given the same thermal resistance they should achieve the required 7 kW output. The objective is to demonstrate the concept to potential manufacturers/investors and validate the system computer models. It is hoped that this work will be completed early in 2013. The second activity is to investigate the heat transfer problems in much greater detail and find cost effective solutions that allow the use of the smaller generators. The work being undertaken includes a range of conductivity measurements on adsorbents to reveal the diverse effects of particle size distribution, bulk density, particle shape and wall geometry on the overall thermal resistance.

4 ACKNOWLEDGEMENTS

The project has been funded by EPSRC / EON project EP/G00387/1 and by the EPSRC Follow on Fund project EP/G00387/1. Instrumentation and test chambers are made available by the AWM / ERDF Birmingham Science City project.

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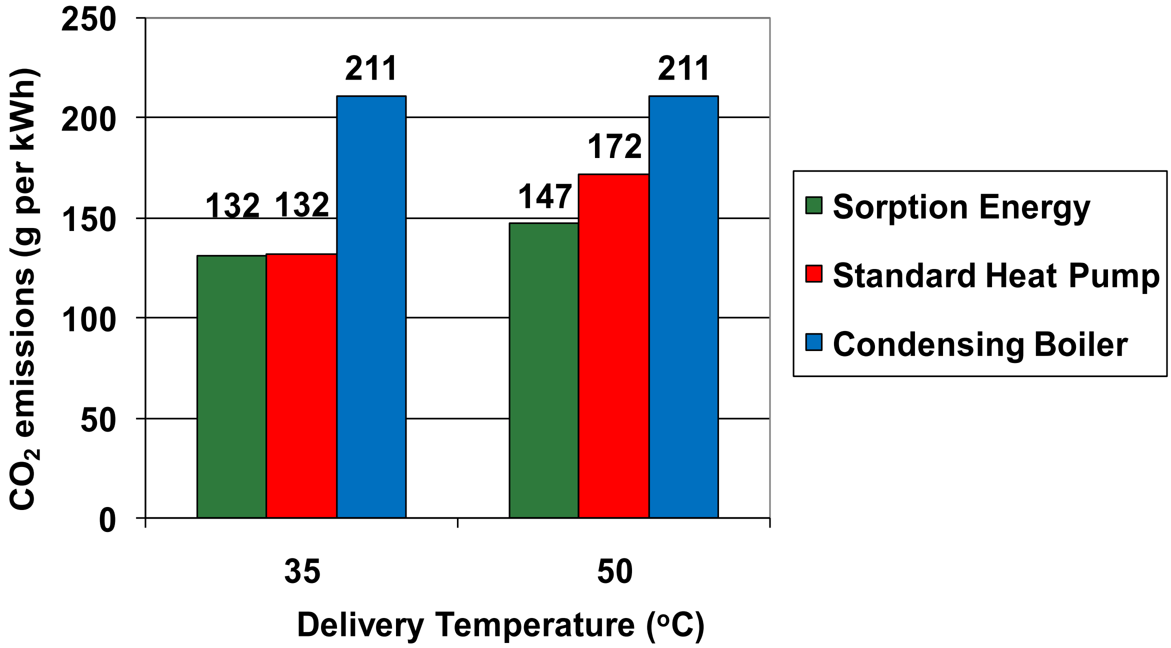
Part of

Thermally driven heat pumps for heating and cooling. – Ed.: Annett Kühn – Berlin: Universitätsverlag der TU Berlin, 2013

ISBN 978-3-7983-2686-6 (print)
ISBN 978-3-7983-2596-8 (online)

urn:nbn:de:kobv:83-opus4-39458
[http://nbn-resolving.de/urn:nbn:de:kobv:83-opus4-39458]



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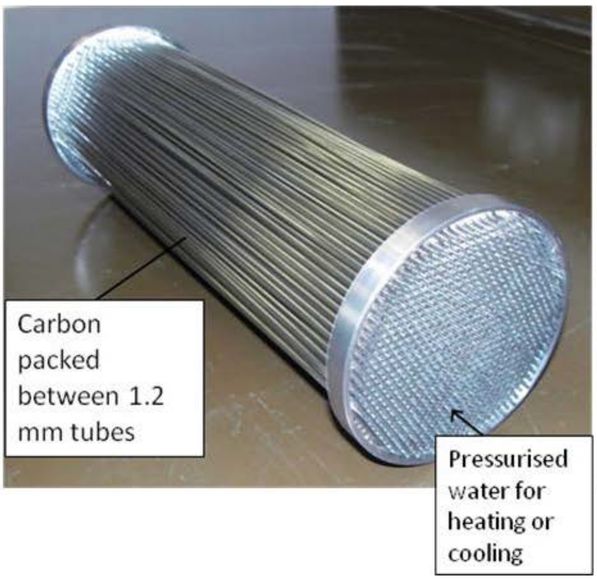

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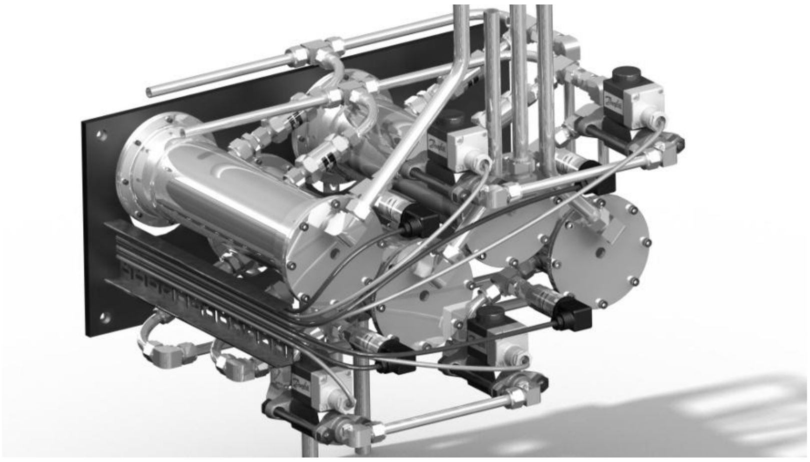

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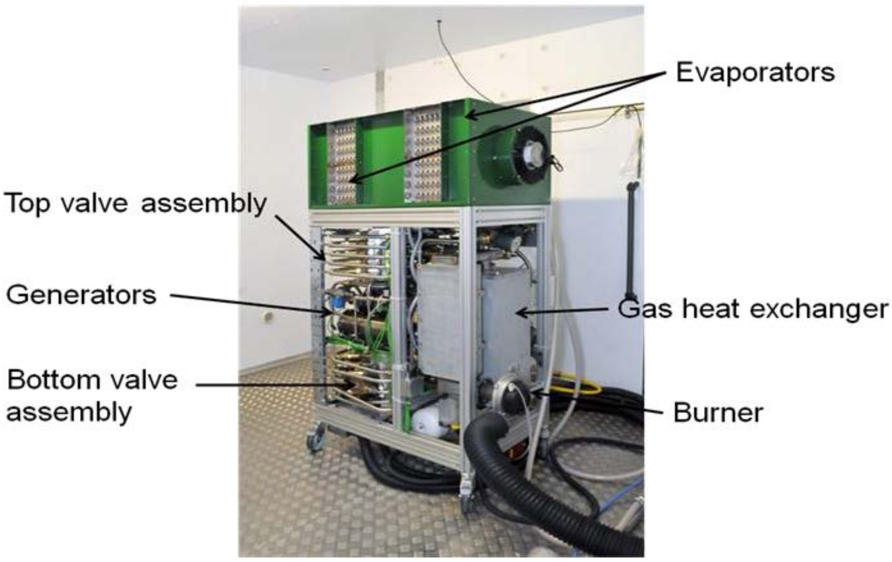

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