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Modelling and development of a generator for a domestic gas-fired carbon-ammonia adsorption heat pump

Angeles M. Rivero-Pacho*, Robert E. Critoph, Steven J. Metcalf

School of Engineering, University of Warwick, Coventry CV4 7AL, UK

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ABSTRACT

Current development of ammonia-carbon gas fired heat pumps at the University of Warwick uses shell and tube adsorption generators with over 1700 water tubes of 1.2 mm outer diameter on a 3 mm pitch filled with vibrated carbon grains and powder. This geometry is not optimised and a dynamic simulation program has been written to determine how far from optimal the design is and also whether an alternative design of finned tubes offer advantages.

Three alternative carbon composites that use Expanded Natural Graphite (ENG), silane and lignin binders have been developed and tested to characterise their thermophysical properties so that they can be included in the simulations in order to improve the thermal transfer in the generators.

Results presented show that the shell and tube geometry is close to optimal and that the best performing material is the lignin+carbon composite.

Other type of geometry, a finned tube design, was modelled as it might offer improvements in performance and help reduce the complexity and cost of the manufacturing technique. Results show that for the same tube radius, the finned tube generator needs 7 times fewer tubes in order to achieve similar performances.

1. Introduction

Previous research at the University of Warwick has utilised shell and tube adsorption generators in heat pump prototypes in which water in 1.2 mm diameter tubes heats or cools granular carbon adsorbent surrounding the tubes which are on a 3 mm triangular pitch as shown in Fig. 1 [2].

The dimensions are thought to be reasonable values but are not optimised. Optimisation of materials or components for adsorption heat pumps is a complex task. For example, improving sorbent conductivity can reduce capital costs and physical size but reduce energy efficiency due to increased thermal mass. Enhancing conductivity of the adsorbent to an extreme level can result in either the water (tube side) heat transfer or tube-adsorbent thermal resistance becoming critical. Also, whatever the physical design of a machine, there is a trade-off of achievable power against efficiency that requires sophisticated control to minimise energy use whilst maintaining required comfort levels.

Two Matlab™ simulation models have been written to explore how varying dimensions, control parameters and adsorbent thermal properties affect the Coefficient of Performance (COP) and power output under specified conditions.

One model keeps the simple shell and tube geometry. This is a costly design to manufacture but has been proved with comparatively low conductivity carbon and high contact resistance.

One possibility of improving the heat transfer in the generator is the use of expanded natural graphite (ENG) as a matrix which has been widely utilised in the development of new types of adsorbents for adsorption refrigeration and air conditioning and heat pumping processes. The thermal conductivity of pure ENG is approximately 8 W/(mK) at a density of 1250 kg/m^3 [4]. ENG has been used as an additive for granular active carbon, in which the mixture thermal conductivity is improved by over 20 times [5]. Special attention must be paid when using compressed ENG matrices as the thermal conductivity of the mixture is highly anisotropic [10] and also increase the thermal mass of the generators.

Other possibility is the use of binders, either chemical or organic, that improve the bulk conductivity of the carbon. Examples of these binder can be vulcanised silicon rubber that increases the thermal conductivity of the granular carbon up to 1.3 W/(mK)

* Corresponding author.
E-mail address: A.Rivero-Pacho@warwick.ac.uk (A.M. Rivero-Pacho).

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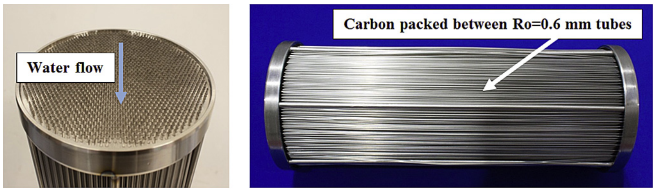

Fig. 1. Shell and (micro) tube sorption generator.

[3] or lignin binder that increases it from around 0.1 W/(mK) up to 0.44 W/(mK) [9].

This 2-D model simulates the heat transfer from water in a single tube to its surrounding unit cell of carbon throughout several thermodynamic cycles until the dynamics stabilise and the heating power per unit volume and COP are calculated.

The second model is based on the previous shell and tube model but it also includes the beneficial heat transfer effect of adding aluminium fins to the tubes as it was reported by Refs. [7] and [11].

Many parameters such as tube pitch, tube radius, tube wall thickness and fin and carbon thickness need to be varied in the simulation and there is of course no 'best' design and the optimum for highest power per unit volume is not the same as that for highest COP, but the trends can be explored and useful designs evaluated.

In order to avoid complicating the modelling task and optimisation a simple two bed cycle with heat recovery and no mass recovery was used. The only two control parameters were time for external heating/cooling to a constant temperature source/sink and the time for heat recovery.

2. Heat pump description

The heat pump that is currently under development at the University of Warwick is intended to be used in a domestic environment (space heating), replacing a gas condensing boiler. For space heating of a typical family home in the UK, a three bedroom semi-detached house, which is required to be maintained at an internal temperature of 18 °C, the heat pump should supply a heating power of 7 kW [6]. The 2-bed machine would be driven by the heat supplied by a gas burner and would use pressurised water as heat transfer fluid. The water used in the heating system of the house is passed through the ammonia condenser and then through the cooler (fluid to fluid heat exchanger) where it increases its temperature.

2.1. Generators design and sorption material

The type of heat exchanger used in this project is the previously mentioned shell and tube. The core of the generators was made of stainless steel 304 and the tubes have an outer diameter of 1.2 mm and an inner diameter of 0.8 mm. The end plates of the generators have a diameter of 144.5 mm and 1777 tubes were nickel brazed creating the core of the generator as seen in Fig. 1. After the core was filled with the carbon, it was slid inside the two halves of the generator shell. Finally, two flanges were attached at the ends of the shell completing the generator assembly.

The generator is effectively a thermally driven compressor and is the most critical part of the design.

The sorption material used in the generators is active carbon type 208C, especially good for heat pumping applications, based on coconut shell precursor manufactured by Chemviron Carbon Ltd.

In the heat exchanger, 3 kg of a mixture of 2/3 grains and 1/3 powder of carbon was vibrated reaching a bulk density of 650 kg/m^3 and yielded a thermal conductivity of 0.1 W/(mK) [8].

2.2. System description

The heat pump prototype was constructed to test the performance of the generators along with the carbon mixture and to validate the computational model developed of the machine. The water schematics and the ammonia pipework of the heat pump are shown in Fig. 2 a and b.

2.3. Experimental results and analysis

The machine was tested with a driving temperature of 150 °C and with an evaporating temperature of 5 °C. The machine was tested for two different delivery temperature cases:

- Underfloor heating: 36 °C flow delivery– 26 °C return.
- Low temperature radiators: 50 °C flow delivery– 40 °C return.

The results of the machine testing at the different delivery temperatures can be seen in Fig. 3a. Fig. 3b shows both the experimental and the simulated prediction of the heating powers of the condenser and cooler of the circled case in Fig. 3a. It is possible to observe that the experiment and the simulation are very similar.

Although the simulations and the experiments match, the performance of the system is low. In order to improve it, a better design of the generators along with a good choice of sorption material (carbon composite with enhanced thermal properties) is essential.

3. Materials

The adsorbents modelled include Chemviron 208C coconut shell loose carbon grains as well as other three different carbon composites that were developed by researchers of the University of Warwick with different binder materials in order to obtain a carbon composite with enhanced thermal properties than the ones of loose carbon grains.

3.1. Lignin binder

These lignin-carbon composites consist of blocks made of a mixture of carbon and ammonium salt of lignosulfonate, a lignin based binder. The composite is made by mixing carbon (grains, powder or a mixture of both), lignosulfonate and hot water (dissolves the binder and helps to create and homogenous mixture). The mixture is then compressed to the desired shape fired in an inert atmosphere in order to carbonise the organic binder.

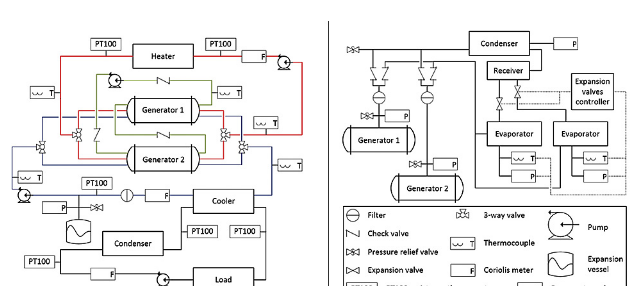

Fig. 2. a) Water and b) Ammonia pipework circuits.