ROTARY REGENERATIVE ADSORPTION AIR CONDITIONING SYSTEM

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Abstract

The paper presents the cooling characteristics a prototype rotary regenerative adsorption air conditioning system that uses high performance multiple modules. This prototype, designed for up to 0.5 kW cooling with a COP of about 0.90 or 1.5 kW at lower COP, has 32 modules built into cylindrical assembly that rotates slowly (typically from 0.05 rpm to 0.20 rpm). Each module is made of two finned stainless tubes (12.7 mm OD, 0.25 mm thickness and 1m long) and has three main sections: the generator with its finned tubes lined with about 2.7 mm layer of monolithic carbon made in situ; the receiver (evaporator-condenser) and the adiabatic section placed between the receiver and the generator in order to reduce the longitudinal conduction heat flow between them. The refrigerant is ammonia. The prototype has three independent air ducting channels for the generator, the evaporator and the condenser respectively. The cycle is highly regenerative since the heat rejected by each module is used to preheat the others. The machine is suitable for gas firing, but the prototype is electrically heated in order to demonstrate the concept of rotary module for continuous cooling production .

Tests on the machine are ongoing at the time of writing.

KEYWORDS *Simulation, adsorption, carbon, ammonia, heat pump, refrigeration, regenerative*

INTRODUCTION

It is well known that the major challenges for adsorption cycles are:

- To improve heat transfer in adsorbate beds, thereby reducing size and cost.
- To improve regenerative heat transfer between beds, thereby increasing COP.

Current progress is reviewed by Meunier [1]. Bed conductivities have been improved from 0.1 W m^{-1} K^{-1} Douss, Meunier and Sun [2], Critoph and Turner [3], to 0.4 W m^{-1} K^{-1} for monolithic carbons, Critoph and Tamainot-Telto [4] and 5 W m^{-1} K^{-1} for graphite composites Guilleminot [5]. Cooling and heating COP and the SCP of a range of sorption machines are given by Pons et al [6]. It is not possible to generalise about them, since many different applications were studied, but it is probably true to say that in air conditioning applications adsorption machines need to be improved if they are to compete with multiple-effect Lithium Bromide absorption systems. The ideas presented below aim at both improving the efficiency and reducing the cost of adsorption refrigeration and heat pumping.

They are the subject of a patent by Critoph [7].

CONCEPT

In order to achieve good regeneration between adsorption and desorption it is necessary to either employ some form of thermal wave as suggested by Miles et al [8] or Critoph [9] or to use many beds as suggested by Meunier [10]. This study examines the possibility of using many simple modular beds in an arrangement that allows effective heat transfer between them. A single module is shown schematically in Figure 1. It is a tube having a sorption generator at one end and a combined evaporator and condenser at the other. The first such module that we have made has a stainless steel tube 12.7 mm in diameter and 500 mm long containing the generator. It is lined with a 3 mm layer of monolithic carbon provided by Sutcliffe Carbons Ltd. The carbon shape is formed within the tube and so the heat transfer between steel and carbon is very high. The other end of the module is a receiver for the liquid adsorbate; ammonia in our work. The adiabatic section separates the generator and receiver, reducing longitudinal conduction between them. In the current design with 0.25 mm wall thickness tube, a 20mm ‘adiabatic’ length reduces mean longitudinal conduction to less than 1W. This could be further reduced if necessary.

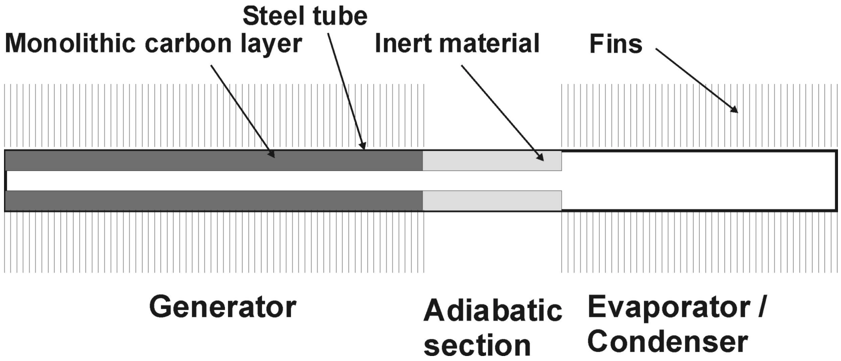
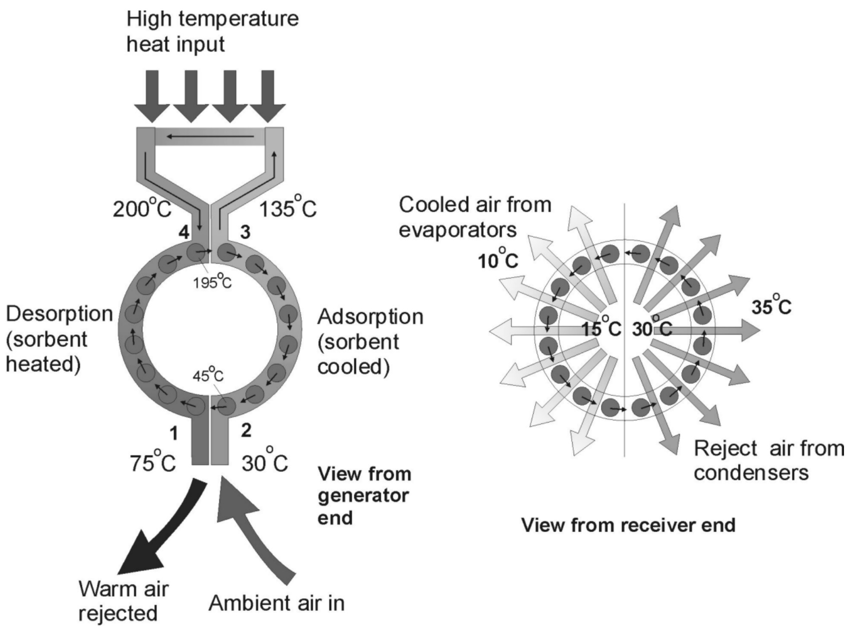


Figure 1: Section through sorption module

Heat may be transferred to or from the generator and receiver by passing air or any other fluid across them. In the case of air, fins can enhance the heat transfer. In desorption, the generator is heated and desorbed refrigerant condenses in the receiver, which is cooled. In adsorption the generator is cooled and heat is provided to boil the refrigerant in the receiver. The whole module is the very simplest type of adsorption refrigerator or heat pump.

It is possible to combine many such modules in an assembly that allows regenerative heating between them. Figure 2 shows one possible way of doing this in schematic form and Figure 3 shows an assembly drawing of a prototype module. In this example the machine is an air-to-air heat pump or air conditioner. Figure 2 shows 16 modules in cross section through the generator section and through the receiver section. The fins are omitted for clarity. All rotate about the central axis typically completing one revolution in 30 minutes. The actual prototype has 32 modules, each of which has two tubes in a single fin block as shown in Figure 3. Air is blown over the tubes, counterflow to their direction of motion and exchanging heat with them. Seals prevent the air from travelling directly between the adsorbing and desorbing zones but allow the tubes to pass through when necessary. Consider the path of a single tube beginning at position 1 in Figure 2. The carbon is at its coldest, perhaps 50ºC and has maximum concentration.



(a) (b)

Figure 2: Cross section through generator and receiver zones

As it moves clockwise through the annular duct it is heated by air flowing in the opposite direction. If the 'thermal mass flow rate' of the generator is approximately the same as that of the air, then the desorption section acts like a counterflow heat exchanger with capacity ratio close to unity. In reality, the effective specific heat of the carbon varies during a cycle but it is still possible to balance the flow rates quite well. The result is that by the time the module reaches the end of the desorption section it is perhaps at 200ºC. Whilst the carbon is heated it desorbs ammonia which condenses in the receiver section of the module. In an air conditioning application, a stream of ambient temperature air cools the receiver section. A similar process occurs in the adsorbing section, but with evaporation occurring in the receiver, which cools the airstream passing over it. In the course of cooling down, the generator tubes heat the stream of ambient air induced at position 2. This pre-heated air is removed from the annular duct at position 3 and heated by an external high grade heat source before being re-introduced to the duct at position 4.

The greater the number of modules, the better the approximation to a continuous process with counterflow regeneration of heat.

The advantages of the system are the absence of refrigerant valves and complex or expensive heat exchangers. Potential problems might include the sealing mechanism to direct the air flows and possible degradation of the carbon due to thermal shock.

INITIAL EXPERIMENTATION WITH SINGLE MODULE

Previous experience with monolithic carbon Critoph, Tamainot-Telto and Davies [11], suggested that monolithic carbon should be proof against the thermal cycling and could be made to adhere strongly to the tube wall. A manufacturing technique was devised and 500 mm lengths of 12.7 mm outside diameter 0.25 mm wall thickness stainless steel tube were lined with 3 mm of active carbon. Fins of 0.12 mm thick aluminium were applied on a 1mm pitch (Figure 3).

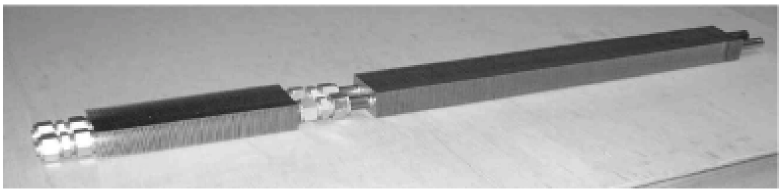


Figure 3: Complete (double tube) module

A simple test rig was built which subjected the generator to alternating flows of hot (150ºC) and ambient air whist the receiver was kept in a flow of ambient air . An optional glass receiver allowed observation of the quantity of liquid ammonia building up or boiling. Repeated heating and cooling for tens of cycles showed no tendency for the carbon to break up and drop into the receiver. This was encouraging, but obviously in a real system there will be many thousands of cycles and further testing is necessary. Detailed results are given in Critoph and Tamainot-Telto [12].

SIMULATION MODEL

A simulation model has been written in Matlab™ which is described fully in Critoph [13], and the optimisation of the design derived from it is described in Critoph [14]. The simulation model includes fin efficiency, sensible heats of ammonia, the effect of dead volume etc.

Figure 4 shows how the cooling COP and cooling power of a 32 module array vary with the fin area per module and the air flow rate through the sorption section. The air flow rate is optimised at each point to maximise the effectivenesss of the array as a counterflow regenerator and hence to maximise COP. It can be seen that COP’s of 0.85 with a cooling power of 400 W are feasible.

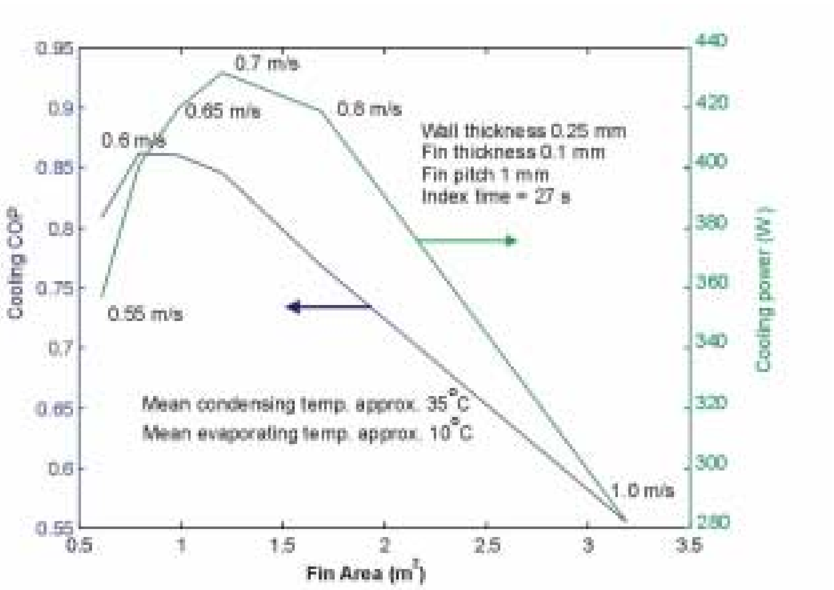


Figure 4: Simulated performance v. fin area and optimised air flow rate.

MECHANICAL DESIGN

The method used to divert the air flows is to use two radially sliding vanes that can move between the modules at positions 1,2 and 3,4 in Figure 2. The vanes can be withdrawn briefly whilst the complete module assembly is indexed from one position to the next. This is convenient in a laboratory rig but a production version would need a more sophisticated mechanism that allowed the modules to move continuously.

The actual experimental prototype is designed to produce up to 2 kW of cooling power and is shown in the labelled photographs Figures 5,6 and 7. Figure 5 shows the air flow paths corresponding to those shown schematically in Figure 2. The prototype consists of two drums (upper generator section and lower evaporator/condenser section), three fans and two pneumatic cylinders to drive the sliding shutters mounted on a hexagonal metallic frame. The carousel carries 32 identical modules and rotates around a central shaft that is driven by a stepper motor through a gearbox system and a belt. The carousel has a height of 925 mm with 459 mm outer diameter. The generator of each module is located at the upper part of the carousel while the receiver is located at the lower part. There are two drums, upper and lower, that house upper and lower carousel parts respectively. The upper drum (height: 581 mm, ID 294 mm, OD 460 mm) has two parts: an inner part that directly fitted on the inner part of the carousel (generator zone) and an outer part that is fixed on the frame side. A return duct is adapted on the outer part of the carousel in order to divert the preheated air stream past a heater (3.7 kW). The lower drum (height: 188 mm, OD 500 mm) has two fixed parts: an inner part that fitted at the bottom of the frame and an outer part that is fixed on the frame edge. This inner part is a divider designed to seal against flow of air from the evaporator compartment to the condenser one and still allows rotational passage of receivers with minimum leakage.

Figure 6 shows the how the upper section of the outer drum is connected to the upper fan blower that corresponds to Figure 2a and how the lower section is connected to two fans to generate cooled and warm air respectively with air stream that corresponds to Figure 2b. The two pneumatic cylinders work simultaneously and are designed to operate the two baffle blades that separate the adsorption and desorption zones and act as an air seal.

At the time of writing (May 2003), the prototype is complete, the modules charged with ammonia, and the system in the process of being tested. The pressure drop of air flowing through the upper module sections is acceptable at 150 Pa when the design flow rate is obtained. When the indexing and shutter mechanisms are fully commissioned the machine will be fully functional.

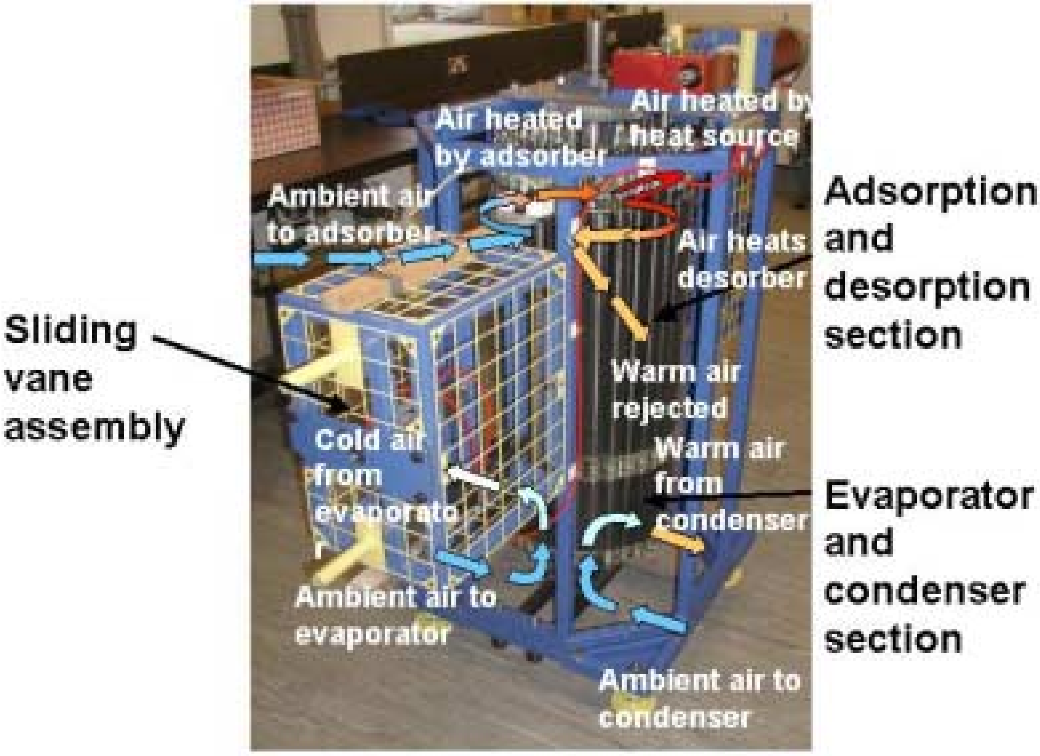


Figure 5: Part assembled prototype showing air flow paths

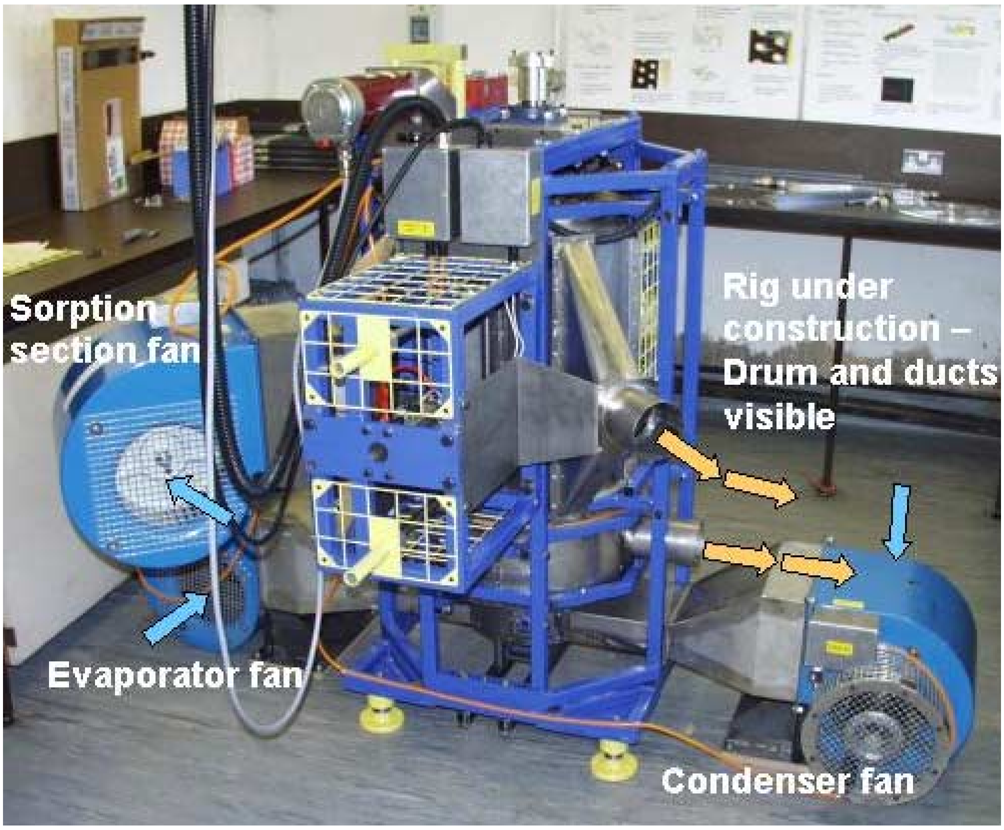


Figure 6: Part-assembled prototype showing fans and ducting

Figure 7: Assembled prototype showing air ducting

CONCLUSIONS

A new continuous adsorption refrigeration system has been described which uses a number of simple tubular modules. A single module has been made and tested and a programme written to simulate many modules in a real system. A 32 module system is under complete and about to be tested.

Acknowledgements

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Nomenclature

COP	Coefficient of performance (-)
SCP	Specific Cooling Power (W kg^{-1} adsorbent)

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