DESIGN AND TEST OF A $4m^3$ SOLAR REFRIGERATOR

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ABSTRACT

A solar thermal adsorption refrigerator has been built and tested under US DoD contract W911QY-07-0073. Previous research at the University of Warwick on a mobile air conditioning system has resulted in a patented concept for a highly compact solid sorption reactor. In the work reported here we apply the technology to solar powered refrigeration using the active carbon – ammonia pair destined for food preservation (0-5°C) in remote areas such as desert. The activated carbon used in this application was developed by ATMI that has a thermal conductivity of 1.3 W/m.K leading to an overall bed UA value of 133 W/K is used. The commissioning test using electrical heating to simulate the solar input shows that the ice bank fins are cooled down to 0°C within 6 hours. In a preliminary field test in Tucson (Arizona) with good conditions (clear sky with 770 W/m^2 measured solar radiation) the machine produced a cooling power within the range of 0.5 kW.

1 - INTRODUCTION & BACKGROUND

The initial specifications of the generator were prescribed by Centro Ricerche Fiat (CRF) in the context of car air conditioning driven by engine waste heat. The specification requires a generator of 1 litre adsorbent capacity of which the first complete prototype is shown in **Figure 1**. 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 SCP **[1].** The stainless steel plates separating each layer of adsorbent 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 **[2]**. The square design ensures equal flow path lengths in every channel and therefore even heating and cooling of the adsorbent. The internal pressure (up to 20 bar when condensing at 50°C) is withheld by the stainless steel shims that act as supporting webs to the outer wall, which only needs to be 3 mm thick despite being straight. The open end of the front face as shown in **Figure 1** is used to insert and remove the adsorbent in order that a range of adsorbents can be tested. Final production versions would be brazed with the carbon in situ and completely enclosed. **Figure 2** shows a photograph of the unit fitted with water manifolds and pressure flanges prior to testing. The top and bottom 'ammonia flanges' are necessary due to the open face and would be unnecessary in an eventual completely enclosed unit. The end pressure flanges are necessary to prevent deformation of the ends of the unit, but could be replaced by lighter domed ends. The first prototype was used successfully in two applications: for a car air conditioning demonstration unit, 1.6 kW cooling power was produced with a COP of 0.*23* **[3]** and laboratory scale gas fired heat pump with 7 kW heating power generated with COP of 1.60 **[4].**

There is a requirement for maintaining chilled food between 0°C and 5°C in transportable containers in remote (desert) areas away from grid electricity. The conventional technology solution is to use vapour compression refrigeration powered from motor-generator sets that burn fuel or diesel. The current oil price and the cost of the logistics required for fuel supply in the desert are the key factors behind the development of this alternative and potentially cost effective solution. The University of Warwick and ATMI (Advanced Technology Materials Inc.) are collaborating in the development of a solar thermal powered system, which has parasitic power for controls and auxiliaries (pumps, valves and fans) supplied by photovoltaic panels. The aim of this paper is to present and discuss the experimental results for both the commissioning test in Coventry (UK) using an electrically simulated heat input and the field test in Tucson, Arizona (US) where solar collectors were integrated with the system.

2 - SYSTEM DESCRIPTION

The solar driven mobile container is designed for food conservation and could produce up to 2 kW cooling with 8 m^2 of solar thermal collectors operating in a desert environment (40°C and -10°C for condensing and evaporating temperatures, respectively). The system driving temperature generated by the solar collectors could reach up to 170°C. **Figure 3** shows the system schematic diagram. Conventional evacuated tubes (10m^2 Thermomax DF100) have been selected for the application. The heating medium is pressurized water at up to 6 bar flowing directly through the collectors and sorption generators The standard insulated container has external dimensions of 2.4 m x 1.5 m x 2.1 m and an internal volume of 4.7m^3. Naturally, any solar powered system requires thermal storage and an ice bank integrated with the evaporator. Approximately 150 kg of ice is needed and this is incorporated into a vertical wall within the container. The wall has enough fins extending into the cold space so that, it is hoped, cooling within the container can be achieved by natural convection. The evaporator (flooded) is combined with an ice bank located inside the cold space. The system is shown both under construction and fully completed in **Figure 4**. For this project a 12 mm layer of adsorbent (10 layers) was enough to minimize the metal thermal mass and to give a high overall UA value for the generator (in the order of 350 W/K providing that the bed thermal conductivity is 2.5 W/m.K). **Figure 5** shows the 12 mm layers prototype version with and without flanges. At this stage of adsorbent development the bed thermal conductivity is 1.3 W/m.K. After a preliminary test designed to evaluate the heat transfer performance, the full characteristics of the generator were established and are summarized in **Table 1**.

3 - EXPERIMENTAL PERFORMANCE

3.1 Commissioning test (Coventry, UK)

This test was mainly designed to check the functionality of all components of the machine including the control system. An electrical heater rated at 9 kW was used to simulate the solar input. The two beds are operated in a simple cycle with both mass (4 seconds) and heat recovery (20 seconds), with typical heating cycle time of 150 seconds. The cooling of the beds is via a conventional fan coil using the pressurized water and with attention being paid to minimizing the fan power. With a driving temperature ranging from 80°C to 120°C and a maximum ambient temperature of about 25°C, the system has operated with satisfactorily for one week (about 10 hours operating time per day). **Figure 6** shows the temperature profile within the cold store space: the ice bank fins reach 0°C within 6 hours.

3.2 Preliminary field test (Tucson, Arizona, US)

The combined sorption cooling system with insulated container and solar collectors in a field test is shown in **Figure 7.** The preliminary tests were carried out with the following set of operating conditions: 180 seconds for the heating cycle time; 10 seconds for the mass recovery time and 20 seconds for heat recovery time. The overall cycle time is 420 seconds. The selected outdoor conditions in Tucson (Arizona) offers the best operating conditions during the month of March 2010: clear sky with about 766 W/m^2 maximum daily measured solar radiation with an average daily temperature of about 25°C. The preliminary experimental data collected are summarized in **Table 2**. The maximum cooling power is about 0.34 kW. This poor cooling production is a consequence of the low bed thermal conductivity (1.3 W/m.K). In fact with the current operating conditions and a bed thermal conductivity of 2.5 W/m.K, our model predicts a cooling power ranging from about 1.2 kW to 2 kW.

Type of carbon	ATMI (Monolithic)
Filter	SS Mesh (grade 180)
Sorbent density	850 kg m^{-3}
Mass of carbon	2 kg
Maximum concentration	0.26 kg NH_3/kg carbon
Adsorbent layer size	12 mm
0perating temperature	200°C (maximum)
Operating pressure	20 bar (maximum)
UA value water channels	1383 WK^{-1}
UA value carbon	147 W K^{-1}
Bed thermal conductivity	1.3 W m^{-1} K^{-1}
Overall bed UA value	133 W K^{-1}

Table 1: Novel generator specifications

Local Time	Solar rad (W/m^2)	NH3 average flow (g/s)	$T_{ambient}$ (°C)	$T_{Evaporation}$ (°C)	$T_{Condensation}$ (°C)	$T_{Driving}$ (°C)	Cooling (kW)
9-10	635.5	0.0602	13.38	3.6	23.3	61.4	0.070
10-11	634.8	0.251	19.16	4.5	29.2	104.5	0.284
11-12	722.5	0.301	22.66	2.2	30.7	126.7	0.338
12-13	766	0.304	25.09	0.9	32.2	136.4	0.338
13-14	744.4	0.294	26.1	-0.2	33.1	137.5	0.325
14-15	664.95	0.265	27.63	-0.7	34.4	136.9	0.292
15-16	531.23	0.223	28.07	-1.2	34.9	130.1	0.245
16-17	342.26	0.161	27.96	-1.9	35.1	112.6	0.176

Table 2: Preliminary experimental performance

CONCLUSIONS

This research programme has proved that the concept of a solar powered sorption refrigeration system for food storage in desert areas can work despite the lower cooling production obtained at this stage (less than 0.500 kW). The limiting factors of the current cooling capacity are clearly identified including the system control strategy and will be addressed in the future.

REFERENCES

[1] Critoph R.E. and Metcalf S J, "Specific cooling power intensification limits in carbon-ammonia adsorption refrigeration systems", *Applied Thermal Engineering*, Vol. 24, Issues 5- 6, pp. 661-679, 2004.

[2] Critoph R. E., Heat Exchanger, Patent US2010024448 (A1) - 2010-02-04

[3] Tamainot-Telto Z., Metcalf S.J., Critoph R.E., "Performance of compact adsorption air conditioning for mobile applications", *International Journal of Refrigeration*, Vol. 32, Issue 4, pp. 727-733, 2009

[4] Metcalf S. J., "Compact high efficiency carbon-ammonia adsorption heat pump", University of Warwick, *PhD Thesis* (2009).

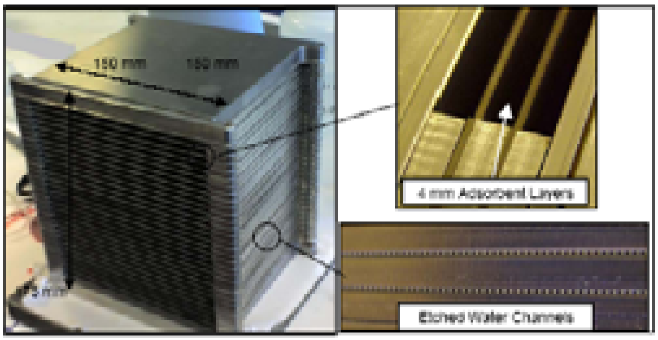

Figure 1: Plate heat exchanger generator design (4 mm adsorbent layers)

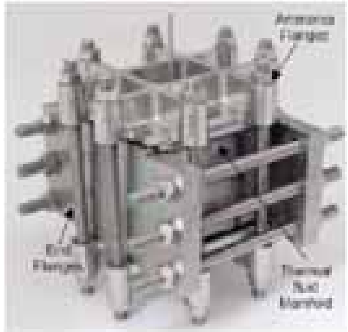

Figure 2: Prototype generator (4 mm adsorbent layers)

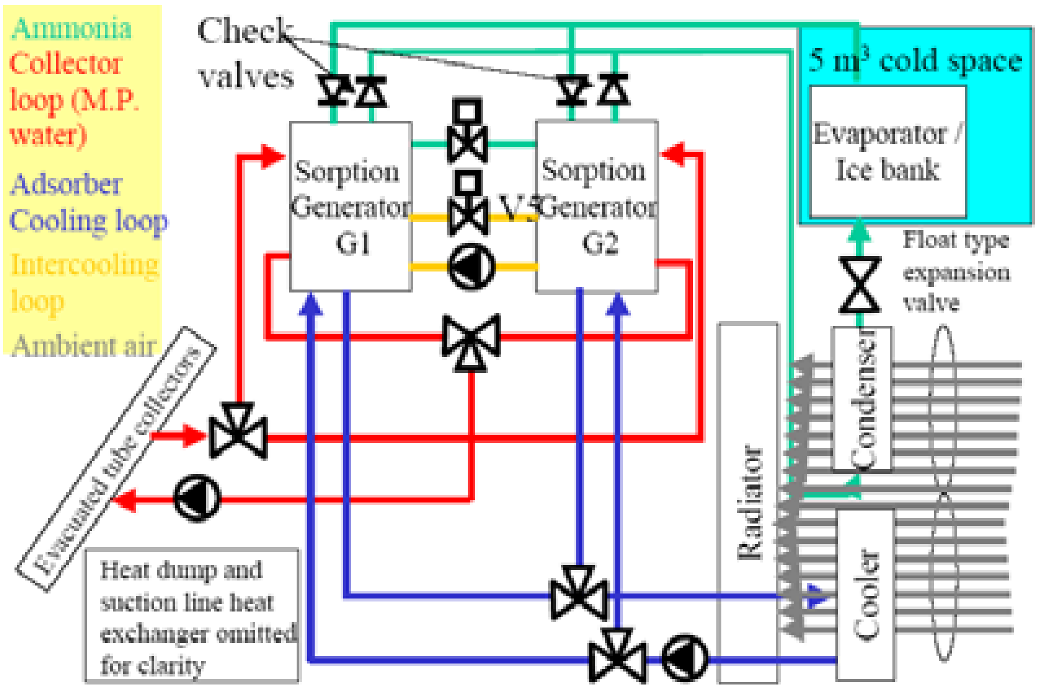

Figure 3: Schematic diagram of the solar driven mobile container

Figure 4: Solar driven mobile container

Figure 5: Sorption generator empty and with retaining pressure flanges

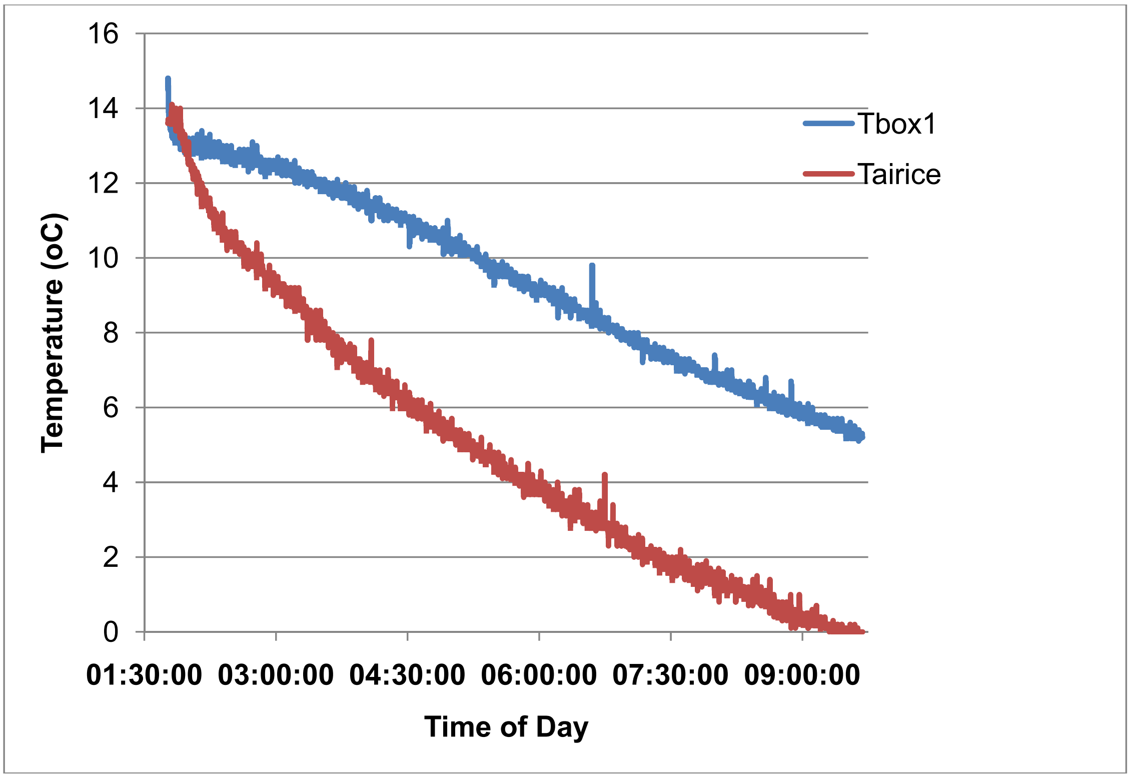

Figure 6: Commissioning cooling test

Figure 7: Initial field testing in Arizona