A NOVEL COOLING CONCEPT AND SYSTEM WITH ZERO OZONE DEPLETION POTENTIAL AND NEAR ZERO GREEN HOUSE GAS EMISSIONS

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Abstract: The use of hydrofluorocarbons (HFCs) in the compression refrigeration has significant advantage over hydrochlorofloro carbons (HCFCs) in terms of ozone depletion potential (ODP) but offers very high global warming potential (GWP). The other demits of HFCs are the requirement of stringent regulatory mechanism to control the manufacture, distribution, usage and disposal of these refrigerants which have a GWP ranging from 120 to 14,800. According to Montreal Protocol these regulations are essential to minimise the green house effects due to HFCs. Besides HFCs there is very limited number of refrigerants available for the compression cycle. These are ammonia, carbon dioxide or butane based compression cycle systems. Ammonia and carbon dioxide systems operate at very high pressure and these refrigerants could be used only with certain specific alloys and materials due to their corrosive nature. Heat driven absorption system also offers zero ozone depletion and global warming potentials. Amongst these the water-lithium bromide absorption systems are popular but require frequent maintenance due to lithium bromide corrosion and vacuum loss. Adsorption systems based on water-silica gel are designed to address some of these corrosion problems but these systems also suffer from a frequent vacuum loss problem which requires continuous operation of vacuum pumps. All waste heat driven systems claim to have a COP of 0.7 to 1.5 depending on the number of evaporations and heat recovery stages used but practically a maximum COP of 0.3 to 1.0 is achievable due to the loss of vacuum particularly after 1-2 years of operation. The sludge generated from the lithium bromide chillers could also be an environmental nuisance and may require safe disposal. In order to address these energy efficiency and environmental issues particularly those related to ozone layer depletion and global warming due to refrigerant emissions, CSIRO Energy Technology has developed a novel cooling concept which could be operated with waste heat, solar energy, gas or electricity. The concept offers a far superior performance in terms of design, maintenance requirements and overall energy saving. This paper describes the novel cooling concept, a laboratory demonstration system and some important performance results.

Key Words: ***desorption cooling, solid sorption cooling, refrigeration.***

1 INTRODUCTION

Synthetic refrigerants have two fold impacts on environment due their fugitive emissions that result in significant ozone depletion and/or global warming. Significant research has been conducted to develop refrigerants with lower ozone depletion potential (ODP) and global warming potential GWP (Little 2002) but a system with zero impact on environment is yet to be developed. Systems based on compression cycle using natural refrigerants are also being developed. These systems either operate around critical point of the refrigerant (transcritical cycle) (Yunho et al 1998) or at lower than the critical pressure (reduced pressure cycle) (Yongming 2007). The reduced pressure cycles have been developed to prevent the problems of leaks and failure of the components used in the transcritical systems. Due to relatively lower density of refrigerants, the reduced pressure cycle offers lower cooling density than the transcritical cycles.

The other category of natural refrigerant based systems is absorption system. The most popular is lithium bromide absorption system which uses water as a natural refrigerant. These systems have a lower COP than the compression cycle due to higher heat load in the regenerator (Talbi et al 2000). Consequently, double, triple effect and ejector assisted (Goktun 1999, Wu et al 1998) systems evolved to reduce the net heat consumed in the regenerator. However, double and triple effect lithium bromide systems require bit higher regeneration temperature than single effect. All lithium bromide based systems produce sludge due to lithium bromide corrosion. Therefore attempts have been made to replace LiBr, LiCl absorbents and also ammonia refrigerants to avoid problems of emission, corrosion (Coronas et al 1996, Bourouis et al 2000, Boer et al 1998) and crystallisation (Horus 1998). The development of desiccant based air conditioning is one of such attempts. The desiccant systems are relatively newer than absorption but they are suitable for large size applications. Silica gel-water adsorption system addresses some of the corrosion issues of the absorption system. However, adsorption systems are larger in size and have lower COP than compression system and further attempts have been made to improve the COP and specific cooling density (SCD). Composite adsorbents manufactured from silica gel and expanded graphite shows greater thermal conductivity than pure silica gel and offers smaller size units due to faster heating and cooling periods (Eun et al part I & II 2000, Poyelle et al 1999, Critoph 1999). Critoph (Critoph 1999) developed a monolithic adsorber (composite carbon) with heat pipes used for fast heating and cooling. A laboratory system based on thermosyphon heat pipes using water as a working fluid has been develop. Heat exchanger adsorbers have been designed (Tatlier and Erdem 1999, Restuccia and Cacciola 1999, Wang and Xu et al 1998, Wang and Wu et al 1998, Bonnissel 2001) to improve the heat and mass transfer rates to improve the cooling density. Coated tubes have better heat and mass transfer than granulated bed or composite (Tatlier and Erdem, 1999; Tatlier and Tantekin et al 1999). Ito et al (Ito et al 1996) developed a direct heat exchanger module (DS module). It has been found that improvement in cooling density does not improve COP (Restuccia et al 1999) but internal heat recovery can improve COP. This could be achieved by recycling the heat exhausted from the cooling of regenerated adsorber (Critoph 1998) and COP up to 1.29 predicted. Four adsorber system enables better heat recovery (Pons and Poyelle 1999) than two adsorber system and six adsorber can even have better heat recovery (Chua et al 2001, Agnew et al 1999). A single adsorber bed operated with thermal wave regeneration concept could obtain a COP of 0.9 (Pons et al 1996). A system based on rotating adsorption modules passed through alternate hot and cold zone was developed to demonstrate high COP by internal heat recovery (Critroph 2001). The modules use ammonia as a refrigerant, the system has several moving parts and sealing of rotating modules to isolate hot and cold stream appears to be the main issue. The modules need to be of special alloy or carbon steel and operate in a particular orientation. Neither absorption, adsorption or desiccant systems are appear to be suitable for mobile applications. The desorption cooling concept overcomes most of these shortcoming and addresses all environmental issues. The desorption cooling concept has been conceived by the author during working on pressure swing adsorption based air separation about fifteen years ago. This paper describes the concept, system and some performance results from the laboratory unit.

2 DESORPTION COOLING CONCEPT

Adsorption of molecules releases heat of adsorption and desorption absorbs an equivalent amount of heat. This is the basic principle of desorption cooling. If evaporation of liquid is compared with the desoption the heat of desorption is likely to have higher magnitude compared to latent heat of evaporation because adsorbed molecules have relatively lower energy state due to relatively less mobile molecules than in the liquid phase. The molecules in the liquid phase always move, collide with each other and bounce (Brownian motion). In the adsorbed state the molecules although rotate and vibrate to a lesser extent. The adsorbed molecules insignificantly collide with each other and the wall of the container and this is why adsorption results in some pressure loss. In other words the adsorbed state could have relatively lower kinetic energy than the liquid state (Groszek 1997). Therefore, with appropriate combination of adsorbent (solid with high surface area where gas molecule adsorb), adsorbate (the gas that adsorbs) and specific conditions as describes latter, a significant extent of cooling could be achieved from desorption process also. A system could be developed with two adsorbents and a working gas (adsorbate) to achieve cooling.

3 DESORPTION COOLING MODULE

The design of desorption cooling module is very simple and it includes a pair of competing adsorbents and an adsorbate gas. If an adsorbent has significantly different adsorptivity at different operating temperatures then a single adsorbent and a working fluid could also be suitable. Figure 1 shows an schematic diagram of a single desorption cooling module which consists of two 700 mm long 19 mm OD identical stainless steel (SS316) chambers (C_1 and C_2) connected by a 6 mm OD stainless steel tube named as connector. The chamber C_1 and C_2 are packed with proprietary grade activated carbons and charged with working gas such as nitrogen, oxygen, carbon dioxide or appropriate mixture of these. Depending on working gas composition and operating temperature, the module was charged with the gas at 0.01-2 MPag.

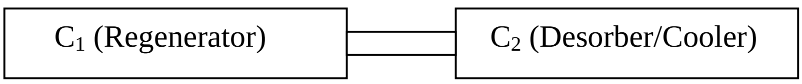


Figure 1: Schematic diagram of a desorption cooling module

4 OPERATION OF A DESORPTION COOLING MODULE

The cooling module operation described here is driven by thermal energy which could be extracted from various exhaust streams or the Sun. The operation is a two step batch process where one of the chambers, say C_1 also named $generator_1$ is initially heated while the other chamber C_2 named cooler or desorber is maintained at room temperature. This is termed as regeneration as shown in Figure 2 where the adsorbate is desorbed from C_1 and adsorbed in C_2. In the next step chamber C_1 is cooled down to room temperature by passing ambient air or water on the surface of chamber C_1. This makes the working gas to adsorb in chamber C_1 and desorb in the chamber C_2 which now cools down below room temperature if there is no heat supplied to the chamber C_2. In a typical laboratory test the chamber C_1 was regenerated at a temperature of around 200 ^oC while the chamber C_2 was maintained around 21 ^oC. In the second step during cooling, the chamber C_1 was cooled down either by water or air around 21 ^oC. In the second step the temperature of chamber C_2 was dropped by about 10-15 ^oC, depending on rate of cooling of the chamber C_1..

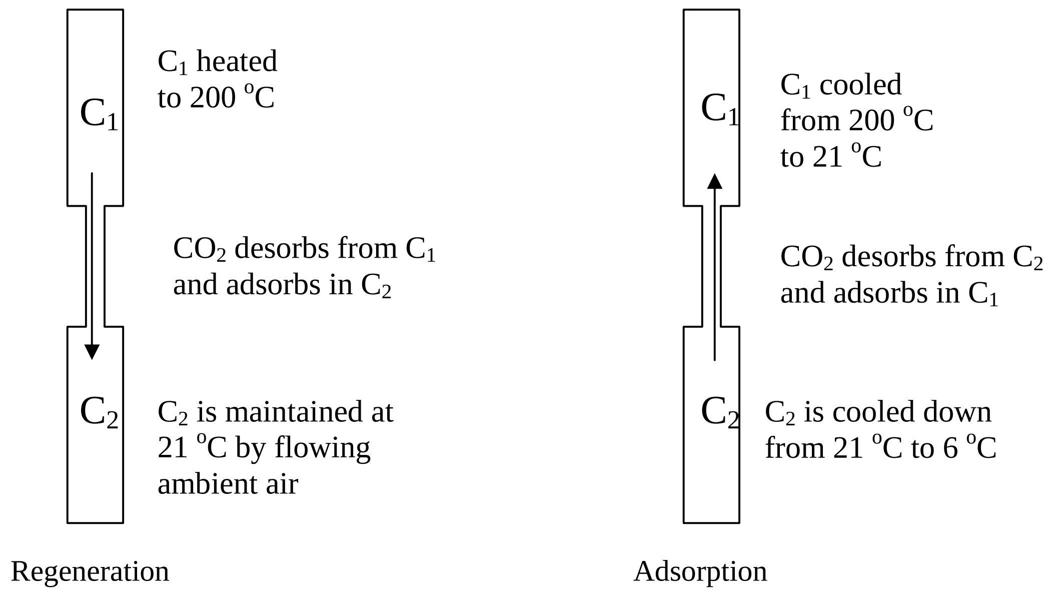


Figure 2: Operation and mechanism of cooling in a single desorption cooling module. The heating and cooling medium could be any fluid, fuel combustion products or electricity

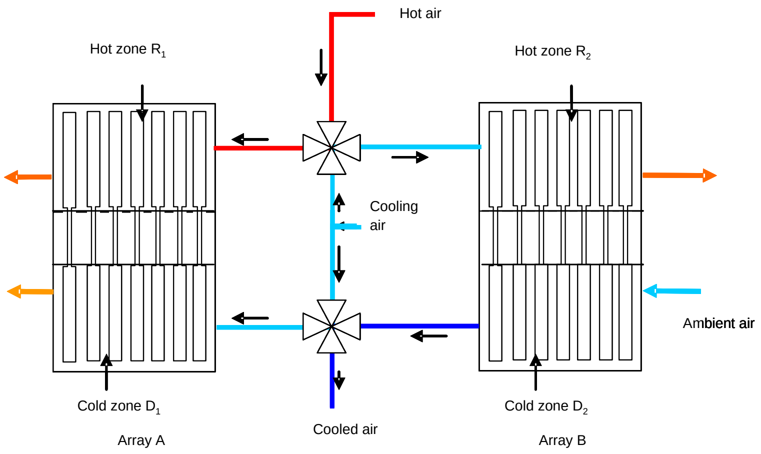
5 LABORATORY SCALE DEMONSTRATION SYSTEM

Since operation of single module is a two step process which requires regeneration or heating of one of the chambers in the first step and cooling in the second step, two identical sets of modules are required for continuous production of cooling. As shown in Figure 3, the schematic diagram has two identical arrays of modules arranged in 40 mm triangular pitch. In order to isolate the hot and cold zones, the zones holding chamber C_1 side were isolated from the zones holding chamber C_2 of all the modules. These zones actually form part of rectangular ducts which were insulated and provided with valves (or dampers) to divert the hot and cold streams from one zone to another.

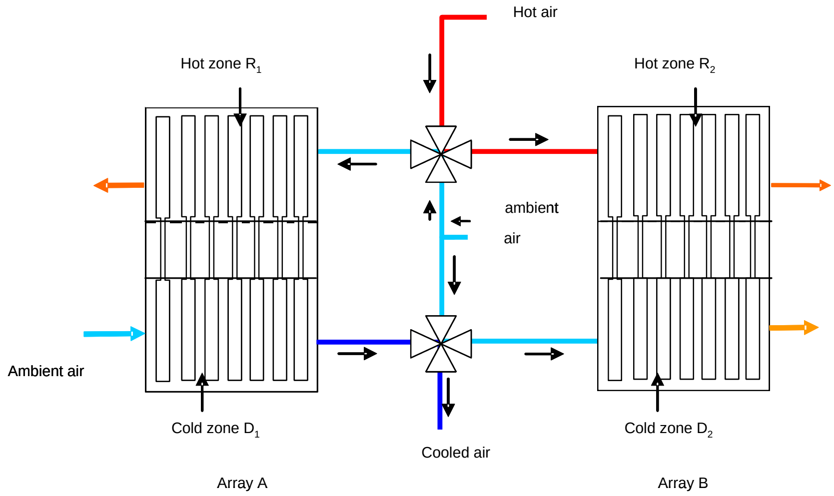
6 OPERATION OF A LABORATORY SCALE DEMONSTRATION SYSTEM

The operation of the laboratory system is illustrated in Figure 3, where the continuous cooling is produced by two identical arrays, A and B, of modules. The hot and cold zones of array A are shown as R_1 and $D_{1,}$ and those of array B are shown as R_2 and D_2, respectively. The sequence of operation is illustrated a time cycle in Table 1.

The time cycle is based on the optimised time required for the regeneration and cooling. As shown in Table 1, when R_1 is regenerated, the working gas is adsorbed in D_1 and R_2 and cooling is achieved in D_2. At 20th minutes changeover takes place to regenerate R_2 and produce cooling in D_2. During this period the working gas is adsorbed in R_1 and D_2. This way continuous cooling is produced in a cycle.



(a) Array A is regenerating while array is producing cold air



(b) array A is producing cold air while array B is regenerating

Figure 3: Conceptual Design and Operation of Desorption Cooling System

Table 1; Time cycle of sequential operation of desorption cooling system

	Time (min)			
	0 – 20	20 – 40	40 – 60	60 – 80
R_1	Regeneration by heating	Adsorption	Regeneration by heating	Adsorption
D_1	Adsorption	Desorption cooling	Adsorption	Desorption cooling
R_2	Adsorption	Regeneration by heating	Adsorption	Regeneration by heating
D_2	Desorption cooling	Adsorption	Desorption cooling	Adsorption

It could be argued that during changeover the cooling may be discontinued. This could be avoided by delaying the changeover in the cold side to continue to extract cooling from the cold zone of one of the arrays until cooling is produced in the cold zone of the other array. This may require installation of independent valves in each zone.

7 RESULTS AND DISCUSSION

Results obtained from the tests performed on the single cooling module and laboratory system are discussed as follows:

7.1 PERFORMANCE OF A SINGLE MODULE

A single module has been tested for cooling capacity and coefficient of performance in the laboratory. The laboratory test involved heating of one of the chambers of the module to typically about 200 °C while the other chamber was maintained at a constant temperature of 21 °C. In this process the working gas desorbed from the heated chamber and adsorbed in the other chamber. In the next step the heated chamber was cooled down from 200 °C to 21 °C with the flow of air. This caused adsorption of the working gas in the chamber cooled from 200 °C to 21 °C and desorption in the other chamber where cooling was observed as temperature dropped from 21 °C to 10 °C.

The positions of thermocouples are shown in Figure 4 and the temperature profile during heating and cooling steps is shown in Figure 6.

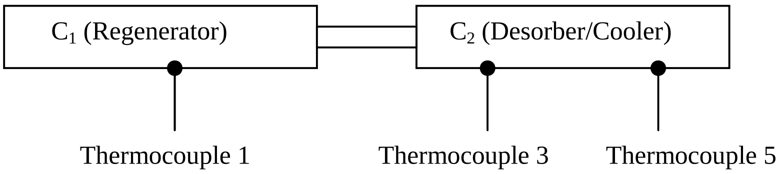


Figure 4: Position of thermocouples during laboratory testing of a single module where chamber C_1 was heated then cooled and cooling produced at C_2. See Figure 5 for temperature profiles

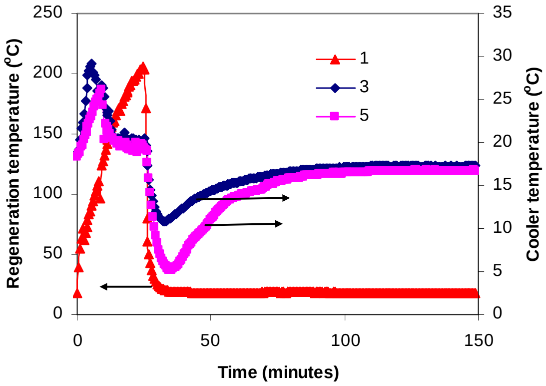


Figure 5: Temperature profiles during a laboratory test performed with a single desorption cooling module. See Figure 4 for the 1, 3, 5 positions of thermocouples

As shown in the temperature profiles a temperature drop by 10-15 °C could be achieved in the laboratory test of a single module. It should also be noted that the cooler shows a temperature gradient. Also these tests were performed with un-insulated cooler surface where heat gain due to natural convection and radiation absorption was allowed. Since it was also difficult to estimate how much heat was supplied to the regenerator, approximate coefficient of performance was estimated from the thermal masses of C_1 and C_2 by integrating the average temperature profiles over heating and cooling periods. The estimated COP was found to be around 0.06. This was considered as very rough estimate as cooler thermal gradient and heat exchanged with the surrounding was unknown.

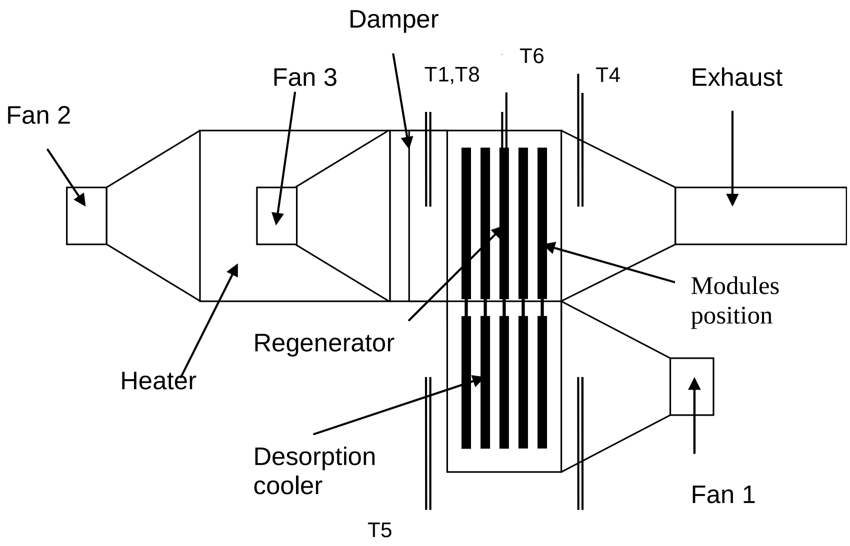
7.2 PERFORMANCE OF LABORATORY SYSTEM

In order to accurately evaluate the performance of the cooling system a laboratory system was constructed. This was essentially one of the two identical arrays described in Figure 3. The laboratory unit was consists of 102 modules stacked in 40 mm triangular pitch. Each module has a 700 long 19 mm ID chambers connected with 10 mm long 5 mm ID connecting tube. The schematic diagram of the laboratory system is shown in Figure 6 where an electrical heater in line with a fan (Fan2) is used to produce hot air to heat and regenerate the cooling modules. Another fan (Fan 1) is used to supply ambient air to the cooler end of the modules which were maintained at ambient temperature of about 21 ^{o}C during regeneration but cooled down by 10-15 ^{o}C during cooling. A third fan (Fan 3) is used to supply ambient air to the hot ends of the module to cool them from the regeneration temperature to about 21^{o}C.

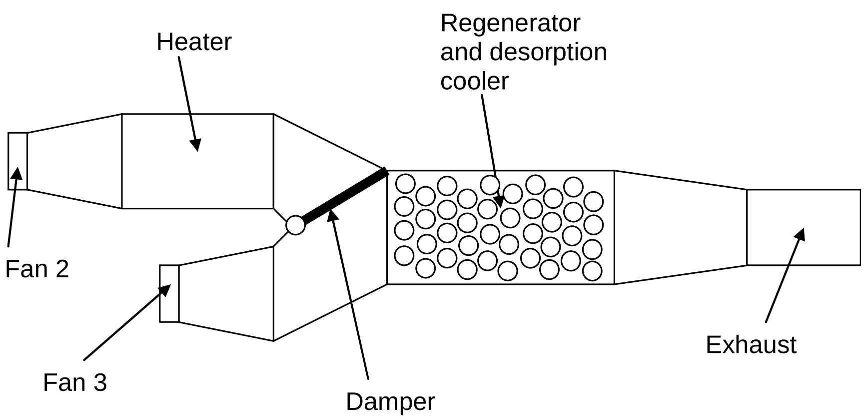
In a typical experiment Fan 2 and heater was turned on to heat the modules. During this time the Fan 1 was also started to remove any heat of adsorption generated at the cooler side of the modules. After modules acquired the regeneration temperature the Fan 2 and heater were turned off and the damper was moved to the other position to shut the hot air supply to the modules. At this time Fan 3 was also turned on to cool the regenerated modules and produce cold air from the cooler side. A number of thermocouples used to continuously record the temperature of air and modules at various points as shown in Figure 6.

The laboratory unit was tested at various air flows from all three fans and regeneration temperatures. Figure 7 shows the temperature profiles of various thermocouple position indicated in Figure 6. The air flow rates from Fan 1, 2 and 3 were at 83.4, 308, 308 l/s respectively. The relative humidity of the inlet air to the fan was maintained at 45%. The cooling capacity and coefficient of performance of the laboratory unit for these conditions was estimated from mass flow rates, specific heat and temperature difference numerically integrated over the heating and cooling periods. Depending of the air flow rate, the temperature of ambient air at cooling side was dropped down by maximum 8 ^{o}C for a regeneration temperature of 200 ^{o}C. The heat absorbed at the regenerator side (heat consumed) and cooler side (cooling produced) was about 11342 kJ and 1364 kJ, respectively. The coefficient of performance was therefore estimated around 0.12. In other test runs where heat losses were comparatively less a COP of 0.15 observed without internal heat recovery (Figure 8). The power consumed by the fan excluded in the calculation of COP at different regeneration temperatures because the power consumed by the fans was negligible as compared to heat exchanged and also it remained constant for different regeneration temperatures.

The COP estimated was smaller than the adsorption and absorption cooler because latter use secondary stages of heat recovery from their respective exhausts. The COP of desorption cooler could also be improved by recovering heat exhausted from the cooling of the regenerator.



(a) Side view



(b) Top view

Figure 6: Schematic diagram of the laboratory tests system, ((a) Side view and (b) Top view.

In order to find out an optimum temperature for the regeneration of modules, the regeneration was carried out at different temperatures at constant air flows through all fans. The results shows (Figure 9) that the extent of cooling achieved by the cooler linearly increases with the temperature from 40 ^oC to 150 ^oC but does not increase significantly with temperature between 150 ^{io}C to 200 ^oC (not shown in the Figure 9) . The COP of the system also does not vary significantly with the temperature. It is important to note that cooling could be produced from the temperature as low as 50 ^oC. This means a system could be developed to operate from very low grade waste or solar heat to a moderate temperate waste heat.

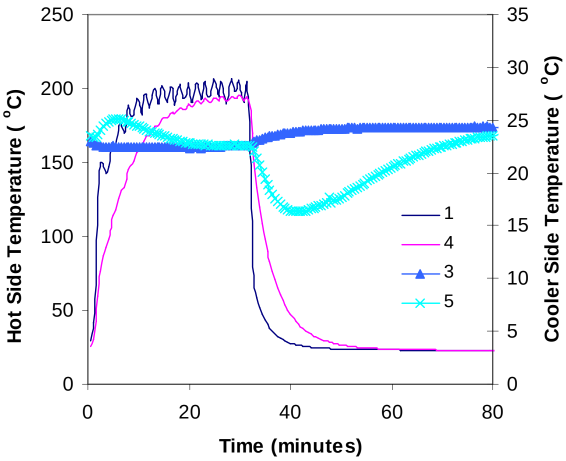


Figure 7: Temperature profiles in a laboratory unit regenerated at 200 °C. The air flows from Fan 1, Fan 2 and Fan 3 were 83.4, 308 and 308 l/s, respectively, relative humidity of ambient air in the laboratory = 45%, ambient temperature = 21 °C.

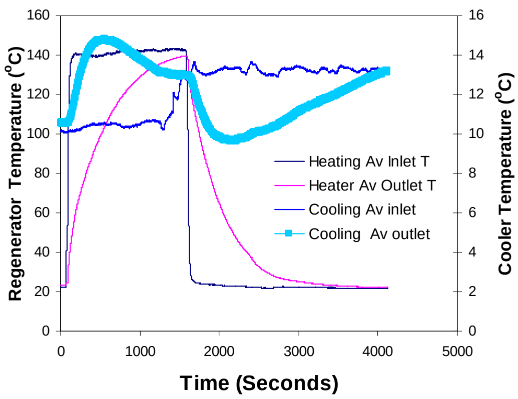


Figure 8: Temperature profiles in a laboratory unit regenerated at 140 °C. The air flows from Fan 1, Fan 2 and Fan 3 were 148.4 152.6 and 162.5 l/s, respectively, relative humidity of ambient air in the laboratory = 45%, ambient temperature = 21 °C, estimated cooling capacity = 1062 kJ, heat load = 6923 kJ and COP = 0.15.

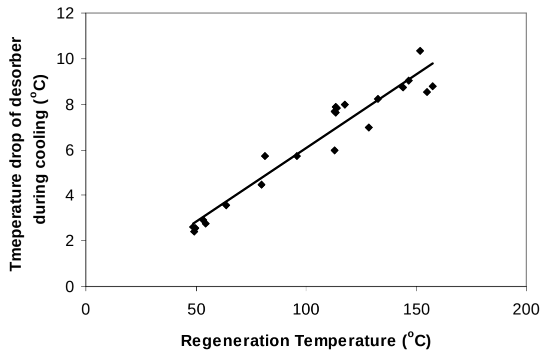


Figure 9: Effect of regeneration on temperature drop in the cooler. These runs were carried out with a constant air flows at Fan 1, Fan 2 and Fan 3. The relative humidity of ambient air was 45% and the temperature was 21 °C.

A higher COP with the desorption cooler was also simulated and results shows that with an internal heat recover of 74% a COP of 1 should be possible (Figure 10). A COP of 4 could be possible with about 85% recovery of heat. Currently, a system with over 85% heat recovery is being designed to demonstrate high COP.

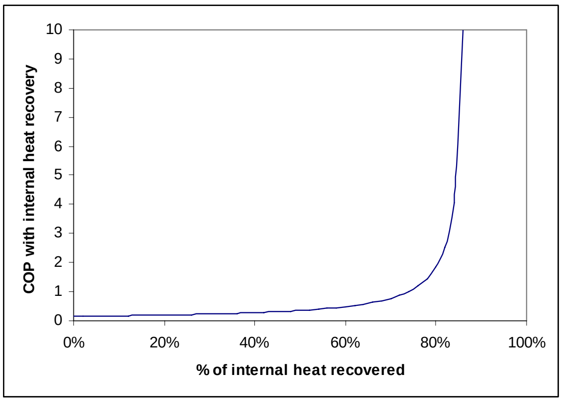


Figure 10: Variation in estimated COP with the percentage of internal heat recovered

8 CONCLUSIONS

A novel desorption cooling concept based on cooling by desorption of natural refrigerant gases such as carbon dioxide has been proposed. This concept does not use compressor and has minimum moving parts. Based on this concept a desorption cooling module has been developed and tested in the laboratory. The COP of the single module was approximately estimated around 0.06 due to several unaccounted heat losses. A laboratory unit with about 102 desorption cooling modules has also been developed to minimise to eliminate the effect of unknown heat losses accurately estimate the cooling capacity and COP. The COP of this laboratory unit was found to be around 0.12-0.15 and further heat recycling from the regenerator exit stream could be a way to further improve the COP. It is also proved that the cooling temperature depends on the regeneration temperature but between 150 and 200 ^oC, the extent of cooling is insignificantly changed. The desorption cooler could also be operated with a low grade heat at a temperature as low as 50 ^oC and with an internal heat recovery option, a higher COP should be possible. The desorption cooler is a modular design which consists of completely sealed modules where the natural refrigerant with lower GWP has least chance to escape to the atmosphere.

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