Continuous sorption cooling in activated carbon-nitrogen system using metal foam as regenerator

Indranil Ghosh
Assistant Professor, Cryogenic Engineering Centre, IIT Kharagpur, India
Email: indranil@hijli.iitkgp.ernet.in

Abstract. In compressor driven solid sorption process, cooling obtained from a desorbing bed (equivalent to an evaporator), is intermittent in nature. Intermittency can be avoided using multiple adsorbent columns. However, connecting a desorbing bed to heat source and adsorbing beds to heat sink in alternate cycles enhances operational complexity and constructional disadvantages. In a recent development, it has been seen that rapid and successive pressurization and depressurization of an adsorbent (solid) bed with adsorbate (gas) creates temperature differential across the column length. The presence of an orifice at the end opposite to gas entrance enhances the temperature gradient. By connecting the hot end to heat sink and the cold end to heat source permanently, one can substantially reduce the operational hazards associated with the intermittent sorption cooling processes. More recently, it has been seen that the introduction of a regenerator in the process makes the cooling process more effective. Though the proposed sorption cooling process apparently looks similar to orifice type ‘pulse tube’ cooler, the former is intrinsically different than the other. In the present manuscript, experimental sorption cooling studies using of metal foam as regenerator has been discussed. Tests have been conducted near room temperature in activated carbon-nitrogen system.

1. Introduction
In solid sorption cooling, the adsorbent beds play different roles. Depending on the processes, adsorbent beds can be used for generating periodic pressure swing, while the required cooling is obtained from the heat of vaporisation [1]. In such situations, adsorbent beds function as ‘thermal compressor’. The vibration-free sorption cooling at cryogenic temperature has been successfully used in several space missions [2, 3]. Activated carbon is a commonly used adsorbent for such applications, while the list of adsorbate depending on the cold end temperature may be different. The list includes nitrogen, hydrogen and helium. On the contrary, concept of compressor driven system for generating sorption cooling is relatively new [4]. In this alternative process, the required pressure variation is generated with the help of a mechanical compressor, while the necessary cooling is achieved from a desorbing bed behaving as an evaporator. Heat of desorption provides the necessary cooling. It is noteworthy that the heat of desorption and the heat of vaporisation are of similar magnitude.

Because of the intermittent nature of sorption cooling, use of multiple adsorbent beds is a usual practice to achieve continuous cooling. Use of multiple beds necessitates connecting the adsorbent beds alternatively to heat sink and heat source in every half cycle. Special valve arrangements are made to bring them in direct connect to heat sink/source sequentially [5]. Alternatively, gas gap heat switch is used to establish (or break) the thermal link [6]. Manoeuvring multiple solenoid operated valves in sequence augments operational hazards.
Recently, it has been observed that rapid pressurisation and depressurisation of adsorbent bed with a suitable gas (adsorbate) creates differential temperature across the length of the tube [7, 8]. It enables connecting one end of the tube permanently to heat sink and the other end to heat source and thereby making the process continuous. It has also been noted that the presence of small opening at one end of the adsorbent tube helps achieving a larger temperature drop across the bed [8, 9]. The way desorption is taking place also have significant effect on sorption cooling [10]. Theoretical analysis reveals that the gas moving in or flowing out carries insignificant energy while activated carbon with the bed has the retains substantial share of the energy [10]. In view of utilising that energy, subsequently, regenerator based sorption cooling process has been proposed by Ghosh [11]. It has been shown experimentally that a thick copper tube inserted within the adsorbent bed works satisfactorily as regenerator. In the present manuscript, however, use of open porous metal foam (Fe-Ni-Cr) as regenerator material in the solid sorption cooling has been studied experimentally.

2. Regenerative Sorption Cooling

Regenerative continuous solid sorption cooling process has been shown schematically in figure 1. An adsorbent bed (1) filled with adsorbent is sequentially pressurised and depressurised. A mechanical compressor (2) generates the required pressure swing in the process. With the inlet valve (3) in open state, gas enters the adsorbent column through the tube behaving as regenerator. Since the orifice valve (4) is always kept open, pressurised gas moves out and gets accumulated in the buffer vessel (5) before getting compressed. After certain interval of time, the inlet valve (3) closes and the exit valve (6) opens. Gas leaves the system (adsorbent bed) retracing the path followed by it during adsorption. Simultaneous depressurisation occurs through both the solenoid and the orifice valves. Desorption produces cooling in the adsorbent. Copper tube in vicinity of the adsorbent becomes cold. Cycle ends with the closure of the exit valve. In the next cycle, inflow of gas occurs through relatively colder cooper tube. This enables cold gas flow to the system.

Figure 1. Schematic of compressor driven regenerative continuous solid sorption cooling process.

It may be noted that the operation of the proposed regenerative solid sorption cycle is, in principle, similar to that of an orifice type pulse tube cryocooler (without orifice side reservoir). On the contrary, there are dissimilarities also [12]. Some of the major differences between the two processes are enumerated in table 1. The sorption cooling is essentially different from pulse tube in respect of the genesis of cooling and operating frequency. Heat of desorption generates the necessary cooling in a compressor driven regenerative solid sorption cooling, while adiabatic compression and expansion of gaseous helium is related to the effective refrigeration in a pulse tube [13]. A pulse tube is typically operated at 1-5 Hz frequency [14], whereas the sorption cooling process is much slower in nature,
usually with a frequency in the range of 0.1Hz or less. Being a slow process, the rotary valve operation can be replaced by solenoid valves. Helium, owing to low boiling point, is the most common choice as the working fluid in pulse tube. On the other hand, one suitable adsorbate-adsorbent pair is essential to achieve cooling in sorption cooler.

Table 1. Comparison between pulse tube and present cooling technique.

| Parameters          | Orifice Pulse Tube  | Regenerative solid sorption cooling |
|---------------------|---------------------|-------------------------------------|
| Origin of cooling   | Gas expansion       | Desorption of adsorbate             |
| Frequency           | Hertz               | Milli-Hertz                         |
| Tube                | Empty               | Filled with adsorbent               |
| Valve               | Rotary              | Solenoid                            |
| Fluid               | Helium (non-adsorbable) | Adsorbate                           |

3. Experimental Set up

The experimental test set up has been shown schematically in figure 2. Activated carbon-nitrogen has been chosen as the adsorbent-adsorbate pair. Instead of operating the system in closed loop condition using compressor, tests have been performed with compressed gas taken from gas cylinder. The desorbed gas is ultimately vented out to the atmosphere. Pictorial view of the experimental test set up and the two adsorbent tubes are shown in figure 3.

The experimental set up consists of one adsorbent tube filled with activated carbon, one regulating (orifice) valve, two solenoid valves to allow in and outflow of the pressurised gas, couple of sensors to measure temperature and pressure at various locations. In one of the adsorbent beds (25.4x10^-3 m diameter, thin walled, stainless steel tube), copper tube (of slightly shorter length) has been inserted coaxially through the adsorbent bed as shown in figure 2(a). The arrangement shown in figure 2(b) is essentially the same except that the 60 PPI metal foam (Fe-Ni-Cr) regenerator is located at one end of the adsorbent column. The metal foam matrix (shown in figure 4), being located outside the column, is not in direct contact to the porous adsorbent.

Systematic opening and closure of the solenoid valves at preset interval of time and completely automatic operation has been performed using LabVIEW software, solid state relays (SSRs) and NI-PCI-6229 data acquisition card. Another data logger DT-80 has been used for acquiring the measured pressure temperature data.

![Figure 2. Schematic of the experimental set up with (a) tube and (b) metal foam regenerator.](image-url)
4. Results and Discussions

The experimental time temperature pressure profiles generated using two different adsorbent tubes are shown in figure 5 and 6 respectively.

Figure 5. Experimental time temperature pressure profiles in adsorbent bed with foam regenerator.
In case of adsorbent tube with metal foam regenerator, the cold end temperature has been found decreasing from an initial temperature of 298K to 285K in 700s. In contrast to that, the temperature of the cold end of the bed with tube regenerator has been found falling from 305K to around 290K in 1100s.

It may be noted that the fall in cold end temperature rates are similar in both the situations. However, the operating pressure, in case of metal foam regenerative system, is of the order to 3MPa, while that in the other situation is slightly higher than 2MPa. It indicates that the sorption cooling can be extracted in a better way if the regenerator is kept inside the adsorbent bed.

Interestingly, the orifice end of the column, which is supposed to be hotter than the ambient, has been found following the cold end temperature profile. Initially it remains hotter than the ambient, but subsequently, it becomes colder than the environment. This clearly indicates the heat of adsorption during the pressurization cycle is also getting removed partially from the orifice end and eventually giving cooling to that end. This would not have happened in absence of the heat of adsorption/desorption. For example, in case of pulse tube refrigerator, where the heat of compression and expansion is primarily responsible for obtaining cooling, the hot end of the tube remains warmer than the ambient.

The poor performance of metal foam as regenerator in comparison to copper tube is mainly because of the following reason. The desorbed gas moving out the adsorbent tube is small and its cold content is also low. Therefore, the metal foam which is in sequence with the carbon bed can exchange heat with the desorbed gas only. On the contrary, the copper tube which is remaining inside the adsorbent bed and coming in contact to cold adsorbent particles during desorption cycle can possess more cold energy and exchange the same with the hot incoming gas during the adsorption cycle.

The adsorbent tube has been kept exposed to ambient. The amount of heat added to the cold end has been estimated to approximately 3W at 290K. It has been calculated assuming that the heat is getting transferred to the cold end by means of natural convective heat transfer process. Further research would be necessary so as to practically reduce the axial conduction of heat through the copper tube.

5. Conclusions
The present experimental study reveals the effect of using regenerator in the continuous solid sorption cooling process. If the regenerator is housed inside the adsorbent bed, regenerative heat exchange is more effective. The orifice end temperature of the adsorbent tube initially remains hotter than the ambient temperature. However, subsequently it becomes colder than the ambient. This fall in
temperature indicates that the sorption cooling is primarily due to heat of adsorption/ desorption. This fall in temperature of the orifice end would not have been possible without partial removal of the heat of adsorption during pressurization cycle.

References
[1] Jones J A and Golben P M 1985 Design, life-testing and future-designs of cryogenic hydride refrigeration systems Cryogenics, 25 212-219.
[2] Bhandari P, Prina M, Bowman Jr R C, Paine C, Pearson D, Nash A 2004 Sorption coolers using a continuous cycle to produce 20K for the Planck flight mission Cryogenics 44 395-401.
[3] Burger J F, ter Brake H J M, Rogalla H, Linder M 2002 Vibration - free 5K sorption cooler for ESA’s Darwin mission Cryogenics 42 97-108.
[4] Leppard C J and Leslie S 1980 Adsorption Heat Pump, US Patent No. 4,183,734.
[5] Park J G, Jiang K J, Lee P S, Lee J Y 2001 The operating characteristics of the compressor-driven metal hydride heat pump system Int. J. Hydrogen Energy 26 701-706.
[6] Bywaters R P and Griffin R A 1973 A gas-gap thermal switch for cryogenic applications Cryogenics 13 344-349.
[7] Ghosh I 2011 An improved sorption cooler and process for producing continuous sorption cooling in a single adsorbent tube/bed with pulsating gas flow Indian Patent 23/KOL/2011.
[8] Koley S and Ghosh I 2013 New technique for generating continuous sorption cooling in a single adsorbent column Appl. Ther. Engg. 55 33-42.
[9] Koley S and Ghosh I 2014 Generating continuous solid sorption cooling in a single adsorbent tube - Experiment and generalised transient analysis Int. J. Heat Mass Trans. 72 470-478.
[10] Koley S and Ghosh I 2016 Role of desorption route in a novel single-column continuous solid sorption cooling process Appl. Ther. Engg. 99 502-513.
[11] Ghosh I 2014 On scope of improving solid sorption cooling - generating it continuously in a regenerative single adsorbent column Proc. of the 2014 Int. Sorption Heat Pump Conf. (Maryland, USA) p 494.
[12] Koley S and Ghosh I 2015 Activated carbon-hydrogen based continuous sorption cooling in single adsorbent bed with LN2 heat sink, Physics Procedia 67 1199-1205.
[13] Radebaugh R 1999-2000 Development of the pulse tube refrigerator as an efficient and reliable cryocooler Proc. of the Inst. of Refrig. (London) 96 11-31.
[14] Hands B A 1986 Cryogenic Engineering (London: Academic Press).