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Generating continuous solid sorption cooling in a single adsorbent tube – Experiment and generalised transient analysis

Susmita Koley, Indranil Ghosh *

Cryogenic Engineering Centre, Indian Institute of Technology, Kharagpur, Kharagpur 721302, West Bengal, India

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ABSTRACT

It is possible to create differential temperature between the two ends of an adsorbent column with quick and sequential inflow and outflow of adsorbate. Being able to generate heating and cooling at the two extremities of the same tube, simultaneous rejection of heat of adsorption to heat sink and retrieval of cooling from heat of desorption, can be achieved in a single tube. Since the production of continuous sorption cooling is not compulsorily related to use of multiple beds and connecting them to heat sink and heat source in alternative cycles, operational hazards are substantially less in this new process. Interestingly, presence of an orifice at the hot end of the column can significantly magnify the temperature difference between the hot and cold ends. Systematic experimental study relating both operating variables and geometrical parameters has been carried out. Generalised and in-depth theoretical analysis involving transient heat and mass transfer equations has been performed. Thermo-hydraulic behaviour within the bed could be explained reasonably well with the theoretical modelling. Afterwards, effects of particle diameter and bed porosity on the cold end performance have been studied theoretically.

1. Introduction

Solid sorption cooling is one of the various promising alternatives capable of generating *clean refrigeration* [1]. The benign nature of the constituents used in the process makes this cooling system environment-friendly [2,3]. This research topic has recently gained momentum [4–7] primarily due to the increasing awareness of our environment [8,9]. However, the advantage of creating pollution-free refrigeration is often affected largely due to poor thermal performance of the solid sorption refrigeration process [10–15]. Intermittent process, longer cycle duration, operational hazards of alternatively connecting multiple adsorbent beds to heat sink and heat source, are some of the key factors which makes them less efficient. In a recent publication, Koley and Ghosh [16] have proposed a new, compressor driven sorption cycle for producing *continuous cooling* in single adsorbent column. This process enables eliminating some of the major hurdles associated with the compressor driven solid sorption system.

Dead end filling (or discharge) of porous adsorbent bed is generally linked to non-isotropic distribution of temperature in the tube [10,16]. However, pressurisation and depressurisation when occurs periodically in quick succession, differential temperature is created along the length of the tube (Fig. 1a). Keeping the exit valve closed and inlet valve open, inflow of compressed gas is allowed in the column till the system pressure reaches target operating pressure. On completion of adsorption, the inlet valve is closed and the exit valve is opened, allowing desorption to occur. Cycle ends with the complete desorption of gas and closure of all valves. Steps are repeated for another cycle to continue. Although local temperature oscillation exists in the bed due to poor thermal conductivity of the adsorbent, a time-averaged value shows that the end through which gas enters or leaves the column always remains colder than the other side (dead end). In equivalence, it can be said that the heat of adsorption is getting released at the hot end, while heat of desorption is generating desirable cooling at the other end. Since differential temperature could be generated between the two ends of the adsorbent column, the hot end and cold end of the tube can be connected all the time with the heat sink and heat source respectively. In the existing compressor driven system, as the entire bed gets heated up (or cooled down), one needs to connect the bed alternatively with the heat sink and heat source in every alternative half cycle. Experimental observations and theoretical studies involving transient heat and mass transfer analysis have been reported by Koley and Ghosh [16]. Subsequently performed systematic and elaborate tests involving parametric variations have been summarised in this paper.

One of the interesting experimental observations indicates that the adjustable opening (Fig. 1a) located at the hot end [16] is linked to creation of larger temperature differential across the tube. However, theoretical explanation describing the effect of fluid flow through the regulating valve has not been discussed earlier [16].

* Corresponding author. Tel.: +91 3222 283588; fax: +91 3222 282258.
E-mail address: indranil@hijli.iitkgp.ernet.in (I. Ghosh).

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Nomenclature

A_1	internal cross-sectional area of the container (m^2)
A_2	area of the annular section (m^2)
$A = A_1 + A_2$	total area (m^2)
C_p	heat capacity of adsorptive (J/kg K)
C_{ps}	heat capacity of activated carbon (J/kg K)
C_{pw}	heat capacity of wall (J/kg K)
D_0	outer diameter of the column (m)
D_{ax}	axial dispersion coefficient (m^2/s)
D_e	effective diffusivity (m^2/s)
D_p	particle diameter (m)
h_{amb}	heat transfer coefficient between wall and ambient air (W/m^2 K)
ΔH	heat of adsorption/desorption (J/mol)
k_b	bed thermal conductivity (W/m K)
L	length of the column (m)
M_g	molecular weight of adsorptive (kg/kmol)
P_c	cold end pressure (Pa)
P_h	hot end pressure (Pa)
$\bar{R}$	universal gas constant (J/kg K)
r	radius of spherical adsorbent particle (m)
T	temperature (K)
T_0	temperature of ambient air (K)
t	time (s)
t_c	half cycle time (s)
u	interstitial velocity (m/s)
q	amount of gas adsorbed (kmol/kg)

Greek symbols

ε	void fraction
μ	kinematic viscosity (N-s/m^2)
ρ	gas density (kg/m^3)
ρ_s	adsorbent density (kg/m^3)
ρ_w	density of the wall material (kg/m^3)
ρ_0	initial gas density (kg/m^3)

An in-depth theoretical analysis elucidating the effect orifice flow for creating larger temperature difference between the hot and cold ends have been carried out and presented.

2. Experimental

While the proposed solid sorption cycle is a 'closed loop' one with a mechanical compressor (Fig. 1a), the actual tests in the laboratory have been performed in 'open loop' condition with the supply of gas from high pressure cylinder (Fig. 1b). This alteration renders practical simplification without violating the basic working principle. Similarly, instead of using separate heat exchanger at the hot end of the tube, the column exterior is allowed to communicate thermally with the surrounding and exchange heat. Since the measurement of lowest cold end temperature under no heat load condition has been planned, the lower half of the column has been kept insulated (Fig. 2). One complete cycle is a two step process comprising of adsorption and desorption occurring in succession. In step one, inflow of compressed adsorptive occurs through the inlet solenoid valve in open condition, while the exit solenoid valve remains closed. The pressure inside the adsorbent tube reaches the operating pressure. During this process (adsorption), the orifice regulating valve is kept open (to a preset degree of opening) allowing flow of gas through it. Second step begins after a fixed duration of time with the closure of inlet solenoid and opening of the exit solenoid valve. These conditions of inlet and exit valves allow desorption to continue for certain pre-determined interval of time. The cycle ends with the closure of the exit solenoid valve. The aforesaid steps are repeated for another cycle to begin. Detail description of the experimental test set up is available elsewhere [16].

Variations of parameters those have been studied in this experimental research are (a) length to diameter ratio, (b) orifice opening, (c) cycle timings for adsorption and desorption and (d) operating pressures.

Typical transient temperature and pressure variation recorded at the hot and cold ends of the column are shown in Figs. 3 and 4. In Fig. 3 data corresponds to operating pressure 3 MPa, while the same in Fig. 4 is for operating pressure 4 MPa. The parameters remaining invariant during experimentation are (i) the length to diameter ratio (255 mm/15.3 mm) = 16.7, (ii) adsorption and desorption cycle times of 5 s, (iii) orifice opening of 0.25 turns. A comparison between Figs. 3 and 4 indicates that larger temperature drop at the cold end is obtained with higher operating pressure. During pressurisation, the gas enters the column through the cold end and flows through the other end with the orifice valve in open condition. Gas flow through packed bed causes obvious pressure drop. During desorption, hot end of the bed which is at relatively lower pressure gets depleted quickly. Consequently, cold end pressure always remains higher than the other side.

Similarly, the effect of above listed parameters has been studied independently by conducting series of experiments keeping all other parameters, except the one being investigated, invariant. Graphical representations of transient time, temperature and pressure for each individual test become space intensive. Alternatively, the outcome of these experimental investigations has been summarised in Table 1. The maximum and minimum values of pressures and temperatures recorded at the hot and cold ends, along with the other variables and conditions have been consolidated in the Table 1. It may be noted that the present experimental study has been performed measuring the lowest cold end temperature achieved under *no heat load condition*. However, an estimation of the cooling that could have been achieved if the cold end were kept *un-insulated* and heat were received from the surrounding through natural convection, has been listed in the last column. This cooling corresponds to the average cold end temperature mentioned in one of columns in Table 1.

Impacts of parametric variations on the cold end temperature have been summarised graphically in Figs. 5 and 6. The abscissa in Figs. 5 and 6 represent adsorption time (in second), desorption time (in second) and opening of the orifice valve. Graphs have generated using the experimental data consolidated in Table 1. The 'closed' condition of the orifice valve has been shown with (0) in the plot. The effect of operating pressure, duration of adsorption and desorption cycles and extent of orifice opening on the cold end temperature has been shown in Fig. 5. It is evident (from Fig. 5) that higher operating pressure and longer adsorption–desorption time help reducing the bed temperature at the cold end. While the reduction in charging time (5-10-0.25) from 10 s to 5 s does not change the cold end temperature significantly, shortening desorption time period from 10 s to 5 s has negative effect (5-5-0.25).

It has also been observed that the cold end temperature depends strongly on the condition of the orifice valve. If the valve is kept closed (10-10-0), the lowest cold end temperature achieved