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Experimental investigation of a single-bed pressure swing adsorption refrigeration system towards replacement of halogenated refrigerants

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ABSTRACT

Replacement of halogenated refrigerants with a suitable refrigeration system in order to prevent ozone layer depletion and minimize global warming has been a matter of research and worldwide attention for some decades. This paper presents the design and description of a single chambered experimental model for cold generation based on pressure swing adsorption mechanism with an objective to propose a feasible refrigeration system to replace halogenated refrigerants. Granular activated carbon (ACG-825-1.5) manufactured indigenously from matured coconut shell and carbon dioxide has been used as representative adsorbent–adsorbate pair. Refrigerating effect and coefficient of performance for the system have been investigated and were found to be 120.61 J/s and 3.014 respectively. The model successfully produced chilled water at 4 °C (277 K) from ambient water available at 26 °C (299 K). Details of the experimental results and adsorption–desorption isotherm for the system has been described. This work also highlights a novel method of capturing carbon dioxide by utilizing it as an adsorbate in such a refrigeration system.

1. Introduction

Halogenated refrigerants such as chlorofluorocarbons (CFCs), hydrochloroflurocarbons (HCFCs) and hydroflurocarbons (HFCs) have been dominating the refrigeration, air-conditioning and heat pump systems over many decades due to their excellent thermodynamic and thermo-physical properties. However, the emission of chlorine and fluorine atoms present in these halogenated refrigerants is responsible for major environmental impacts such as ozone layer depletion, global warming and adverse climatic changes with serious implications for the future development of the refrigeration based industries [1]. Further, the production of CFCs has been banned by more than 100 signatory countries of the Montreal Protocol [2], the production of HCFCs will stop in 2015 [3] and HFCs have also become one among the six targeted green house gas under Kyoto Protocol [4] meaning that their production will be banned in near future. Therefore, the replacement of these halogenated refrigerants to control green house gas (GHG) emissions and finding suitable alternative to conventional refrigeration system becomes an urgent necessity. However, phase-out of these detrimental halogenated refrigerants is possible when a technical and economically feasible alternative exists and this urge of finding alternative has opened favorable opportunities for the development of green refrigeration technologies.

Conventional vapor-compression refrigeration systems are questioned due to the ozone depletion potential (ODP) and global warming potential (GWP) caused by the CFCs or HCFCs [5]. Liquid absorption, thermoelectric and thermo-acoustic cycles offer limited other options [6]. Liquid absorption refrigeration systems are quite complicated, require advanced knowledge for maintenance, involve a large installation area with high installation cost and have low coefficient of performance (COP). Thermoelectric systems are seldom scalable to large capacities and the thermo-acoustics is still in developmental stages [6]. Adsorption refrigeration is one of the most attractive technologies for refrigeration applications, because it is quite benign to the environment: zero ODP, zero GWP, simple control, low initial investment, less noise, high performance to avoid extra primary energy consumption [7–9]. Again solid adsorption based refrigeration systems have the advantage of scalability to all capacities, ranging from a few watts to several kilowatts [10]. Adsorption refrigeration system uses solid adsorbent beds to adsorb and desorb a refrigerant vapor or an adsorbate gas in

Abbreviations: ACG-825-1.5, A special grade of activated carbon; CFC, chlorofluorocarbons; HCFC, hydrochloroflurocarbon; HFC, hydroflurocarbon; GHG, green house gas; ODP, ozone depletion potential; GWP, global warming potential; COP, coefficient of performance; PSA, pressure swing adsorption; PSR, pressure swing refrigeration.

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Nomenclature

ss	stainless steel
ID	internal diameter, cm
h	height, cm
D	thickness, cm
m_{ac}	mass of activated carbon, g
s_{ac}	standard specific heat of activated carbon, J/g/K
ΔT	temperature drop of chamber, pipelines and activated carbon, K
ΔT^*	temperature drop of water, K
H	cooling required for chamber, pipelines and activated carbon, J
H^*	refrigeration extracted by water, J
H_C	total cooling produced, J
T_{total}	total cycle time, s
H_W	cooling, W
m_c	mass of copper tube inside the sample chamber, g
s_c	specific heat of copper, J/g/K
m_{sst}	mass of stainless steel tube, g
m_{ssc}	mass of stainless steel chamber, g
s_{ss}	specific heat of stainless steel, J/g/K
m_w	mass of water, g
s_w	specific heat of water, J/g/K
m	mass of the gas, g
n	number of moles, mole
ρ_b	bulk density, gm/cm^3
$P = P_2$	final operating pressure, kg/cm^2
P_1	initial pressure, kg/cm^2
R	molar constant, J/mol K
OD	outer diameter, cm
V_g	volume of the gas occupied, L
M	molecular weight of the gas, g/mol
T	final absolute temperature, K
V_c	volume of charcoal, cm^3
L	length of the pipe, cm
V_{AC}	calculated volume of adsorption chamber, cm^3
V_{IO}	calculated internal volume of the gas inlet and outlet pipe, cm^3
V_{CC}	external volume of the cooling coil, cm^3
$\Delta T'$	temperature rise, K
T_{adsorb}	time taken for adsorption, s
H_a	heat of adsorption, J
h_a	heat of adsorption of CO_2 at 0.5 MPa, J/g activated carbon

response to either a change of temperature or a change in pressure. A considerable amount of work on temperature swing adsorption refrigeration systems have been done in the last couple of decades but the exploitation of pressure swing adsorption (PSA) in refrigeration is still limited.

The PSA system has already revolutionized the gas separation industries over the last decade, and may also find increasing application in refrigeration industries. Many works have been reported in the literature towards replacement of halogenated refrigerants by adsorption–desorption mechanism [11–13]. The typical physical adsorption working pairs that have been used in adsorption refrigeration system are mainly silica gel–water [14], zeolite–water [15], activated carbon–ammonia [16], activated carbon–ethanol [17], activated carbon–methanol [18] and activated carbon–R134a [19]. However these working pairs are mainly solid adsorbent–liquid adsorbate pairs and have been studied with temperature swing adsorption. Hence, a gas-active carbon system can be investigated to produce adequate refrigeration using a suitable alternative refrigeration system based on pressure swing adsorption–desorption principle.

Table 1
Dimensions of adsorption–desorption chamber.

Parameter	Value	Parameter	Value
Material of construction	SS-304	Thickness	6.0 mm
Chamber ID	100.0 mm	Copper coil length	1980.0 mm
Height	162.0 mm	Copper coil ID	2.0 mm

Refrigeration system based on pressure swing adsorption–desorption mechanism with activated carbon granules as adsorbent and carbon dioxide gas as adsorbate is a feasible proposition because activated carbon has excellent gas adsorption capacity and heat of adsorption of carbon dioxide is quite high. Most of the earlier works are either based on desorption requiring source of heat or cold production in the bed only but practical utilization of the cold for conventional refrigeration has not yet been tried. The present article enumerates how the refrigerating effect generated in the bed is utilized in producing practical chilled water for conventional refrigeration purpose. This paper describes the design and experimental procedure of such a refrigeration system and investigates its feasibility in terms of cooling effect generated, refrigeration produced, coefficient of performance and adsorption–desorption isotherm.

2. Materials and methods

2.1. Materials

This experimental investigation has been carried out using granular activated carbon as adsorbent and carbon dioxide as adsorbate. Activated carbon was prepared indigenously from hard matured coconut shell and well characterized. Its preparation and characterization has been discussed in the following section. Carbon dioxide gas cylinder was procured from the local market.

2.2. Experimental setup

The experimental model has been designed as per ASME pressure vessel code section VIII for an internal pressure of 0.5 MPa. It was observed earlier with a small stainless steel vessel filled with activated carbon that the heat of adsorption of carbon dioxide did not further substantially improved beyond 0.5 MPa. The experimental setup consists basically of a single adsorption–desorption chamber, a cooling coil, various pipelines and valves. Details of the adsorption–desorption chamber has been put in Table 1. The necessary sealing arrangements at both ends are made as represented in Fig. 1. The ambient water is circulated through this cooling coil embedded in the chamber. The cooling coil is employed to remove the heat of adsorption in the adsorption phase and to extract the refrigeration produced in desorption phase. An arrangement is made to insert the probe of thermocouple sensor for measuring the temperature. The thermocouple used in this system is Type T (copper–constantan) normally used for reading temperatures from (−150 °C to +350 °C). Such thermocouples consist of a bimetallic junction that produces a voltage output that is related to the temperature of the junction. A digital temperature display has been attached to the system to record the temperature readings. A carbon dioxide gas cylinder mounted with pressure gauge is fitted with the gas inlet pipe of the chamber for supply of gas as per the process requirements.