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Research paper

Continuous vapour adsorption cooling system with three adsorber beds

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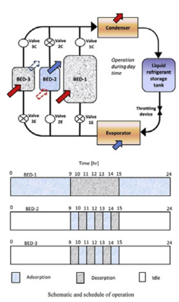
HIGHLIGHTS

- A three-bed silica gel–water continuous adsorption cooling system is analyzed.
- Cold energy is stored in the form of liquid refrigerant at ambient temperature.
- The influence of mass of beds and cycle time on the system performance is discussed.
- Sizing of the beds for a given cooling capacity is recommended.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, the design of a new solar operated adsorption cooling system with two identical small and one large adsorber beds, which is capable of producing cold continuously, has been proposed. In this system, cold energy is stored in the form of refrigerant in a separate refrigerant storage tank at ambient temperature. Silica gel–water is used as a working pair and system is driven by solar energy. The operating principle is described in details and its thermodynamic transient analysis is presented. Effect of COP and SCE for different adsorbent mass and adsorption/desorption time of smaller beds are discussed. Recommended mass and number of cycles of operation for smaller beds to attain continuous cooling with average COP and SCE of 0.63 and 337.5 kJ/kg, respectively are also discussed, at a generation, condenser and evaporator temperatures of 368 K, 303 K and 283 K, respectively.

1. Introduction

Use of refrigeration for air conditioning, food preservation, chemical plants, electronic industries, petrochemical plants, etc. has become essential in daily life. With the increase in demand for energy over the years, it is a challenge for the researchers to build efficient, environmentally friendly energy storage systems that reduce the mismatch between the energy supply and energy demand while using low grade heat sources such as solar energy and industrial waste heat.

Significant focus has been paid to the vapour adsorption refrigeration systems after the imposition of international restrictions on the use of CFCs and HCFCs. Adsorption systems are environment friendly, as they can use variety of working fluids that have zero ozone depletion as well as global warming potentials. In comparison with the vapour compression refrigeration systems, adsorption refrigeration systems have the benefits of vibration free operation, simpler control and lesser operation costs. Moreover, it can be powered by low grade heat such as solar energy or waste

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heat. In comparison with the absorption systems, adsorption systems can be operated with no moving parts, are less sensitive to shocks and to the installation position, need neither solution pump nor rectifier and are corrosion free [1].

Despite several benefits of adsorption systems, they have the disadvantages of low coefficient of performance (COP) and low specific cooling effect (SCE) mainly due to the thermal inertia of the adsorber beds. These drawbacks can be overcome by improving heat and mass transfer in the beds and by the enhancement of sorption kinetics of the working pairs used. In the mass recovery process, the valve applied between adsorber and desorber is opened at the end of the adsorption/desorption process. The adsorber continuous to be cooled and the desorber heated. The adsorber adsorbs the vapours from desorber, results in increases in the mass fraction and also recovers some heat. In the heat recovery process, the adsorber is connected with the desorber by water switch system, results in recovery of heat and enhances COP of the system. When both heat and mass recovery is involved, mass is recovered first and then heat recover happens.

For the utilization of low grade heat for refrigeration purpose, solid adsorption system is well suited, as it can be used for generation temperature below 100 °C. A variety of solar powered adsorption refrigeration systems have been studied in literature. A simulation for solar powered adsorption refrigerating system using activated carbon–methanol as a working pair has been performed by Hassan et al. [2]. They obtained solar coefficient of performance of 0.211 and specific cooling power of 2.326 W/kg. A theoretical and experimental study of solar powered adsorption system used for making ice has been presented by Li et al. [3]. Their emphasis is mainly on the study of the intermittent refrigeration phenomenon influenced by sky cloudy cover. An unsteady state analysis and performance prediction on solar powered intermittent adsorption refrigerator, using flat plate collector was carried out by Anyanwu et al. [4] using activated carbon–methanol pair. The predicted performance of the refrigerator shows good agreement with the actual measured performance data. Anyanwu et al. [5] have also presented the design and test run of a solar powered solid adsorption refrigeration system by using a flat plate collector of exposed surface area of 1.2 m^2. Activated carbon–methanol is used as a working pair. Their experimental results yielded maximum cooling of 266.8 kJ/m^2 and useful overall COP of 0.02. A collector of surface area 2 m^2 is used for an adsorption refrigeration system powered by solar energy using silica gel–water as a working pair built by Hildbrand et al. [6]. The result shows net COP of 0.13. Li et al. [7] built a flat plate solid adsorption refrigeration system for demonstration purpose using methanol as a refrigerant and activated carbon as an adsorbent. The system is capable of producing 4–5 kg and 7–10 kg of ice with a collector surface area of 0.75 m^2 and 1.5m^2 respectively. An experimental demonstration of solar powered adsorption refrigeration system, using domestic type charcoal and methanol as a working pair was performed by Khattab et al. [8]. The system gave net solar COP of 0.136 and 0.159 for cold and hot climate respectively. It is observed that most of the solar powered adsorption cooling systems reported are of intermittent operation, since solar energy itself is intermittent in nature. The selection of working pair is determined by the amount of heat taken out from the evaporator and change in the concentration of the adsorber per cycle [9]. Silica gel–water, Activated carbon–ammonia, Activated carbon–methanol are the most popular working pairs.

In fact, very little attention has been paid towards the development of continuous vapour adsorption refrigeration system. A solar powered continuous adsorption refrigeration system using parabolic collector has been studied by Fadar et al. [1]. Activated carbon–ammonia is used as a working pair and the system prompted storage of solar energy in the form of hot water. The results illustrate that the system could produce a daily cooling of 2515 kJ per 0.8 m^2 of solar collector area. Wang et al. [10] have proposed a hybrid solar powered adsorption system, used for water heating and ice making in which methanol is used as a refrigerant and activated carbon as adsorbent. The system is proficient enough to produce 10 kg of ice as well as heating 60 kg water to 90 °C per day using 2-m^2 collector. Alghoul et al. [11] presented a theoretical design and performance of solar powered dual-operated continuous vapour adsorption system used for heating water and refrigeration for domestic purpose by using activated carbon–methanol as a working pair. Heat is stored in the system by using storage tanks and the system is capable of producing 160 kg of hot water and 12 kg of ice per day. The systems discussed above store solar energy in the form of hot water used for generation of refrigerants from beds throughout the day. In these cases, there is always a heat loss to the ambient and a large volume storage tank is needed. These drawbacks can be overcome by storing energy within the system by accumulating refrigerant in refrigerant storage tank at ambient temperature.

One of the application of sorption process (using water as an adsorbate) is desalination of water [12–14]. In the adsorption desalination process, sea water is evaporated from the evaporator and is taken up by adsorbent. Heat of adsorption during process is rejected by employing cooling water circuit. Desorption is initiated by supplying hot water, and heat of condensation is rejected by using cooling tower. By this process, cooling is achieved at the evaporator and potable water is collected from the condenser, bridging the gap between demand and supply of clean water.

In this paper, an analysis of a novel continuous 3-bed vapour adsorption refrigeration system with liquid refrigerant storage tank powered by solar energy is presented. Silica gel–water is used as a working pair because of its low generation temperature i.e. about 95% regeneration is obtained at 95 °C [15–17].

2. System description and working principle

A schematic diagram of the proposed solar operated adsorption refrigeration system for continuously producing cold is shown in Fig. 1. This system is composed of six main components; three beds, one solar collector, one condenser and one evaporator. Out of three beds, Bed-1 is larger in size compared to other two identical beds. It also consists of a refrigerant storage tank and six refrigerant flow regulating valves. Valves 1E, 2E and 3E connect beds to the evaporator and valves 1C, 2C and 3C connect beds to the condenser.

The proposed system yields cold continuously by sequential operation of the valves. Cooling is produced in the evaporator by adsorbing Bed-1 during night time (say 15:00 h to 9:00 h). During the day time (say 9:00 h to 15:00 h) when Bed-1 undergoes desorption, Bed-2 and Bed-3 work out of phase i.e. undergo adsorption and desorption alternately. Thus produces continuous cooling within their respective adsorption period. Cooling is provided by Bed-1 during night time and Bed-2 and Bed-3 provides cooling alternately during day time.

During day time, when solar heat input is sufficient to generate vapour (say 09:00 h), the solar heating system is connected to Bed-1 and Bed-3 to facilitate desorption. The desorbed refrigerant is condensed in condenser and is collected in the storage tank. Bed-3 gets desorbs for, say 1 h (9:00 h to 10:00 h), whereas Bed-1 takes 6 h for its desorption (say 09:00 h to 15:00 h). Bed-2 and Bed-3 operates out of phase i.e. when Bed-3 is being heated up and desorbs refrigerant into the condenser, at the same time Bed-2 is cooled down and adsorbs refrigerant vapour from evaporator, producing cooling effect. Both beds 2 and 3 undergo adsorption alternately and produce continuous cooling effect in the daytime.