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Simulation of a high efficiency multi-bed adsorption heat pump

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ABSTRACT

Attaining high energy efficiency with adsorption heat pumps is challenging due to thermodynamic losses that occur when the sorbent beds are thermally cycled without effective heat recuperation. The multi-bed concept described here enables high efficiency by effectively transferring heat from beds being cooled to beds being heated. A simplified lumped-parameter model and detailed finite element analysis are used to simulate a sorption compressor, which is used to project the overall heat pump coefficient of performance. Results are presented for ammonia refrigerant and a nano-structured monolithic carbon sorbent specifically modified for the application. The effects of bed geometry and number of beds on system performance are explored, and the majority of the performance benefit is obtained with four beds. Results indicate that a COP of 1.24 based on heat input is feasible at AHRI standard test conditions for residential HVAC equipment. When compared on a basis of primary energy input, performance equivalent to SEER 13 or 14 are theoretically attainable with this system.

1. Introduction

Adsorption heat pumps utilize heat to drive thermodynamic cycles that transfer heat from a lower temperature to a higher temperature for applications such as space cooling and refrigeration or for improving energy efficiency of space heating or water heating. Although some power is still needed for valves and fans, heat-driven technologies are able to use waste heat and alternative energy sources, such as exhaust heat [1] or solar [2,3], and thereby substantially reduce power demand. The challenges are attaining competitive energy efficiencies and minimizing system costs by reducing system size and complexity. Energy efficiency of adsorption heat pumps is reduced by thermodynamic losses that are largely attributed to the temperature gaps between the cycle and the external sources and sinks [4]. In addition, the thermal mass of the sorbent media and the hardware that must be thermally cycled contribute to efficiency losses, and the sorbent capacity and ratio of hardware mass to sorbent mass are key factors affecting efficiency [1,5]. Many approaches have been developed to improve efficiency including multi-bed regenerative [6], thermal wave [7,8], and cascading [9] cycles. Reducing the size and cost of the sorbent beds requires shortening the thermal cycle times, which is limited by heat transfer. Advancements have been made in improving thermal conductivity of monolith sorbent media [10] and adding high conductivity fillers [11,12], as well as through advanced bed designs that reduce overall thermal resistance [13].

Energy efficiency can be improved by using multiple beds and recovering heat from beds being cooled to preheat beds entering the generator half of the cycle [5]. A multi-bed concept that embodies this approach was originally developed for compressing CO_2 from the Martian atmosphere as a raw material for in situ propellant production [14]. The potential for this patented technology [15–17] to improve heat pump energy efficiency is evaluated here through computer simulation. Performance is assessed for an ammonia adsorption system using ATMI monolithic carbon and a stacked-plate bed architecture [1].

2. Concept

A highly-recuperative multi-bed compressor of an adsorption heat pump is depicted schematically in Fig. 1. Each wedge in the octagon represents a bed in an 8-bed system where the beds conceptually rotate counter-clockwise by moving the inlets and outlets using a system of valves. Adsorption onto the media occurs at position 5 and vapor is produced at higher pressure at position 1. Bed temperature increases as a bed moves from position 5 to position 1 along the right side and decreases as it continues counter-clockwise from position 1 back to position 5. Heat is effectively recuperated from the beds being heated to beds being cooled through a heat transfer fluid flowing sequentially from bed

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