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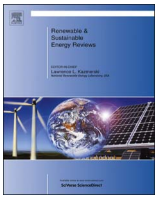

An overview of modelling techniques employed for performance simulation of low–grade heat operated adsorption cooling systems

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ABSTRACT

With increasing social and economic developmental activities, high grade energy sources are depleting at faster rate and also inviting menace of environmental problems. Therefore, to reduce dependency on high grade energy sources for cooling applications and to protect environment, adsorption cooling systems are promising alternatives that are powered by low grade heat sources like solar heat, industrial/automobile waste heat etc. and also use environment friendly refrigerants. But, these systems have still low performances, large size and high cost. Therefore, in order to overcome these difficulties, many researchers are focussing on different ways to improve heat and mass transfers in the heat exchangers of the system to enhance its performance. These strategies include the use of advanced adsorbent material and advanced adsorption cycles, design improvement in heat exchangers and development of mathematical models for optimization of design/operating parameters of the cooling systems. In this paper, various mathematical models for adsorption systems are presented that include thermodynamic models, lumped parameters models; and heat and mass transfer models. These models include equations governing the heat and mass transfer in the main components of the cooling systems. The advantages of this method are that it can produce large volumes of results at no more cost and it is very cheap to perform parametric studies, for instance, to optimize equipment performance. The various numerical methods and experimental validations have been also presented and discussed.

1. Introduction

Various adsorption cooling and heat pump systems have been studied as potential solutions for cooling as well as heating purposes as they have the advantages of being environmentally benign, having zero ODP as well as zero GWP due to the use of natural refrigerants or alternative refrigerants of CFCs, HCFCs or HFCs [1,2]. In addition, they have advantages of being powered by low temperature driving sources like solar heat, industrial/automobile waste heat and geothermal heat [3–5], which can reduce the dependence on fossil fuel resources. These systems have simpler control, less vibration and lower operation cost, compared to conventional vapour compression systems. Moreover, these systems have some attractive advantages over absorption cooling systems [6,7]. Adsorption cooling systems can work with wide range of low grade heat source temperatures (50–500 °C) without any corrosion problem, whereas corrosion occurs in absorption cooling systems above 200 °C. Adsorption systems do not use moving parts for circulation of working fluids and hence they operate without noise and vibration. Due to the use of solid adsorbents in these systems, they are preferred in fishing boats, locomotives etc. where there are chances of serious vibration and shocks. In these physical adsorption systems, commonly used working pairs are activated carbon–methanol [8–10], activated carbon–ethanol [11–13], activated carbon–ammonia [14–16], silica gel–water [17–19], and zeolite–water [20–22]. Despite the above advantages, these systems have still some drawbacks, such as low COP, low SCP, large size and high capital cost.

Therefore, in order to overcome these difficulties, many researchers are focussing on different ways to improve heat and mass transfers in the heat exchangers of the chiller to enhance its performance [23]. These strategies include the use of advanced adsorbent material and advanced adsorption cycles, design improvement in heat exchangers and development of mathematical models for optimization of design/operating parameters of the chillers. Adsorbent bed affects the performance of the chiller significantly. Nowadays, consolidated/composite adsorbent beds are being used to improve adsorption properties of the chiller [24]. In basic adsorption cooling cycle, the efficiency is low and the cooling output is not continuous. Therefore, many adsorption cycles have been designed to improve the perfor-

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Nomenclature

AC	activated carbon
ACF	activated carbon fibres
BET	Brunauer-Emmett-Teller theory
CFCs	chlorofluorocarbons
CPC	compound parabolic concentrator
COP	coefficient of performance, (dimensionless)
DA	Dubinin–Astakhov (equation)
DR	Dubinin–Radushkevich (equation)
GWP	global warming potential
HE	heat exchanger
HCFCs	hydro chlorofluorocarbons
HFCs	hydro fluorocarbons
ODP	ozone depletion potential
SCP	specific cooling power, W kg^{-1}

mance and make the cooling process continuous. These advanced cycles include the cascading cycle [25], combined heat and mass recovery [26], thermal wave [27], hybrid system [28,29] and passive heat recovery technique [30,31]. Better heat transfer performance of the adsorber improves total heat transfer coefficient of the adsorber and increases the heat transfer rate between adsorber and heat media. Similarly, better mass transfer in the adsorbent reduces the adsorption/desorption of refrigerant into/from the adsorbent and shortens the adsorption/desorption time of the cycle. Both processes enhance the SCP of the system and this can be achieved only by improving the design of adsorber [32]. However, the size and weight of these systems are still major challenges of this technology [33]. Optimization of such systems can be done using mathematical models of the heat and mass transfer. Thus, the behaviour of different chillers can be evaluated and different designs can be compared with the help of dynamic simulations [34].

Many researchers have taken keen interest in adsorption cooling and heating systems. This is the reason that there are many review papers published about these systems. Meunier [35] has analysed the possibilities and limitations of low temperature heat powered solid adsorption cycles. Hassan et al. [36] have summarized the equations of state for the adsorption pairs commonly used in adsorption cooling systems and concluded that the selection of better adsorbent-refrigerant pair results better performance of the system. Dieng et al. [37] have presented various solar based adsorption cooling systems and discussed different technologies involved for ice-making and air conditioning purposes.

Fan et al. [38] have summarized solar sorption technologies in which development history and recent progress in solar sorption refrigeration technologies are reported. These technologies are classified on the basis of cooling temperature demand. These systems have been discussed into three categories: air-conditioning (8–15 °C) for spaces, refrigeration (0–8 °C) for food and vaccine storage, and freezing (< 0 °C) for ice-making or cogeneration purposes. Wang et al. [39] have discussed recent developments in consolidated adsorbents for adsorption systems. In this study, the authors have presented a number of consolidated technologies of adsorbents to enhance the performance of the systems. Sah et al. [40] have summarized many adsorption cooling systems with different adsorption working pairs for production of ice.

Yong and Sumathy [41] have presented a review paper on mathematical modelling of closed adsorption heat pump and cooling systems powered by low grade heat sources. But there are still many more recent works related to the modelling of adsorption cooling systems, which are not covered in that review, need to be summarized.

In the present study, a state of art overview on mathematical modelling of adsorption cooling systems is discussed. The mathematical models are further classified into thermodynamic models, lumped parameter models; and heat and mass transfer models and are presented in later sections.

2. Working principle of a two-bed adsorption cycle

Fig. 1 shows a schematic diagram of a single stage two bed silica gel-water adsorption chiller [42]. It consists of four heat exchangers: an adsorber, a desorber, an evaporator and a condenser. Low pressure refrigerant (water) is evaporated in the evaporator due to external cooling load (chilled water) and adsorbed into the solid adsorbent filled in the adsorber bed1. During evaporation process, the valve V2 is open and cooling water cools the adsorber to maintain the adsorption of the refrigerant in bed1. On the other side, when the valve V3 is open, the bed2 is heated by hot water to maintain desorption of refrigerant. The desorber bed2 is connected to the condenser, which condenses the refrigerant coming out from the bed and the condensate returns to the

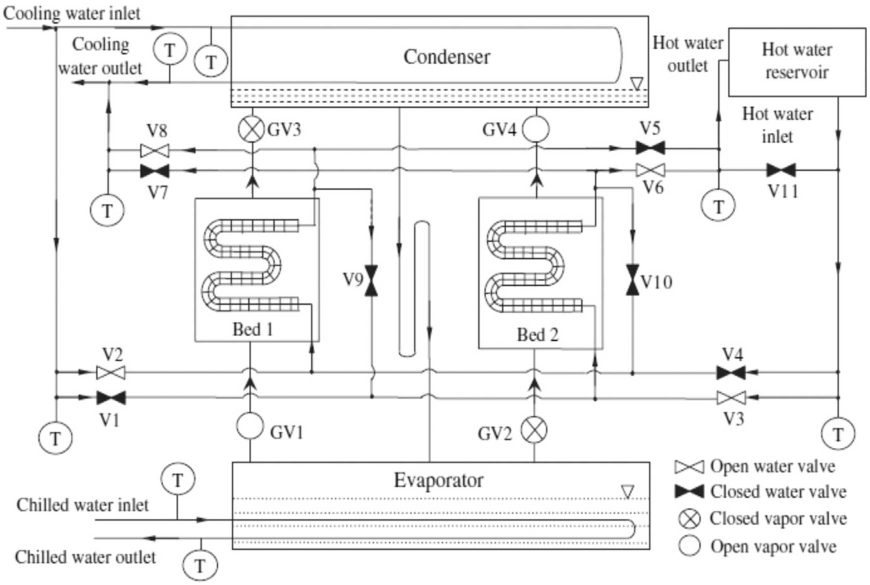

Fig. 1. Schematic diagram of a single stage two bed adsorption chiller [42].