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Review

Review article: Numerical simulation of adsorption heat pumps

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ABSTRACT

The primary advantages of the AHP (adsorption heat pump) including using environmentally friendly working fluids and their capability of using low-grade waste heat as their primary driving energy have raised a great deal of attention in recent years. In this work, computer models of AHPs and the latest relevant findings are reviewed since the performance of an AHP system greatly depends on the coupled heat and mass transfer rates inside the adsorbent bed and the design parameters of the adsorber. The nonlinearity of the coupled heat and mass transfer equations makes the qualitative analysis of such systems difficult and hence many researchers have proposed various models to predict the performance of the system and optimize the design parameters to boost the performance. The available models in the literature have been categorized into thermodynamic models, lumped-parameter models, and distributed-parameter (heat and mass transfer) models. The results of the literature review indicate that recent numerical modeling of AHPs relies on the distributed-parameter models. Majority of the modeling works are focused on validating the proposed model and used the model to optimize the adsorber design parameters and operating conditions of the system. Based on the literature review, some potential future research areas are suggested.

1. Introduction

AHPs (adsorptive heat pumps) have gained considerable attention in the recent years due to their remarkable virtues including their low environmental impact, not requiring electricity for their operation and no moving parts. While the conventional VCCs (vapor compression cycles) use CFCs, HCFCs and other ozone-depleting gases, most of the adsorption heat pumps use environmentally friendly refrigerants such as water, ammonia and methanol and hence can decrease greenhouse gases emissions significantly. The compressor in the VCCs accounts for the primary energy consumption component in the form of electricity. However, in the AHP, the compressor is replaced by the adsorber/desorber and heat is implemented to drive the system. Even though the COP (coefficient of performance) of the AHPs is lower than that of the traditional VCCs, AHPs have potential application where the low-grade heat source such as solar energy or waste heat is readily available [1–6]. Comprehensive reviews of the AHPs technology have been provided by Meunier [7] and Srivastava and Eames [8]. A typical adsorption cycle consists of four main components including: (a) adsorber/desorber, (b) condenser, (c) evaporator and (d) expansion valve. The adsorber is the main component of the system where the adsorbate is being adsorbed and desorbed into/from the surface of the adsorbents. Due to the exothermic/endothermic nature of adsorption/desorption, and required diffusion of adsorbate inside the adsorbent bed and particles, heat and mass transfer in the adsorber play a major role in the rate of adsorption and thus the performance of the AHPs. In order to accommodate for the heat transfer requirements of the adsorption/desorption process, adsorbent particles are usually attached to the external surface of the heat exchangers where the heat transfer fluid is flowing inside the heat exchanger. Early experimental works on the AHPs using zeolite in form of powder and pellets [2,9–11] indicated that the major limitation of this technology is poor heat transfer inside the bed which leads to long cycle times. The major barriers of heat transfer inside the adsorber originates from the low thermal conductivity of the adsorbent material, weak contact between the heat exchanger surface and the adsorbent, and the low heat transfer

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Nomenclature

Abbreviations

AHP	adsorption heat pump
ADI	alternating direction implicit
ANOVA	analysis of variance
CDS	central difference scheme
COP	coefficient of performance
HTF	heat transfer fluid
LDF	linear driving force
LMTD	log mean temperature difference
OCFEM	orthogonal collocation finite element method
QUDS	quadratic upstream difference scheme
SCP	specific cooling power
VCC	vapor compression cycle

Symbols

A	heat transfer area (m^2)
C_p	specific heat (kJ kg^{-1} K^{-1})
D	tube diameter (m)
h	heat transfer coefficient (kW m^{-2} K^{-1})
K	thermal conductivity (kW m^{-1} K^{-1})
K_sa_p	mass transfer coefficient (s^{-1})
P	pressure (mbar) or (pa)
q	adsorbate uptake (kg kg^{-1} of adsorbent)
q^*	equilibrium uptake (kg kg^{-1} of adsorbent)
Q_{st}	heat of adsorption (kJ kg^{-1})
t	time (s)
T	temperature (K)
u	velocity (m s^{-1})
W_s	mass of adsorbents (kg)
W_w	mass of liquid adsorbate (kg)
Z	axial coordinate (m)

Greek letters

δ	fin thickness (m)
ε_t	total porosity of the adsorbent bed
ρ	density (kg m^{-3})
ΔH_{ads}	heat of adsorption (kJ kg^{-1})

Subscripts

a	ambient, adsorbate
ads	adsorbent bed
adst	adsorbent bed-tube metal
f	fluid
fin	fin
ft	fluid-tube metal
in	inside
out	outside
t	tube
v	vapor

coefficients of the heat transfer fluid. To address such challenges and increase the contact area between the zeolite particles, new designs with consolidated layers of adsorbent along with using materials having a higher thermal conductivity have been proposed [12–16]. However, synthesizing consolidated layers of adsorbent on the external surface of the heat exchanger increases the external mass transfer resistance and hence can decrease the performance of the system. From this discussion the coupling effect of heat and mass transfer in the adsorbent bed is quite evident. The rate of mass diffusion is a function of the temperature and the variation of temperature in the bed is also determined by the rate of adsorption. Consequently, a simultaneous study of heat and mass transfer inside the adsorbent bed is absolutely indispensable. Many different types of adsorber configurations have been investigated. Adsorbents can be deposited on the external surface of the heat exchangers or can be introduced in form of the packed beds. In terms of the heat exchanger type, a wide variety of choices such as finned tube, plate-tube, spiral plate, shell and tube, and, annulus tube can be implemented. In this work, recent developments of modeling of the adsorption heat pumps will be reviewed. The innumerous combination of the adsorber design parameters for a certain operating condition necessitates a robust model, which is capable of predicting the performance of the system within an acceptable error margin. Such modeling works can be used to modify and optimize the design parameters to maximize the measures of the system performance such as the coefficient of performance or specific cooling power depending on the application of the system.

2. Types of model

For the adsorption and desorption process, three types of modeling are usually considered: (a) thermodynamic model, (b) lumped-parameter model, and, (c) distributed-parameter model. The major difference among these models is the assumption regarding the heat and mass transfer. The thermodynamic model does not consider the heat and mass transfer kinetics inside the adsorbent bed. This model assumes thermodynamic equilibrium between the adsorbent and adsorbate to predict the upper limit of the system performance. The computations are quite simple and straightforward. The lumped-parameter model considers the heat and mass transfer between the surrounding and the adsorbent bed, however the temperature gradient inside the adsorbent bed is zero and no mass transfer resistance inside the bed is considered. This type of modeling is more accurate than the first model, yet computationally more expensive. The last type of modeling considers both heat and mass transfer inside the adsorbent bed. Unlike the previous model, this type of the model considers the temperature gradient inside the bed. Pressure gradient inside the bed i.e. external mass transfer resistance and non-equilibrium condition between the vapor and the adsorbent i.e. internal mass transfer resistance, are the major characteristics of this type of model. The heat and mass transfer model is the most accurate type of the model. However, the computations involve solving transient and spatial coupled heat and mass transfer balance equations with complicated boundary conditions. Advanced numerical methods are often required to solve these nonlinear equations, which makes the computations time consuming and expensive. A comprehensive review related to each category of models is provided in this section. The last type which considers both heat and mass transfer provides much more insight regarding the adsorption phenomena occurring in the adsorbers of the heat pumps and thus has gained much more attention in the recent years.

2.1. Thermodynamic model

Thermodynamic models rely on the analysis of the first and second laws of thermodynamics. All the thermodynamic models as well as the other two types of the modeling discussed