



Scaling analysis of heat and mass transfer processes in an adsorption packed bed



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ABSTRACT

In this article, a scaling analysis of heat and mass transfer processes in an adsorption packed bed is presented. New scaling parameters that characterize the performance of the adsorption cooling bed are derived and their importance are discussed. In addition, a numerical study is performed to illustrate the roles played by the newly derived scaling parameters. It is found that the presence of heat of adsorption makes the apparent heat capacity of an adsorption bed much larger than the heat capacity of the adsorbent material itself. The present results indicate that the heat diffusion and vapor penetration depths can be used to specify the desired working pair properties and the adsorbent layer thickness for producing the maximum cooling power. From the results of scaling analysis, it can be concluded that the inter-particle permeation resistance has a considerable effect on the performance of an adsorption silica gel bed when the particle diameter to adsorbent layer thickness ratio is less than 0.1. It can also be concluded that performance of a silica gel packed bed is controlled by the conductive thermal resistance when the Fourier number of the adsorbent-adsorbate layer (F_c) is less than 1.0. The convective resistance (i.e., external resistance) dominates the bed performance when the dimensionless temperature ratio (θ) of adsorption silica gel packed bed is more than 0.2.

1. Introduction

A vast majority of global cooling and heating demands is covered by traditional vapor compression systems, employing refrigerants that have high Global Warming Potential (GWP) [1–3]. Abundant renewable energy resources such as low-grade waste energy or solar energy can be converted into beneficial cooling and electricity using promising clean energy technologies like adsorption, absorption and Organic Rankine Cycle (ORC). Therefore, adsorption cooling/heat pump technology, which has received much attention in the recent years, is an attractive alternative for conventional refrigeration and air conditioning systems. Adsorption cooling systems convert low-grade heat source into useful cooling/heating power and utilize refrigerants with zero Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) [4–6].

Over the years, many researchers have focused on characterizing the thermo-physical properties of adsorption working pairs [7–10], studying the effect of adsorption kinetics, operating conditions and adsorbent grain size on adsorption cycle performance [11–15], and investigating various bed configurations to optimize the operating conditions and system design [16–19].

Different bed designs have been proposed and studied. Mohammed et al. [13] proposed a new packed bed that consists of repeated packed bed modules. Each module has two layers of packed silica-gel particles separated by a narrow vapor passage. The performance of the new bed packed with silica gel was simulated. The optimal particle size of silica gel was found to be about 0.5 mm, and the proposed compact bed produces a specific cooling power (SCP) of 630 W/kg, which is much higher than finned-tube heat exchanger beds. Kubota et al. [20] investigated the performance of a prototype finned tube heat exchanger packed with silica-gel. It was experimentally confirmed that the optimized fin-type silica-gel bed could achieve more than two times higher cooling output per unit adsorbent volume than un-optimized module. Sapienza et al. [21] experimentally studied the impact of operating conditions on the performance of an adsorption chiller. Their results indicated that the cycle time and the duration of adsorption and desorption steps are the main parameters strongly controlling the system performance. Li et al. [22] studied the transient heat transfer behavior of silica-gel heat exchanger with fins. A correlation for the transient heat transfer coefficients was presented at sub-atmospheric pressures and assorted application temperatures. Freni et al. [23] tested experimentally the performance of a heat exchanger coated with a compact

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layer of SWS-1L (CaCl₂ in mesoporous silica gel). The experimental setup recorded an SCP of 150–200 W/kg of adsorbent and a cycle time of 10–20 min.

Although extensive studies have been conducted to enhance the performance of adsorption systems, they still suffer from low specific cooling power (SCP), low coefficient of performance (COP) and large size [13,24]. It has also been reported that the low performance is due to the high thermal resistance and high intra-particle mass diffusion resistance within the adsorption bed packed with adsorbent beads. The main goal of this study is to derive new scaling parameters that can be used to specify the optimal bed dimensions and select the appropriate working pair to achieve the maximum cooling power. Therefore, the study performs an order of magnitude analysis and scaling analysis on the terms in the governing conservation equations to identify the importance of each term on the bed performance.

2. Theory of heat and mass transfer in an adsorption packed bed

An adsorption bed is basically a heat exchanger packed with a nanoporous adsorbent whose particle diameter is in the range of 0.18–3.0 mm. The different bed configurations can be simplified as a layer of adsorbent with vapor adsorbate coming from an evaporator. The other side is a cold wall that could be a fin or a surface exposed to a cooling fluid as presented in Fig. 1a. Vapor penetrates into the void spaces between particles, which is characterized by the inter-particle permeation resistance as shown in Fig. 1b. The inter-particle permeation resistance causes a pressure drop across the adsorbent-adsorbate layer. When the vapor reaches the surface of the adsorbent particles, adsorption occurs via mass diffusion through the nanopores of the adsorbent particles (i.e., intra-particle mass diffusion resistance) and it is accompanied with the release of heat of adsorption. The heat generated is removed by a cooling fluid facilitating continuous adsorption. However, this heat must first be conducted through the adsorbent bed to the heat transfer surface for the adsorption process to continue. Since the effective thermal conductivity of a packed bed is low, the adsorbent layer should be small to reduce its thermal resistance. The particles eventually reach an equilibrium condition and no further adsorption occurs. The change in uptake depends on the bed pressure and temperature during the adsorption period. Accordingly, adsorption bed performance is controlled by inter-particle permeation resistance, intra-particle mass diffusion resistance, heat diffusion through the adsorbent-adsorbate layer and convective heat transfer resistance [29]. Fig. 1c summarizes the thermal resistances of adsorbent embedded heat exchanger in a typical adsorption heat transfer process [22].

3. Mathematical model

The governing equations are derived by taking volume averaging of the microscopic conservation equations. The mathematical model developed in this study is primarily based on the following assumptions

and simplifications [13]:

- The effective thermal conductivity of the adsorbent is spatially uniform.
- The adsorbent and adsorbate phases are in thermal equilibrium.
- The vapor phase of the adsorbate is assumed to be an ideal gas.
- The thermodynamic properties of the adsorbent are temperature independent in the range of operating conditions of adsorption cooling systems.

The mass conservation equation for the adsorbate gas is written as [25,26]:

$$\epsilon_t \frac{\partial \rho_v}{\partial t} + \nabla \cdot (\rho_v \vec{U}) + \rho_b \frac{\partial X}{\partial t} = 0 \tag{1}$$

where ρ_v is the vapor density, ρ_b is the adsorbent packed beads density, \vec{U} is the vapor velocity vector, ϵ_b is the bed porosity, and X is the adsorption uptake that can be calculated using the linear driving force model (LDF) as [27]:

$$\frac{\partial X}{\partial t} = \frac{15D_s}{r_p^2} (X_o - X) \tag{2}$$

where r_p is the average radius of the particle, D_s is the surface diffusivity, and X_o is the equilibrium uptake that can be estimated from the following equation [28,29]:

$$X_o = X_\infty \exp\left(-k \left(\frac{T}{T_{sat}} - 1\right)^n\right) \tag{3}$$

where X_∞ is the maximum capacity of the adsorbent, T is the adsorbent temperature, k and n are constants and their values depend on the working pair, and T_{sat} is the saturated vapor temperature.

The inter-particle vapor flow resistance can lead to significant bulk pressure gradient. Darcy's equation, including only viscous effects, is used to describe the velocity field of the vapor adsorbate in the bed, while the inertial effects are ignored due to the very low vapor velocity flowing through the voids between the adsorbent particles [30,31].

$$\vec{U} = -\frac{K}{\mu} \nabla P \tag{4}$$

where P is the vapor pressure, μ is the vapor dynamic viscosity and K is the bed permeability that can be calculated by Ref. [13]:

$$K = \frac{r_p^2 \epsilon_b^3}{37.5(1 - \epsilon_b)^2} \tag{5}$$

The energy equation inside a bed can be expressed as [32,33]:

$$(\epsilon_b \rho_v C_{pv} + \rho_b C_{ps} + X \rho_b C_{pw}) \frac{\partial T}{\partial t} + \rho_v C_{pv} \vec{U} \cdot \nabla T = \nabla \cdot (k_b \nabla T) + \rho_b Q_a \frac{\partial X}{\partial t} \tag{6}$$

where ρ_b is the packed bed density, C_{ps} is the adsorbent specific heat,

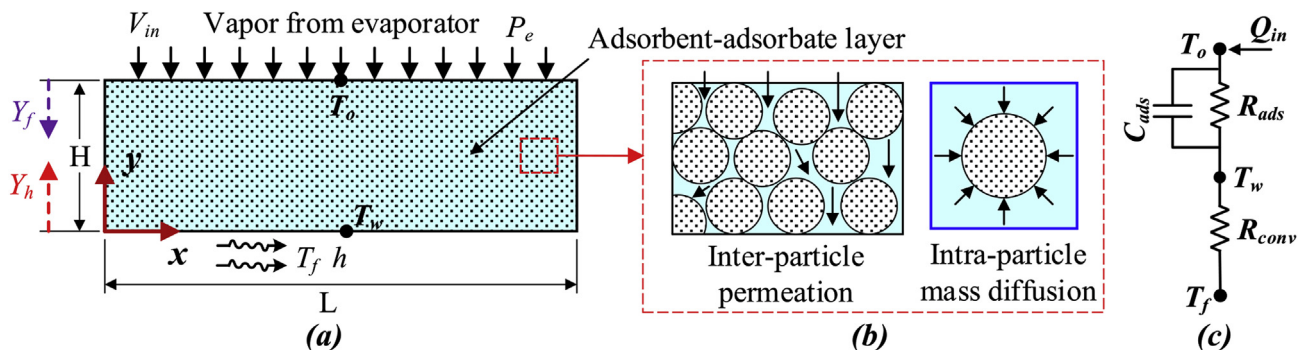


Fig. 1. Schematic representation of (a) an adsorbent embedded heat exchanger, (b) mass transfer resistances, and (c) thermal resistances of a bed.

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