CrossMark

Scaling analysis and numerical studies on water vapour adsorption in a columnar porous silica gel bed

Sourav Mitra, N. Aswin, Pradip Dutta *

Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560012, India

A B S T R A C T

This article presents a theoretical analysis of heat and mass transfer in a silica gel + water adsorption process using scaling principles. A two-dimensional columnar packed adsorber domain is chosen for the study, with side and bottom walls cooled and vapour inlet from the top. The adsorption process is initiated from the cold walls with a temperature jump of 15 K, whereas the water vapour supply is maintained at a constant inlet pressure of 1 kPa. The first part of the study is dedicated to deriving relevant scales for the adsorption process by an order of magnitude analysis of energy, continuity and momentum equations. In the latter part, the derived scales are compared with the outcome of numerical studies performed for various domain widths and aspect ratio of bed. A good correlation between scaling and simulation results is observed, thereby validating the scaling approach.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Cooling systems and heat pumps based on adsorption can make use of low grade thermal energy to accomplish their purpose and are regarded as viable alternatives to conventional vapour compression systems. Such systems comprise of thermal compression in place of mechanical compression found in existing systems. Thermal compression possesses the advantages of requiring predominantly heat input for performing compression and the absence of moving parts. The core component of such a system is the adsorber which contains the adsorbing material (adsorbent) and the heat exchanger (metal tubes and fins). The compression takes place within this adsorber and it comprises of four cyclical processes: adsorption, preheating, desorption and precooling. Details of these processes for silica gel (adsorbent) + water (adsorbate) pair may be found in the literature [1].

Over the years, significant work has been reported in the field of silica gel + water adsorption. Majority of these studies may be classified as (i) thermo-physical characterisation of the adsorption pair [2–4]; (ii) grain level experimental and modelling studies [5–11] for investigating the effect of kinetics, grain size and multi-layering on adsorption performance; (iii) bed level experimental and modelling studies [12–20] of single and multi-stage multi-bed adsorption systems carried out to characterize the system performance and optimise its operational parameters. One of these studies [20] experimentally depicts the adverse effect of vapour

flow resistance in an adsorber bed on the system throughput. In addition, there have been few numerical studies to evaluate the heat and mass transfer performance of adsorber heat exchangers [21–24]. Table 1 describes the prior art in the above mentioned areas for silica gel + water adsorption pair.

The present study aims at a theoretical analysis of silica gel + water adsorption process using scaling principles. For the analysis, a two-dimensional geometry of a porous silica gel bed is chosen with its height significantly larger than its width (columnar domain). The adsorption process is initiated by subjecting the domain boundary to a temperature jump. The boundary conditions are applied in such a way that the width represents the length scale across which heat transfer predominantly occurs and its height denotes the predominant direction along which vapour flow occurs. The study implements an order of magnitude analysis of mathematical equations governing flow of water vapour and heat in this domain in order to identify the dominant terms and ignore the negligibly small ones. The intention is to derive relevant length and time scales through which one can identify the limiting parameters in the adsorption process. The results obtained through scaling analysis are then validated with a corresponding numerical study for various domain widths and heights.

2. Adsorption process

An adsorber bed is a heat exchanger packed with micro-porous silica gel particles subjected to a vapour pressure. The pores within this bed (void spaces) get filled with water vapour at the subjected pressure. Adsorption within an individual silica gel particle occurs

---

* Corresponding author.
   E-mail address: pradip@mecheng.iisc.ernet.in (P. Dutta).

Nomenclature

c	uptake (kg/kg)
C_p	specific heat capacity at constant pressure (kJ/kg K)
C_v	specific heat capacity at constant volume (kJ/kg K)
d	diameter (m)
E	energy (kJ/kg)
h_{ads}	heat of adsorption (kJ/kg)
k	thermal conductivity (W/m K)
P	pressure (Pa)
P_b	far end bed pressure (Pa)
t	time (s)
T	temperature (K)
$v, \tilde{v}$	superficial velocity of water vapour in y-direction (m/s)
x	coordinate along width of domain (m)
X	domain width (m)
y	coordinate along height of domain (m)
$Y, \tilde{Y}$	domain height (m)

Greek symbols

$\alpha, \tilde{\alpha}$	thermal diffusivity (m²/s)
ε	porosity
λ	permeability of porous adsorbent bed (m²)
μ	viscosity of water vapour (Pa s)

Π	ratio of specific heat capacities of water vapour and silica gel
ρ	density (kg/m³)

Subscripts

ads	adsorption
amb	ambient
bed	adsorbent bed
cr	critical value
e	evaporator
eff	effective value
f	final
i	initial
in	inlet to the domain
max	maximum
min	minimum
p	silica gel particle
s	silica gel
th	thermal
v	water vapour
w	water
$wall$	wall

through the micro-pores (Fig. 1) and it is accompanied by release of heat of adsorption [2–4]. This heat is removed by the heat exchanger facilitating continuous adsorption. The particle eventually comes to an equilibrium at which point it is saturated and no further adsorption occurs. The overall uptake at equilibrium can be related to the local water vapour pressure (bed pressure) and temperature. The relation between this equilibrium uptake and pressure for a specified temperature is conventionally described in the form of an adsorption isotherm. In the present study Tòth's isotherm relation [2,3] is used to describe

Table 1
Literature on silica gel + water adsorption pair.

Classification	Literature	Remarks
Thermo-physical characterisation	Chua et al. [2], Wang et al. [3]	Comparison of type A and RD silica gel thermo-physical properties and measurement of adsorption isotherm data
	Thu et al. [4]	Three types of silica gel: RD, A5BW and A⁺⁺ have been investigated for their suitability in adsorption desalination cycles based on their thermo-physical properties and water vapour uptakes
Grain level studies	Aristov et al. [5]	Measurement of adsorption kinetics of RD silica gel + water vapour for various grain sizes using isothermal pressure jump method
	Aristov et al. [6]	Experimental measurement of dynamic uptake for SWS-1L (CaCl₂ in silica gel) with water vapour by applying a temperature jump at constant pressure
	Glaznev and Aristov [7], Aristov et al. [9]	Adsorption kinetics measurement of RD silica gel + water for isobaric temperature jump method. Various grain sizes, boundary condition effects, mono and multi-layer configurations are studied in detail
	Freni et al. [8], Mitra et al. [10], Chakraborty et al. [11]	Numerical study of coupled heat and mass transfer of loose silica gel grains in mono and multi-layer configurations. Optimum configuration which leads to maximum cooling capacity has been determined
System level studies	Suzuki and Sakoda [12]	Development of a small scale apparatus having a columnar packed silica gel (type A) bed to simulate an actual adsorber chiller. A lumped heat and mass transfer model also has been presented
	Chua et al. [13], Liu et al. [14], Ng. et al. [15], Mitra et al. [16]	Transient studies of single-stage adsorption systems through experimental and/or simulation means. The effect of operational parameters on system performance has been investigated in detail
	Saha et al. [17], Mitra et al. [18,19]	System performance and bed transience studies for two-stage adsorption systems
	Mitra et al. [20]	Design of a laboratory scale two-stage multi-bed adsorption system. Adverse effect of vapour flow resistance on system throughput has been experimentally evaluated
Adsorber heat exchanger studies	Alam et al. [21]	Modelling the effects of heat exchanger design parameters like number of transfer units, fluid channel radius, adsorbent thickness, etc. on the system performance
	Ilis et al. [22]	Numerical studies on heat and mass transport in an annular bed with radial fins by assuming uniform pressure within the bed
	Niazmand and Dabzadeh [23]	Two-dimensional numerical study of heat and mass transport in an annular finned heat exchanger. The study has taken pressure non uniformity also into account. System performance indicators have been compared for various fin configurations
	Mahdavikhah and Niazmand [24]	Three-dimensional simulation of a plate finned heat exchanger. The effect of fin height and spacing on system performance has been investigated