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Transient and conjugate heat and mass transfer in hexagonal ducts with adsorbent walls

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ABSTRACT

Honeycomb type adsorbent beds, either in the form of cycling adsorbent beds, or in the form of rotary wheels, are increasingly used in air purification, dehumidification, and energy recovery, etc. The temporal behaviors of operation require a dynamic analysis of the heat and mass transfer in the elementary ducts in the wheels or beds. In this paper, the transient heat and mass transfer in the honeycomb adsorbent ducts of hexagonal cross sections are studied both numerically and experimentally. The transient equations governing the momentum, energy and mass conservation in the air stream and in the porous solid walls are solved simultaneously as a conjugate problem. The velocity, temperature, humidity and water content contours in the ducts are obtained. The effects of operating time and solid wall thickness on the air side convective heat and mass transfer coefficients are analyzed. Different from traditional steady-state heat transfer tubes, the effects of wall thickness are disclosed here. The Nusselt and Sherwood numbers for the fully developed (both axially and temporally) hexagonal ducts with various wall thickness ratios are obtained. They provide guidelines for future component design and performance optimization of adsorption systems.

1. Introduction

Honeycomb type adsorbents beds are increasingly used in various industries, such as air purification [1], dehumidification [2,3], and energy recovery [4], due to their high specific contact areas (1000 m^2/m^3). They can be operated either as cycling fixed beds [1] or as rotary wheels [2–4]. Small ducts (channels) with porous adsorbent walls are the basic elements to form these beds, as depicted in Fig. 1. Layers of corrugated plates are stacked together to form a bed, where numerous small straight ducts are formed. Air exchanges heat and mass with the wall materials when flowing through these ducts. The duct cross sections can be triangular, sinusoidal, or/and hexagonal. Hexagonal ducts are a common structure, as shown in Fig. 1(c). To assemble such a bed, layers of these corrugated adsorbent plates are stacked together to form the honeycomb type bed, as indicated by the arrows in the figure, from 1(a)–1(c).

Convective heat and mass transfer coefficients in the ducts, which are co-determined by the porous solid walls and the air stream, are the key parameters for performance analysis. Studies of fluid flow and convective heat transfer in simple hexagonal ducts, i.e., the traditional metal tubes of hexagonal cross sections, can be dated back to 1970s [5–7]. They were continuously researched until recently [8–12]. However in these studies only air side transport parameters were studied by assuming uniform temperature or uniform heat flux boundary conditions. The transport phenomena in the solid side were neglected. At the same time, many studies of desiccant wheels investigated the transport phenomena in the solid side, while neglecting air side transfer properties. For instance, Zhang and Niu [13,14] investigated the two-dimensional heat and mass transfer in a desiccant wheel. Zhang et al. [15] simulated the one-dimensional heat and mass transfer in a desiccant wheel. Sphaier and Worek [16,17] investigated the gas diffusion and heat conduction in desiccant wheel channels in wall thickness. Ruivo et al. [18,19] investigated heat and moisture transfer in a single duct in the desiccant wheel with models similar to [13,14]. Antonellis et al. [20] investigated the performance of heat and mass transfer in a desiccant wheel with rotational speed. In all these researches, air side flow was modeled

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Nomenclature

a_a	thermal diffusivity of air (m^2/s)
c_p	specific heat (kJ kg^{-1} K^{-1})
C_s	shape factor for the adsorption isotherm
D	diffusivity (m^2/s)
D_h	hydrodynamic diameter (m)
f	friction factor
h	convective heat transfer coefficient (kW m^{-2} K^{-1})
k	convective mass transfer coefficient (m/s)
k'_m	internal mass transfer coefficient based on humidity difference (1/s)
k_m	internal mass transfer coefficient of adsorbents (1/s)
K_p	partition coefficient [(kg water/kg material)/(kg vapor/kg air)]
L_0	length of duct edge (m)
Le	Lewis number
L_W	overall width of the duct (m)
$\dot{m}$	mass flux (kg m^{-2} s^{-1})
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
q	heat flux (kW m^{-2})
q_{st}	adsorption heat (kJ/kg)
Re	Reynolds number
RH	relative humidity
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
t	time (s)
u	velocity (m/s)
U	velocity coefficient
w	water uptake (kg/kg)
w_{max}	maximum water uptake in wall material (kg/kg)
x	traverse coordinate (m)
y	longitudinal coordinates (m)
z	axial coordinates (m)
z_L	length of duct (m)

Greek letters

β	wall thickness ratio
α	aspect ratio of duct, height/width
ρ	density (kg/m^3)
θ	dimensionless temperature
τ	dimensionless time
ν	dynamic viscosity (m^2/s)
ω	humidity ratio (kg moisture/kg air)
μ	kinematic viscosity (Pa s)
λ	thermal conductivity (kW m^{-1} K^{-1})
δ	wall thickness (m)
ε_t	porosity

Superscript

*	dimensionless

Subscripts

0	initial conditions
a	air
ad	adsorption process
b	bulk
c	cooling fluid
cyc	cycle
de	desorption process
eq	equilibrium
gel	silica gel
h	heating fluid
H	uniform heat flux (for heat) or uniform mass flux (for mass) boundary conditions
i	inlet
m	mean
max	maximum
min	minimum
n	normal directions
o	outlet
s	solid
tot	total
T	uniform temperature (for heat) or uniform concentration (for mass) boundary conditions
v	vapor
w	wall, water

with a fully developed slug flow assumption. The effects of solid walls on air side were not considered.

In heat and mass transfer analysis, dimensional heat and mass transfer coefficients are expressed in dimensionless terms by Nusselt (Nu) and Sherwoood (Sh) numbers. Therefore the Nu and Sh data are the critical properties for heat and mass exchanger design. They are highly designed. Traditionally, the air side Nusselt and Sherwood numbers, which are the basic dimensionless data for heat and mass transfer analysis, were directly adopted from the fully developed data for the simple and steady-state metal heat transfer tubes under ideal boundary conditions [5,8]. The effects of coupling between the solid walls and the air streams were neglected. It should be noted that recently several studies in some degree considered the interactions between the porous solid walls and the air streams. For example, Al-Sharqawi and Lior [21,22] investigated the transient transport properties in channels formed by packed adsorbent pallets for desiccant dehumidification. The wall properties were coupled to the air flow to calculate the temperature and concentration contours in the developing regions. However, only parallel plates and triangular ducts were calculated. Further, even for these very simple duct geometries, the Nusselt and Sherwood numbers were not given. They were dimensional and case-sensitive. Little information was provided for system design. From above background review, it can be concluded that the Nusselt and Sherwood numbers for practical hexagonal adsorbents ducts in thermal and mass developing regions under real boundary conditions are highly desired for modeling and optimizing honeycomb type beds or desiccant wheels. They are not available yet.

To address these shortcomings, in this study the transient heat and mass transfer in hexagonal adsorbent ducts are investigated as a conjugate problem. Compared to previous researches, current research has three novelties: (1) the hexagonal duct, one of the most popular duct geometry, is studied; (2) conjugate heat and mass transfer between the fluids and the solids are considered. The real boundary conditions on the walls are obtained. Previous studies neglected the influences of solid walls on air side heat and mass transfer, which makes calculation erroneous. The major challenges are that numerical models for both air streams and the solid should be solved together. This is a conjugate problem. Further, boundary-fitted coordinate system should be used to solve the non-rectangular domain. (3) The temporal behaviors of heat