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Modelling of heat and moisture transfer in desiccant packed bed utilizing spherical particles of clay impregnated with $CaCl_2$

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HIGHLIGHTS

- Three models are developed for heat and mass transfer in clay + $CaCl_2$ packed bed.
- The numerical results are compared with the experimental data from literature.
- The diffusivity is estimated by comparing the numerical results with experimental data.
- The adiabatic diffusion model showed the best agreement with experimental data.
- Maximum absorbent ratio of $0.09 kg_{CaCl_2} kg_{clay}^{-1}$ provides a maximum adsorbed mass per kg of desiccant.

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ABSTRACT

Desiccant packed beds of clay particles impregnated with $CaCl_2$ (clay + $CaCl_2$) are employed for air dehumidification in different applications. For such beds, three mathematical models are developed for heat and moisture transfer, namely; isothermal, adiabatic and adiabatic diffusion. The models are solved numerically by finite difference method. In order to examine the accuracy of the developed models, the numerical results are compared with the available experimental data. The diffusivity of clay + $CaCl_2$ particles is identified. In addition, the effect of the absorbent ratio on the bed operation is investigated numerically.

1. Introduction

The process of air dehumidification is shared by many practical applications like, air conditioning, food industry, water desalination and water extraction from air. Recently, desiccant systems have been utilized as an alternative for the commonly used refrigeration based dehumidification systems. The design and development of desiccant dehumidification systems have attracted much of the researchers' interest [1,2]. Investigations of heat and moisture transfer processes were conducted for different configurations of desiccants (e.g., vertical packed bed [3,4], vertical fluidized bed [5], inclined fluidized bed [6], radial flow packed bed [7,8] and rotating desiccant wheel [9]). In the same context, many researches were carried out for new desiccant material. Heat and mass transfer in a corrugated dehumidifier matrix using four materials as alternative desiccants were investigated experimentally [10]. The use of polyvinyl alcohol foam and polyvinyl alcohol/silica gel/molecular sieve composite as a desiccant material was studied numerically [11]. While, Lee and Lee [12] studied the sorption characteristics of a new polymer desiccant named super desiccant polymer (SDP). On another hand, Aristov et al. [13] and Dawoud and Aristov [14] developed desiccant material by impregnating a host porous material with hygroscopic salt. Composites of $CaCl_2$, LiBr, and different types of silica gel can adsorb up to 0.75 g H_2O per 1 g of the dry sorbent [13]. The kinetics of water sorption on mesoporous silica gel and alumina in comparison with the two composites SWS–1L and SWS–1A formed by impregnating these host matrices with $CaCl_2$ was studied experimentally [14]. Moreover, Saha et al. [15] studied the thermophysical properties of $CaCl_2$–silica gel as a composite desiccant. A detailed review of the composite desiccants and working pairs in desiccant cooling cycles can be found in Refs. [16,17].

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Nomenclature

A	cross section area [m^2]
a	volumetric surface area [m^{-1}]
C	air absolute humidity [kg m^{-3}]
c	specific heat capacity [kJ kg^{-1} K^{-1}]
D	diffusivity [m^2 s^{-1}]
d	diameter [m]
dv	incremental volume [m^3]
HA	heat of adsorption [J kg_w^{-1}]
h	convictive heat transfer coefficient [W m^{-2} K^{-2}]
h_m	convective mass transfer coefficient [kg m^{-2} s^{-1}]
L	height [m]
$\dot{Q}$	flow rate of air [m^3 s^{-1}]
Re	Reynolds number
RH	relative humidity
r	radius [m]
T	temperature [°C]
t	time [s]
W	bed water content [kg_w m^{-3}]
W_P	Intra particle water content [kg_w kg_d^{-1}]
X	salt concentration [kg_{CaCl_2} $kg_{solution}^{-1}$]
y	axial position in the bed [m]
Greek	
α	solution ratio [$kg_{solution}$ kg_{clay}^{-1}]
β	absorbent ratio [kg_{CaCl_2} kg_{clay}^{-1}]
ε	porosity
λ_{eff}	effective thermal conductivity [Wm^{-1} K^{-1}]
ρ_b	bed density [$kg_{clay+CaCl_2}$ m^{-3}]
v	superficial velocity of air stream [m s^{-1}]
Subscripts	
0	initial condition
a	air side property
b	bed side property
d	desiccant (clay + $CaCl_2$)
i	inlet
e	outlet
P	particle
v	water vapour
w	water

Hamed [18] pioneered the use of composite desiccant of clay + $CaCl_2$ particles, and investigated it performance theoretically and experimentally. The theoretical model assumed isothermal processes and a uniform air humidity throughout the bed. Tretiak and Abdallah [19] proposed empirical relations of moisture accumulation during adsorption and desorption processes in packed bed of clay + $CaCl_2$ particles. In addition, Hiremath and Kadoli [20] investigated the transient characteristics of moisture adsorption on clay + $CaCl_2$ particles in a vertical packed bed, and. presented a theoretical model based on the pseudo gas side resistance [21].

However, numerical simulation of heat and moisture interactions between air stream and the particles in a desiccant bed provides useful insight into the dynamics of the bed and its performance characteristics. To the best of our knowledge, the modelling of heat and moisture transfer in a packed bed utilizing particles of clay + $CaCl_2$ considering the intra-particle moisture diffusion has not been investigated so far. Furthermore, it is strongly believed that the intra particle moisture diffusion should be considered for better simulation of such transport processes. Hence, in the current study, three different mathematical models for heat and moisture transfer in packed bed of clay + $CaCl_2$ particles are presented. These models are isothermal, adiabatic and adiabatic diffusion. The isothermal model neglects the effect of heat of adsorption, while the adiabatic model abandons the intra-particle moisture diffusion, on another hand, the adiabatic diffusion model considers the intra-particle moisture diffusion. Experimental data collected from previous work [18–20] are used to obtain the diffusivity in the desiccant particle and to validate the theoretical models. Moreover, the effect of the absorbent ratio, (i.e. the mass ratio of $CaCl_2$ to clay particles), on the performance of the bed is investigated numerically.

2. Mathematical modelling

The physical model for the packed bed of clay + $CaCl_2$ is illustrated in Fig. 1. Through such beds, the desiccant material partially adsorbs the moisture content of the flowing air in transient heat and moisture transfer processes. This adsorption process is accompanied by a significant release of heat, which leads to a strong coupling between heat and moisture transfer processes. The mathematical models are developed considering the following assumptions:

1. Pressure drop across the bed is small that it has a negligible effect on properties of the air stream.
2. Air velocity is uniform along the radial direction, and the flow is in the axial direction only.
3. Average bed porosity is assumed at all locations in the packed bed.
4. Water vapour is the only adsorbable species in the air stream.
5. Heat and moisture transfer processes take place only by forced convection to or from the air stream.
6. Moisture diffusion in the spherical clay + $CaCl_2$ particle takes place only in the radial direction.

The clay + $CaCl_2$ particles are prepared by immersing the spherical dry clay particles in a pool of a $CaCl_2$ solution with an initial concentration of 0.5 $kg_{CaCl_2} kg_{solution}^{-1}$ for 24 h [18]. Applying the gravimetric analysis for the obtained desiccant particles, the water content is obtained as follows,

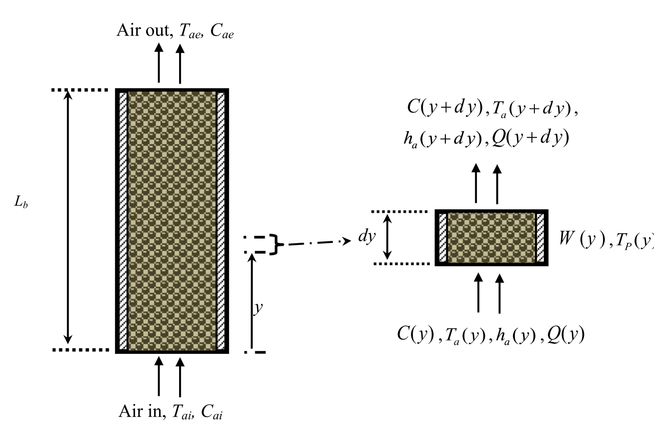

Fig. 1. Physical model of clay + $CaCl_2$ bed during adsorption/desorption processes.