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Research Paper

Modelling and experimental analyzes on air-fluidised silica gel-water adsorption and desorption

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HIGHLIGHTS

- Method for prediction of silica gel-water adsorption in fluidised beds is proposed.
- Extensive experimental research to validate the modelling method is carried out.
- Mass transfer controlling mechanism during desorption is intra-particle diffusion.
- Pressure drop depends only on diameter and density of air-fluidised particles.
- Novel method is reliable especially for desiccant particles smaller than 3 mm.

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ABSTRACT

In this paper a novel modelling method for performance prediction of silica gel-water adsorption and desorption air-fluidised systems is presented. The mathematical model describing these phenomena was developed and extensive experimental research was carried out to validate the model. Experiments were performed for desiccant particles diameters in the range of 1–5 mm, air superficial velocities in the range of 2.3–6.2 m s^{-1} and inlet temperatures in the range of 17–72 °C. Main statements of the model were experimentally confirmed, namely during adsorption the mass transfer controlling mechanism is air to air film convection while during desorption it is intra-particle diffusion. Developed model gives reliable results for modelling adsorption and desorption of silica gel-water in air-fluidised systems, especially for desiccant particle diameters smaller than 3 mm. Moreover, superficial velocity, particle diameter and air humidity influence the adsorption and desorption performance. Kinetics of the adsorption and desorption enhance for larger air superficial velocities and smaller particle diameters. Increase of air humidity causes speeded adsorption and slowed desorption.

1. Introduction

Cooling technologies utilizing low-temperature heat instead of electricity, such as adsorption [1], desiccant [2] and fluidised desiccant coolers are nowadays considered as alternatives to vapor compression cooling. R&D works on adsorption [1] and desiccant cooling [2] devices are proceeding since the beginning of XXth century, and these technologies are currently well developed and widely described in the literature. Fluidised desiccant cooling is still on the early stage of technical development. It is expected to be cheaper than low-pressure adsorption cooling and it was reported to be more effective than fixed bed desiccant cooling [3]. The main component of fluidised desiccant cooler is fluidised dehumidifier in which the air dehumidification process is carried out. The design concepts of fluidised dehumidifiers were presented in Refs. [4–7]. The key to further development of fluidised desiccant cooling systems is the development of the reliable modelling methods of dehumidification process. The chaotic nature of fluidisation makes its modelling difficult. The results of modelling works on this phenomena were presented in Refs. [8,9,3]. The modelling of mass transfer in confined fluidised bed, including the consideration of resistances associated with internal and external diffusion and kinetics of adsorption was presented in [8]. However, this modelling method was not validated experimentally. Another method [9] was developed basing on a modification of model dedicated for fixed-bed dehumidification process [10]. This model

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Nomenclature

Symbols

a_{sor}	specific surface of sorbent ($m^3\ kg^{-1}$)
A_{sor}	surface of sorbent ($m^3\ kg^{-1}$)
c	specific heat ($J\ kg^{-1}\ K^{-1}$)
d_p	desiccant particle diameter (m)
D	intra particle diffusion ($m^2\ s^{-1}$)
D_0	maximum intra particle diffusion ($m^2\ s^{-1}$)
D_{bed}	fluidised bed diameter (m)
E	energy of activation ($J\ K^{-1}$)
g	gravitational acceleration ($m\ s^{-2}$)
h_m	mass transfer coefficient ($kg\ m^{-2}\ s^{-1}$)
h_{th}	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_{ads}	heat of adsorption ($J\ kg^{-1}$)
H_{bed}	height of sorbent column (m)
K_0	adsorption equilibrium constant ($kg\ kg^{-1}\ kPa^{-1}$)
$\dot{m}_a$	air mass flow ($kg\ s^{-1}$)
M_{sor}	mass of sorbent in fluidised bed (kg)
p_{eq}	equilibrium pressure (kPa)
R	Universal gas constant ($J\ mol^{-1}\ K^{-1}$)
R_w	individual gas constant of water ($J\ kg^{-1}\ K^{-1}$)
t	time (s)
T	temperature (K), (°C)
U	air superficial velocity ($m\ s^{-1}$)
V_a	air control volume (m^3)
V_{bed}	volume of sorbent column (m^3)
V_p	volume of sorbent without voids (m^3)
W_{sor}	water uptake of sorbent ($kg\ kg^{-1}$)
W_{eq}	equilibrium water uptake of sorbent ($kg\ kg^{-1}$)
X_a	air humidity ($kg\ kg^{-1}$)
X_{a-p}	air humidity at the surface of particle ($kg\ kg^{-1}$)
ε_0	theoretical voidage of packed bed
$\varepsilon_{d/D}$	voidage in finite container
ε_ϕ	voidage of nonspherical particles bed
ε_f	voidage of fluidised bed
μ	dynamic viscosity ($Pa\ s^{-1}$)
ρ	density, bulk density ($kg\ m^{-3}$)
ρ	density of the particle ($kg\ m^{-3}$)
Ar	archimedes number
Le	Lewis number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
a	air
bed	bed
dry	dry
f	fluidised
h	humid
in	inlet
mf	minimum fluidisation
out	outlet
p	particle
sor	sorbent
v	vapor
w	water

included the porosity distribution along the bed and it was validated experimentally for adsorption. Porosity distribution was found to be irrelevant parameter. The models enabling predicting the pressure drop in fluidised bed and its adsorption performance were presented in [3]. In these models it was assumed that air to air film mass convection is controlling mechanism during adsorption and desorption. However, the reliability of these models is questionable as only a few experimental data related to adsorption were presented. This brief literature review clearly indicates that the modelling works on air-fluidised silica gel-water adsorption and desorption were proceeded by different researchers, few models are available, however any of the proposed models was found to be reliable for predicting both the adsorption and desorption performance. In this paper a novel modelling method of predicting the pressure drop together with the adsorption and desorption performance is presented. The model was validated through an extensive experimental study which was carried out on the laboratory test-stand. Obtained experimental results showed a good agreement with the modelling results.

2. Modelling

The model was derived and implemented in PYTHON programming language basing on the following assumptions:

(1) The temperatures of the air and the desiccant are uniform throughout the fluidised bed, due to rigorous mixing [11]. Moreover, the air humidity and the desiccant water uptake are uniform. Due to the mentioned uniformity, discretization of space is not applied. The fluidised bed is calculated at once in a single time step.
(2) The mass transfer controlling mechanism during adsorption is air to air film convection. The air film maintains equilibrium with the desiccant particle [5,12]. Intra-particle diffusion is mass transfer controlling mechanism during desorption [13–15].
(3) Mass transfer coefficient during adsorption is calculated basing on analogy between heat and mass transfer (known as Chilton Colburn analogy) comprehensively described in [5,16].

Fig. 1 shows a scheme of fluidised bed. Silica gel is enclosed within vertical tube. Metal wire screens placed at the bottom and at the top of the tube prevents silica gel from flowing out of the tube. The stream of humid air flows to the tube through the inlet in the bottom. When superficial velocity of the air in the tube reaches the minimum fluidisation velocity, the particles of silica gel become fluidised. Fluidisation intensifies the processes of heat and mass transfer, ensures rigorous particles mixing [11] and provides the pressure drop reduction (compared to fixed bed systems) [5]. When the tube is supplied with cold air, silica gel adsorbs the moisture contained in the gas. When the tube is supplied with hot air, silica gel desorbs the moisture to the surrounding air (humidification, regeneration of the desiccant). Adsorption (dehumidification) and desorption (humidification) last until equilibrium between desiccant and surrounding air is obtained. Modelling of adsorption and desorption under fluidised conditions involves energy (Eqs. (1) and (2)) and mass conservation (Eqs. (3)–(5)) equations.

$$V_a\rho_a c_a dT_a = (\dot{m}_{a,dry}c_a((1+X_{a,in})T_{a,in} - (1+X_{a,out})T_{a,out}) - h_{th}M_{sor}a_{sor}(T_{a,i} - T_{sor,i}))dt \quad (1)$$