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Parametric study on silica gel regeneration by hot air combined with ultrasonic field based on a semi-theoretic model

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A B S T R A C T

To improve the adaptability of the proposed semi-theoretic model in our previous paper (Ref. [1]), the equations of heat and mass transfer coefficient dependent on the regeneration temperature, the air flow rate, the ultrasonic power and frequency are formulated based on a series of experimental data. The semi-theoretic model with the empirical equations of heat and mass transfer coefficient has been validated by experiments. Afterward, the ultrasonic-assisted regeneration for a silica gel packed bed is simulated with the theoretic model under a wide range of conditions, i.e., the inlet air temperature and humidity ranges from 35 to 80 °C and from 0.01 to 0.035 kg/(kg dry air), respectively; the regeneration air flow rate from 0.1 to 1.5 m/s; the acoustic frequency from 20 to 35 kHz combined with the power from 20 to 80 W; the particle size of silica gel in the bed from 1.0 to 7.0 mm. The key variables during the ultrasonic-assisted regeneration are then investigated based on the simulation data, including the acoustic pressure distribution and corresponding oscillation velocity induced in the packed bed, the temperature and moisture ratio distribution in the packed bed and the enhancement of silica gel regeneration brought by ultrasound.

1. Introduction

The desiccant regeneration is the core link of air dehumidification with the adsorption/absorption method which is considered admittedly to be superior to the cooling dehumidification method in terms of energy efficiency. The regeneration method has great influence on the energy performance of desiccant system. The conventional heating method for the regeneration is found to be energy-wasting if the requirement of regeneration temperature of desiccant is high. To improve the regeneration efficiency of the traditional desiccants under the lower regeneration temperatures, a new regeneration method with ultrasound (non-heating method) is put forward and studied in recent years [1–5]. The mechanical effect of ultrasound causes a series of rapid and successive compression. It can reduce thickness of boundary layer near surface of solid desiccants and bring about the enhancement of mass transfer during the regeneration. Meanwhile, the ultrasonic heating effect causes a temperature rise in solid desiccants and enhances moisture diffusivity inside known as 'rectified diffusion'. To further improve the performance of the new regeneration method and have a better application in the real situations, it is necessary to develop an appropriate model to describe the process of regeneration assisted by ultrasound. By using the model, an overall parametric analysis can be made instead of numerous experiments with high cost of man power and material resources. As well known, only small number of parameters, like the exit air conditions (temperature and humidity) and the total mass of moisture desorption over a period of time, can be measured conveniently through experiments. In addition, the conditions for the experimental study are very limited, which make it difficult to describe comprehensively the regeneration process at any complicated conditions through experiments. In the previous paper [1], a semi-theoretic model for the ultrasonic-assisted regeneration has been developed However, some key coefficients in the model, i.e., the heat and mass transfer coefficient, are required to be determined under a wider conditions to make the model more generalized.

In the present study, the heat and mass transfer coefficients (which is dependent on the regeneration temperature, the air flow rate, the ultrasonic power and frequency) in the semi-theoretical

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Nomenclature

a_c	ultrasonic absorptivity by media
c	specific heat, J/(kg °C)
cosh	hyperbolic cosine function
cos	cosine function
d	diameter, m
ER	enhanced ratio (ER) of regeneration brought by ultrasound
G	mass flow rate, kg/m^2 s
H_{ads}	adsorption heat of moisture on the silica gel, kJ/(kg water)
h_a, h_b	undetermined parameters in the heat transfer equation
H_m	coefficient of heat transfer, W/(m^2 °C)
i	unit of the imaginary number
I	sound intensity, W/m^2
k	sound wave number
k_a, k_b	undetermined parameters in the mass transfer equation
K_m	coefficient of mass transfer, kg/(m^2 s)
m	mass, kg
MR$_o$	initial moisture ratio in silica gel, kg
MRS	mean regeneration speed, g/s
p	pressure, Pa
q	moisture ratio in media, kg/(kg dry medium)
R	dynamic flow resistance
Re	Reynolds number
S_b	volumetric surface area in the packed bed, m^2/m^3
sinh	hyperbolic sine function
sin	sine function
t	temperature, °C
UP	ultrasonic power, W
UF	ultrasonic frequency, W
u	velocity, m/s
V	volume of the packed bed, m^3
w^*	humidity of air on the surface of solid, kg/(kg dry air)
w	humidity of air in the main stream, kg/(kg dry air)
x	along the transverse direction of the bed
y	along the axial direction of the bed
z	acoustic impedance in media, Pa s/m^3

Greek letters

ν	dynamic viscosity of fluid medium, Pa s
α	ultrasonic attenuation coefficient in media
ε	fraction of volume that is not occupied by the solid (also called void fraction)
ω	acoustic angular frequency
λ	coefficient of thermal conductivity, W/m °C
ρ	density, kg/m^3
η_T	electromechanical conversion efficiency of ultrasonic transducer, usually $\eta_T = 0.8$
τ	time, s
ϑ	tortuosity factor of the packed bed
δ	specific heat ratio

Subscripts

a	air
e	equivalent size of pore in the packed bed
in	inlet regeneration air of bed
m	mean value
o	on the radiation surface of ultrasonic transducer or initial value
p	at constant pressure
qb	saturated water vapor
v	water vapor
s	solid phase
gel	silica gel
u	in the presence of ultrasonic radiation; or induced by ultrasound; or ultrasound

model are formulated based on a large number of experimental data. Afterward, the ultrasonic-assisted regeneration for a silica gel packed bed is simulated with the semi-theoretic model, and the following objectives are formulated based on the simulation results:

①. Investigate the acoustic pressure distribution and corresponding oscillation velocity in the packed bed considering the acoustic frequency and power, the particle size and the inlet air temperature.
②. Investigate the temperature and moisture ratio distribution in the packed bed under different acoustic frequencies and power levels.
③. Investigate the enhancement of silica gel regeneration assisted by ultrasonic under different conditions including the acoustic frequency and power, the inlet air conditions (temperature and humidity), the air flow rate, the particle size, the mass load and the initial moisture content in the silica gel.

2. Model and method

2.1. Basic equations

The model describing the ultrasonic-assisted regeneration has been developed mainly based on the fundamental theory of heat and mass transfer and the ultrasonic wave propagation in porous media. The physical model is presented in Fig. 1. The air passes through the bed in horizontal direction (x), and the ultrasound waves propagate along the in vertical direction (y). Equations relevant to the heat and mass transfer of silica gel packed bed during the regeneration process can be summarized as below [1]:

$$(1-\varepsilon)\rho_s c_s \frac{\partial t_s}{\partial \tau} = H_m S_b (t_a - t_s) - H_{ads} K_m S_b (w_s^* - w_a) + \frac{a_c \eta_T I_o}{(1-\varepsilon)V} \tag{1}$$

$$-(1-\varepsilon)\rho_s \frac{\partial q_s}{\partial \tau} = K_m S_b (w_s^* - w_a) \tag{2}$$

$$\rho_a c_{p,a} u_a(x) \frac{\partial t_a}{\partial x} = H_m S_b (t_s - t_a) + K_m S_b c_{p,v} (w_s^* - w_a)(t_s - t_a) \tag{3}$$

$$\rho_a u_a(x) \left(-\frac{\partial w_a}{\partial x}\right) = (1-\varepsilon)\rho_s \frac{\partial q_s}{\partial \tau} \tag{4}$$

Eqs. (1) through (4) correspond to the energy and moisture conservation of the solid and gas media in the bed, respectively.

Equations relevant to the ultrasonic wave propagation in the porous media are listed as follows: