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Mechanism study on the enhancement of silica gel regeneration by power ultrasound with field synergy principle and mass diffusion theory

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ABSTRACT

The enhancement of silica gel regeneration by power ultrasound has been validated by a series of experiments in our previous studies, but there still lacks theoretical basis for illustrating its mechanism. In this paper, the mechanism of ultrasound-enhanced regeneration has been explored. Firstly, the benefit of ultrasonic mechanical effect to the enhancement of regeneration has been illustrated by the field synergy principle. The average synergy degree ($\bar{\kappa}$, only considering intersection angle between the velocity and the temperature gradient) and the average overall synergy degree ($\bar{\kappa}_{overall}$, considering local values of velocity and temperature gradient based on $\bar{\kappa}$) in terms of the near wall region are suggested for analysis, and they are obtained based on the *k*–omega model which is suitable for the near wall free-shear flow velocity predicting. Results manifest that the ultrasonic mechanical effect can significantly enlarge the synergy degrees between the temperature and the velocity field around the particle, and this can be used to explain the enhancement of convective heat and mass transfer on the gas side due to the mechanical effect of ultrasound. Afterwards, a moisture diffusion model is developed to investigate spatial distributions of moisture ratio and temperature in a silica gel particle as well as its surface equilibrium humidity during the regeneration with and without ultrasound. Results show that ultrasonic heating effect can lead to an increase in the average temperature and moisture diffusivity in the silica gel particle, and this confirms the contribution of ultrasonic heating effect to the enhancement of silica gel regeneration.

1. Introduction

Silica gel has been utilized for dehumidification processes in industrial and residential applications due to its great pore surface area and good moisture adsorption capacity [1–3]. Generally, process air flows through the silica gel bed, and the moisture in the air is absorbed by the silica gel. After the silica gel is saturated with moisture, it needs to be regenerated (i.e., moisture removal) for recycling. The thermal heating method is a traditional way for regenerating the desiccants. But, such regeneration method is of poor energy efficiency, especially for the desiccants with a relatively higher regeneration temperature. This is because, on one hand, the higher regeneration temperature is not good for the utilization of lower-grade thermal energy (e,g., solar energy, waste heat), and on the other hand, it will result in more energy dissipation and loss. Thus, we often expect the regeneration temperature to be as low as possible during the applications of desiccants like silica gel. For such reason, some non-thermal methods have been developed for the desiccant regeneration, e.g., the use of pulsed corona plasma [4], pulsed vacuum [5], centrifugal forces [6], and electrical fields [7–9]. These non-thermal methods can definitely improve the kinetics of heat and mass transfer during the regeneration of desiccant, and hence, help to decrease the regeneration temperature to some extent. Another new regeneration method by using power ultrasound has been put forward recently. A series of studies [10–13] manifest that the way of applying ultrasound in silica gel regeneration process can distinctly increase the regeneration rate and become a promising non-thermal regeneration method. As shown in Fig. 1, the mechanism of enhancement of regeneration by power ultrasound may be qualitatively illustrated as below:

(1) The special effect of mechanical vibration induced by the high-intensity ultrasound helps to intensify the fluid turbulence near the solid medium and reduce the thickness of boundary layer on the gas–solid interface, and this will decrease the external resistance of heat and mass transfer.

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Nomenclature

a	energy absorption coefficient
c_p	specific heat capacity, J/(kg °C)
d_p	average pore size in silica gel, m
D	diffusivity, m^2/s
f	acoustic frequency, H_z
H_{ads}	adsorption heat of silica gel, J/kg
HF	heat flux, W/m^2
j	imaginary number
k	turbulent kinetic energy, m^2/s
K	sound wave number,
m	mass, kg
$\dot{m}$	mass diffusion rate, kg/(m^2 s)
Nu	Nusselt number
p	pressure, *Pa*
Pr	Prandtl number, dimensionless
q	moisture ratio, kg/(kg drysample)
r	distance, m
r_s	radius of silica gel particle, m
Re	Reynolds number, dimensionless
P	power of ultrasound, *W*
S_r	wave surface area at the distance of r from center of silica gel particle, m^2
T/t	temperature, K/°C
$\bar{T}$	dimensionless temperature
u	velocity, m/s
$\vec{u}$	fluid velocity vector, m/s
$\bar{\vec{u}}$	dimensionless fluid velocity vector
V	near wall region
w	humidity, kg water/(kg dryair)
w^*	surface equilibrium humidity of silica gel, kg water/(kg dryair)
x_i	cartesian coordinates

Greek symbols

α_m	convective mass transfer coefficient, m/s
λ	thermal conductivity, W/(m °C)
δ	thermal boundary layer thickness, m
ε	porosity
∇T	temperature gradient, K
$\nabla \bar{T}$	dimensionless temperature gradient, K
θ	field synergy angle between velocity vector and temperature gradient, degree
ρ	density, kg/m^3
φ^*	surface relative humidity of silica gel, %
ϖ	specific dissipation, 1/s
κ	local synergy degree, dimensionless
$\bar{\kappa}$	average synergy degree, dimensionless
$\bar{\kappa}_{overall}$	overall synergy degree, dimensionless
μ	molecular dynamic viscosity, kg/(m s)
μ_t	turbulent eddy viscosity, kg/(m s)
ω	angular frequency, $\omega = 2\pi f$, rad/s
τ	time, s

Subscripts

a	moist air or on the gas side
atm	standard atmosphere
eff	effective
H_2O	water molecule
i	current spatial grid point
N	number of spatial grids in silica gel particle
s	silica gel particle
sv	water vapor in the saturated air
vib	vibration
U	in the presence of ultrasound
NU	in the absence of ultrasound
ult	ultrasound
w	wall surface
∞	value at great distance from a body

Superscripts

n	current time point
0	initial condition

(2) The heating effect of ultrasound leads to a temperature rise of medium, and this will increase the internal moisture diffusion in the solid desiccants.

The above mechanisms have been used to explain the experimental results on the ultrasound-assisted regeneration and develop corresponding models [10–13]. But, the mechanisms still lack of theoretical basis. In this paper, the mechanisms of the enhancement of solid desiccant regeneration by power ultrasound are further discussed in a quantitative way. For the first mechanism analysis (i.e., due to the mechanical vibration effect of ultrasound), the field synergy theory is employed; and for the second (i.e., due to the heating effect of ultrasound), the diffusion theory is adopted.

2. Enhancement of regeneration by ultrasonic mechanical effect

2.1. Field synergy principle

Many studies on the heat and mass transfer enhancement mostly focused on the heat and mass transfer coefficient which reflects the convection intensity between fluid and solid wall [14–17]. Although the heat and mass transfer coefficients can be often used to analyze some key variables (like the fluid velocity and temperature difference) that affect the heat and mass transfer rate, they can not reveal the mechanism of the heat and mass transfer enhancement. The theory of boundary layer (known as the layer of fluid in the immediate vicinity of a bounding surface where the effects of viscosity are significant) is often employed to study and explain the phenomena of heat and mass transfer enhancement [18–22]. It has been considered that the resistance of heat and mass transfer mostly happens within the boundary layer. However, the mechanism analysis based on the layer boundary theory is only qualitative since the boundary layer thickness is very difficult to obtain in most cases, particularly for the situations where the vibration is used for the heat and mass transfer enhancement.

In 1998, Guo et al. [23] first proposed a novel concept of optimizing and enhancing convective heat transfer of parabolic flows which is called field synergy principle (FSP). The FSP has been successfully employed to study the relationship between local behavior of heat transfer and heat transfer enhancement and analyze how local behaviors affect the overall thermal performances [24–29]. For example, He et al. [26] employed the field synergy principle to study the effects of the five parameters (i.e., Re number, fin pitch, tube row number, spanwise and longitudinal tube pitch) on the heat transfer performance of the finned tube banks. They found that the enhancement or deterioration of the convective heat