Separation of Ultrasonic Contributions and Energy Utilization Characteristics of Ultrasonic Regeneration

Kun Yang
Institute of Refrigeration and Cryogenics, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

Ye Yao
Institute of Refrigeration and Cryogenics, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

Key Laboratory of Energy Thermal Conversion and Control, Ministry of Education, School of Energy and Environment, Southeast University, Nanjing 210096, China

Shiqing Liu
School of Mathematics and Physics, Zhejiang Normal University, Jinhua, Zhejiang Province 321004, China

Beixing He
Institute of Acoustics, Chinese Academy of Sciences, Beijing 100190, China

DOI 10.1002/aic.14360
Published online January 23, 2014 in Wiley Online Library (wileyonlinelibrary.com)

The method of applying ultrasound to silica gel regeneration process has been proved to be able to improve regeneration efficiency and reduce regeneration temperature. The average regeneration rate can be increased by 10% and the benefits should owe to the special "vibration effect" and "heating effect" induced by ultrasound. In this article, a dynamic one-dimensional mathematical model, validated by experiments, has been developed. It is then used to investigate energy utilization efficiency of the ultrasonic regeneration and respective contribution ratio of the two ultrasonic effects. The results show that the contribution ratio of vibration effect dominates and the energy utilization efficiency of silica gel regeneration with ultrasound can be 1% higher. The ultrasonic regeneration is more energy-saving when the contribution ratio of vibration effect is greater. The results also show that the enhancement of regeneration brought by ultrasound is not a simple sum of their respective contribution. *AIChE J*, 60: 1843–1853, 2014
Keywords: mass transfer, drying, energy, mathematical modeling, porous media

Introduction

Humidity control has been recognized as one of the important technologies in various fields. In a conventional air-conditioning system, air is cooled below dew point temperature to reduce its humidity ratio, and then reheated to the desired supply temperature. The cooling dehumidification method requires the evaporation temperature in the air conditioner being lower than dew point, which greatly decreases the energy efficiency of the air-conditioning system. Therefore, the separation treatment of latent load using an independent desiccant-based air handling unit has attracted more and more attention. Usually, desiccant is used to absorb the water in air before the evaporative cooling process.

Silica gel, as a type of environment-friendly desiccant material, has been major used in desiccant-based air-conditioning systems and cooling systems due to its high moisture adsorption capacity.[1] It requires considerable heat to be regenerated to work repeatedly after saturated with moisture.[2] Due to the releasing of adsorption heat, the temperature of silica gel bed will increase in dynamic adsorbing process. Correspondingly, the required regeneration temperature will be high. The technology, which can decrease the required regeneration temperature, will be attractive for some waste heat sources and solar thermal applications.[3] Researchers have introduced some new methods to the desiccant regeneration process, such as microwaves[4] and electro-osmosis.[5,6] Power ultrasound (between about 20 and 100 kHz, a few tens of Watts), for the induced effects of heating, acoustic cavitation, and acoustic streaming, has been generally used for heat- and mass-transfer processes intensification.[7,8] Gogate et al.[9–12] have made a deep study on different design of large scale sonochemical reactors and a model has been given to help to choose desired equipment.

The mechanism of the regeneration enhancement (RE) brought by high-intensity ultrasonic is depicted in Figure 1. The power ultrasound can cause high frequency vibration of the air near the silica gel (microvibration effect), which leads to turbulence near the surface of silica gel and promotes heat- and mass-transfer process. Meanwhile, part of the

Correspondence concerning this article should be addressed to Y. Yao at yeyao10000@sjtu.edu.cn.

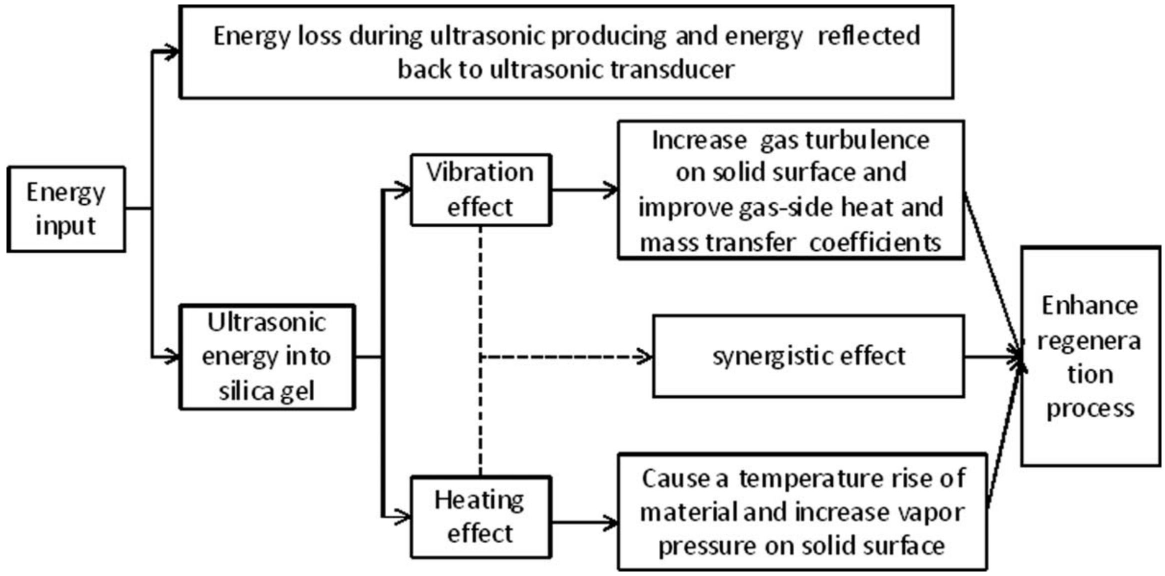


Figure 1. Mechanism of RE brought by high-intensity ultrasound.

ultrasonic energy will be directly absorbed and bring about a temperature rise (heating effect) in the silica gel, which will increase the water vapor pressure in equilibrium with the silica gel. The respective contribution ratio of the two effects to the RE will be discussed in this article to help us further understand the mechanism of RE brought by ultrasound.

In our previous study, we have experimentally investigated the regeneration process of silica gel in a packed bed with ultrasonic radiation. The results have proved that the regeneration efficiency can be significantly improved when the ultrasonic radiation is applied.[13–16] However, the mechanism of the regeneration with high-intensity ultrasonic as well as the energy utilization efficiency has not been investigated. The aim of this article mainly includes the following two parts:

1. Make a quantitative analysis on the contributions of the "vibration effect" and the "heating effect" of the power ultrasonic to the enhancement based on the model simulation;
2. Investigate the energy efficiency of silica gel regeneration assisted by the power ultrasound.

Theoretical Model

A theoretical model of the regeneration characteristics of packed silica gel bed with ultrasound is developed based on the theory of energy and mass conservation. For the convenience of modeling, some assumptions are necessarily to be made as below:

1. The direction of airflows in the bed is only in x direction;
2. The silica gel particle is considered as a rigid nondeformable porous body, and the silica gel has different temperatures and moisture contents with the air flowing in pores;
3. Heat conduction as well as mass diffusion within both air stream and desiccant material is negligible;
4. The latent heat of evaporation of water is assumed to be totally provided by silica gel particles;
5. The inlet conditions of air are uniform in space;
6. The pressure loss of the air stream is negligible;
7. The thermal conductivity and mass diffusion coefficient of air and water vapor are assumed to be constant.

Fundamental equations

The moisture conservation for the regeneration air and the silica gel can be expressed as

$$\rho_a\left(\varepsilon\frac{\partial w}{\partial \tau}+u\frac{\partial w}{\partial x}\right)+(1-\varepsilon)\rho_s\frac{\partial (MR)}{\partial \tau}=0 \tag{1}$$

The first term on the left-hand side of the above equation is the air moisture change caused by airflow movement and the second one represents the change of air moisture content in a control volume. The third term on the left-hand side stands for moisture variation in the silica gel.

The change of the moisture ratio of silica gel can be calculated as

$$-(1-\varepsilon)\rho_s\frac{\partial (MR)}{\partial \tau}=Ka\rho_a(w^*-w) \tag{2}$$

The term on the left-hand side is the moisture change rate in the silica gel and that on the right-hand side is the moisture exchange between air and silica gel.

Energy balance for the drying air flowing through the silica gel bed can be expressed as

$$\rho_a c_{p,a}\left(\varepsilon\frac{\partial t_a}{\partial \tau}+u\frac{\partial t_a}{\partial x}\right)=ha(t_s-t_a)+Ka\rho_a(w^*-w)\cdot c_{p,v}(t_s-t_a) \tag{3}$$

The left-hand side of the equation describes the sensible heat energy storage and the energy change in a control volume. The first term on the right-hand side of Eq. 3 expresses the convective heat transfer between the air and the silica gel. The second term on the right-hand side denotes the sensible heat transfer between the air and the silica gel, which is related to the convective transfer of moisture. Heat conduction in the air is neglected.

By applying the principle of energy conservation to the silica gel, we have

$$(1-\varepsilon)\rho_s c_{p,s}\frac{\partial t_s}{\partial \tau}=ha(t_a-t_s)-H_{ads}Ka\rho_a(w^*-w)+\frac{a_u\delta P_u}{V} \tag{4}$$

The left-hand side of the equation describes the energy storage terms of the silica gel. The first term on the right-hand side is similar to that in Eq. 3. The second term describes the released adsorption heat. And, the last term expresses the acoustic energy absorbed by the silica gel.

Boundary and initial conditions

The initial temperature and humidity ratio of the regeneration air and are assumed to be uniform

$$\tau=0 \quad MR(x,0)=MR_0, \quad t_s(x,0)=t_{s,0}, \quad w(x,0)=w_0, \quad t_a(x,0)=t_{s,0} \tag{5}$$

The temperature and humidity ratio boundary conditions for the air are given as below

$$x=0 \quad w(0,\tau)=w_0, \quad t_a(0,\tau)=t_{a,0} \tag{6}$$

Model parameters

The acoustic energy attenuation coefficient (ξ) in the silica gel bed can be gotten by experiments. Driven by the ultrasonic producer, the ultrasonic transducer produces ultrasound with stable intensity. The acoustic intensity on the other side of tested material can be measured by an ultrasonic receiver. It can be proportionally expressed in the form of voltage on the oscilloscope. And, the experimental data can be fitted by Eq. 7

$$E(z)/E(0)=\exp(-\xi \cdot z) \tag{7}$$

The absorption coefficient of ultrasound (a_u) is also determined by experiments. It is assumed that the acoustic energy absorbed by the silica gel be all converted into heat. And, the amount of acoustic energy absorbed by silica gel can be calculated with respect to the temperature variation of the silica gel. Four thermo-couples are evenly arranged in the thermal insulated silica gel bed to observe the material's surface temperature. The absorption coefficient of ultrasound for the silica gel can be calculated by Eq. 8, and the experimental results are listed in Table 1

$$m_s c_{p,s} \frac{dt_s}{d\tau}=a_u \delta P_{ult} \tag{8}$$

The determination of other parameters has been illustrated in our previous papers[17] and they are shown in appendix.

Data Process

The regeneration rate (R_r) and the average regeneration rates ($R_{r,ave}$) are calculated by Eqs. 9 and 10, respectively

$$R_r=G(w_o-w_i) \tag{9}$$

$$R_{r,ave}=\frac{1}{\tau_f}\int_0^{\tau_f} R_r d\tau \tag{10}$$

where τ_f is the regeneration time required for the moisture ratio of silica gel arriving at MR_f ($\tau_f=\tau_f^{NU}$ for regeneration without ultrasonic and $\tau_f=\tau_f^{U}$ for regeneration with ultrasound).

The RE and the enhancement ratio of average regeneration rate (ERARR) are used to evaluate the effect of ultrasound on the silica gel regeneration

$$RE=R_{r,ave}^{U}-R_{r,ave}^{NU} \tag{11}$$

$$ERARR=\left(\left(R_{r,ave}^{U}-R_{r,ave}^{NU}\right)\Big/R_{r,ave}^{NU}\right)\times 100\% \tag{12}$$

The electricity utilization efficiency (EE) is suggested to investigate the energy efficiency of silica gel regeneration with and without ultrasound, which is defined as below

$$EE=\frac{\left(\int_0^{\tau_f} R_r d\tau\right)\times H_{des}}{P_{ove}\,\tau_f}\times 100\% \tag{13}$$

where P_{ove} is the power input ($P_{ove}^{NU}=P_t, P_{ove}^{U}=P_t+P_{ult}\, P_t=Gc_{p,a}(t_{a,i}-t_{amb})/\eta$). Taking the heat loss of the air duct into account, the efficiency of the electric heating system, η, is estimated as 0.8.

To make a quantitative study on the contribution of vibration effect and heating effect to the RE, the silica gel regeneration process with the separate effect of vibration and heating of ultrasound are simulated, respectively. The RE in the regeneration process with the vibration effect (RE_{veff}) is calculated by assuming the ultrasonic absorption coefficient of silica gel be zero, and the RE in the regeneration process with the heating effect (RE_{teff}) is counted on the assumptions that the vibration of air caused by ultrasound makes no contributions. Then, the contribution ratio of vibration effect and heating effect to the RE can be calculated, respectively, by Eqs. 14 and 15

$$CR_{veff}=(RE_{veff}/RE)\times 100\% \tag{14}$$

$$CR_{teff}=(RE_{teff}/RE)\times 100\% \tag{15}$$

However, we have found in the simulation that the sums of RE_{teff} and RE_{veff} under different regeneration conditions are different and all less than 100%. Guo et al.[18] has raised the field synergy principle and pointed out that the heat- and mass-transfer process is influenced by the synergy degree between velocity field and temperature gradient field. In our study, there may be a synergy effect between vibration effect and heating effect, and the synergy degree between them may be different under different operation conditions. As we know, the regeneration rate is equal to the product of contact area, mass-transfer coefficient, and driving force. Due to the vibration effect and the heating effect, the mass-transfer coefficient and silica gel temperature in the regeneration with ultrasound are greater than that in the regeneration without ultrasound. Part of the temperature rise of silica gel is the result of the adsorption of ultrasound, and the other part is caused by the heat-transfer enhancement (brought by vibration effect). The increase of silica gel temperature will result in the increase of the humidity in equilibrium with silica gel. Therefore, the RE brought by ultrasound can be expressed as

$$\begin{aligned}RR=&(K+\Delta K)aV\rho_a\left(w^*+\Delta w_{teff}^*+\Delta w_{veff}^*-w\right)\\&-KaV\rho_a(w^*-w)=KaV\rho_a\Delta w_{teff}^*\\&+aV\rho_a\left[\Delta K(w^*-w)+K\Delta w_{veff}^*\right]+\Delta KaV\rho_a\Delta w_{teff}^*\end{aligned} \tag{16}$$

Table 1. Results of Acoustic Energy Absorption Experiments

	ΔT_1 (°C)	ΔT_2 (°C)	ΔT_3 (°C)	ΔT_4 (°C)	ΔT_{ave} (°C)	c_s J/(kg K)	P_u (W)	τ (s)	a_u (%)
Silica gel	11.0	3.9	1.3	0.4	4.15	1076	40	180	10.5

where ΔK represents the increase of mass-transfer coefficient brought by vibration effect; Δw^*_{teff} describes the variation of air humidity in equilibrium with the silica gel due to ultrasonic adsorption (heating effect); and Δw^*_{veff} is the variation of air humidity in equilibrium with silica gel caused by heat-transfer enhancement (vibration effect).

The first term of the right-hand side of Eq. 16 expresses the contribution of heating effect, and the second term is the contribution of vibration effect. It is interesting that there still is an extra term ($\Delta K a V \rho_a \Delta w^*_{\text{teff}}$) which is related to both heating effect and vibration effect. We defined the extra term as contribution of "synergistic effect." So, the contribution ratio of synergistic effect is shown as

$$\text{CR}_{\text{syn}} = \Delta K / \left(K + \left(\Delta K \frac{w^* - w}{\Delta w^*_{\text{teff}}} + K \frac{\Delta w^*_{\text{veff}}}{\Delta w^*_{\text{teff}}} \right) + \Delta K \right) \tag{17}$$

Experimental Study and Model Validation

Experimental setup

The schematic diagram of experimental system is presented in Figure 2, and the basic information of the instruments is listed in Table 2. The regeneration air conditions (temperature and humidity) can be adjusted by regulating the input power of the electric heater and the atomizing humidifier. The air flow rate in each subduct is controlled through adjusting the air valves, and measured by a digital anemometer. The frequency of the ultrasound used in the experiment is 23 kHz.

Raw material

The silica gel used in this study has the particle size distribution of 5.0 ± 1.0 mm in diameter. The basic physical properties of the trial sample are as follows: specific surface area = 300–400 m^2/g; pore diameter 8–10 nm; specific pore volume = 0.8–1.0 mL/g. The mass of the wet sample before the regeneration is 195 ± 0.1 g, and the initial moisture ratio is identified as 0.211 kg water/(kg dry silica gel).

Experiment results and model validation

The operating conditions include four inlet air temperatures (40, 50, 60, and 70°C), three inlet air humidity ratios (0.01, 0.015, and 0.02 kg water/DA), two inlet air velocities (0.3 and 0.4 m/s), and two ultrasonic power levels (40 and 60 W). The comparisons of simulated and experimental instantaneous regeneration rates at each minute under these conditions are shown in Figure 3. The discrepancy between the experimental results and simulated data is mostly less than 10%, and larger deviation mostly appears at the beginning or end of the regeneration process when the regeneration rate is small. Overall, the calculated results by the model have a good agreement with the experimental data.

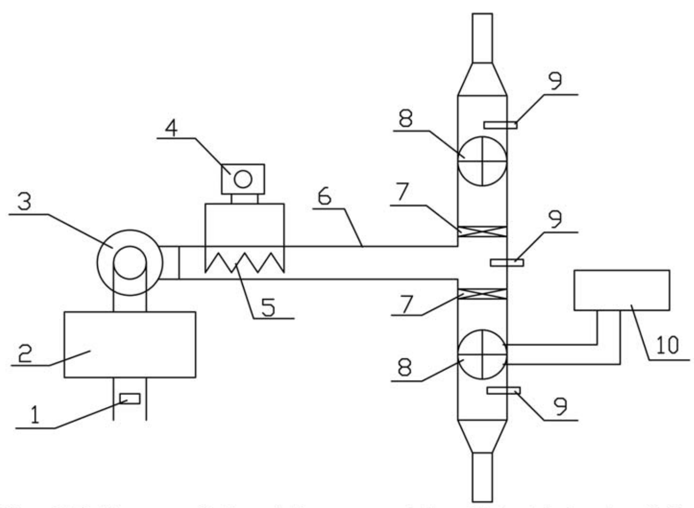
Simulation and Discussions

The temperature, humidity, and velocity of the regeneration air, the ultrasonic power as well as the silica gel moisture ratio at the end of the regeneration (MR_f) are crucial parameters that significantly affect the performance of silica gel regeneration with ultrasound. So, the effects of these parameters on the contributions of ultrasonic to the regeneration and the corresponding energy utilization efficiency are investigated with the model simulations. For the above study cases, the initial and final moisture content of the silica gel are set, respectively, as 0.211 and 0.1 kg/(kg dry silica gel).

Effects of regeneration temperature

The regeneration processes of silica gel with and without ultrasound are simulated under the regeneration temperature ranging from 40 to 100°C. The average regeneration rates and the ERARR vs. the regeneration temperature are plotted, respectively, in Figures 4 and 5. The results show that, with the regeneration temperature increasing, the average regeneration rates with and without ultrasound both increase, the gap between them also grows, and the ERARR decreases. This can be explained by the fact that the mass-transfer driving force $[(w^* - w)]$ becomes larger under higher regeneration temperature; and more RE can be brought about by vibration effect. So, the applying of ultrasound can bring about more RE under higher regeneration temperature.

It can be also found that the effect of applying ultrasound is equivalent to that of increasing the regeneration temperature. As shown in Figure 4, the average regeneration rate under the regeneration temperature of 90°C plus ultrasonic is



1 Humidifier; 2 Buffer case, 3 Fan, 4 Power regulator, 5 Electric heater, 6 Air duct, 7 Air damper, 8 Silica gel container, 9 Temperature & humidity sensor, 10 ultrasonic generator

Figure 2. Schematic diagram of the experimental system.

Table 2. Instruments and Equipments in the Experimental Study

Name	Number	Basic Information	Type/Manufacturer
Digital anemometer	1	±3% of the measured data	VC816/Victor, China
Temperature and humidity sensor	3	±0.8 in relative humidity (%); ±0.1°C in temperature	HHC2-S/OTRONIC, Sweden
Electronic balance	1	±0.1 g in absolute error	BS1500M /Shanghai Yousheng
Ultrasonic producer	1	Produce ultrasonic ranging from 0 to 100 MHz in frequency and 0–300 W in Power	UGD/Taheda Hi-tech Company, China
Ultrasonic transducer	3	Compatible frequency:19 kHz; Maximum power input: 150 W	UGD/Taheda Hi-tech Company, China
Oscilloscope	1	Measurement precision: 2 mV	DS1052E/PuYuan, China
Centrifugal fan	1	Rated power: 800 W; Wind pressure: 700 Pa	SYDF/Shanghai Yingda Fan Company
Air valve	2	DN25	
Atomizing humidifier	1	Atomizing rate: 0.25 kg/h	Shiteng Electronic

even bigger than that under 95°C in the absence of ultrasonic.

Figure 6 gives the contribution ratio of the vibration effect (CR_{veff}), the heating effect (CR_{teff}), and the synergistic effect (CR_{syn}) to the enhancement of regeneration. The results show that the contribution of the vibration effect dominates in the RE brought by ultrasound, and it becomes increasingly significant as the regeneration temperature rises. In contrast, the contribution ratio of heating effect decreases with the increase of regeneration temperature. As seen from Figure 6a, the CR_{veff} increases from 68 to 86.8%, whereas the CR_{teff} decreases from 30 to 12.7% when the regeneration temperature rises from 40 to 100°C. This is because the heat- and mass-transfer driving force becomes larger as the regeneration temperature increases, which will promote the effect of ultrasonic vibration on the regeneration process. Besides, the RE brought by heating effect is less influenced by the regeneration temperature. Thus, the contribution ratio of vibration effect increases with the regeneration temperature increasing.

The results presented in Figure 6b show that the contribution ratio of the synergistic effect (CR_{syn}) decreases as the regeneration temperature rises. When the regeneration temperature grows, the temperature rise of silica gel caused by vibration effect ($\Delta t_{s,veff}$) becomes greater, and that caused by heating effect ($\Delta t_{s,teff}$) stays unchanged. Under the same moisture content, the air humidity in equilibrium with the silica gel (w^*) is only related to the silica gel temperature, so w^* and Δw^*_{veff} increase faster than Δw^*_{teff} when the regeneration temperature rises. As known from Eq. 17, the result of CR_{syn} decreases as the regeneration temperature increases.

To investigate the energy utilization efficiency in the regeneration process with and without ultrasound, the electricity utilization efficiency(EE) against regeneration temperature is plotted in Figure 7. It can safely conclude that the EE_{NU} decreases with the increase of the regeneration temperature. In contrast, the EE_U first increases and then decreases with the regeneration temperature, and it peaks at the temperature of about 60°C. To explain this phenomenon, the definition of electricity efficiency is rewritten as

$$EE = \left(R_{r,ave} H_{des} / P_{ove}\right) \times 100\% \tag{18}$$

For the regeneration process without ultrasound, the overall power input is just equal to the power of air heater ($P_{ove} = P_t$), which increases linearly with the regeneration temperature. As known from Figure 4, the average regeneration rate increases slower than regeneration temperature does. So, the EE_{NU} decreases with the increase of the regeneration

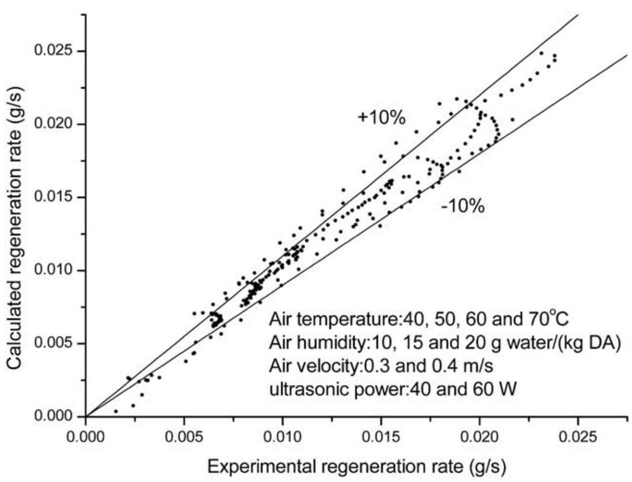


Figure 3. Comparison of predicted and experimental regeneration rates at every minute of regeneration process.

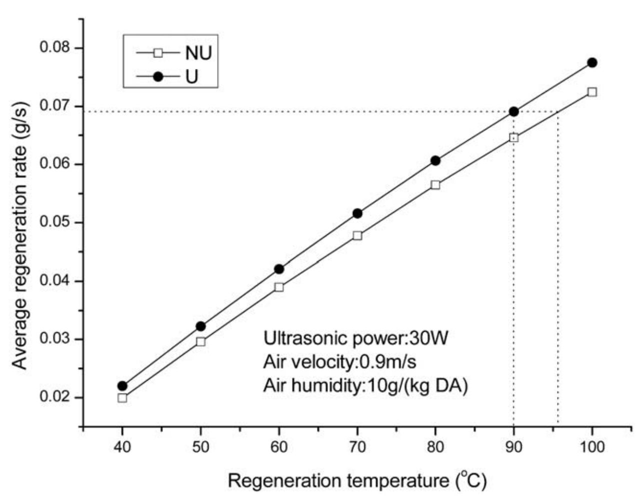


Figure 4. Average regeneration rates under different regeneration temperatures.

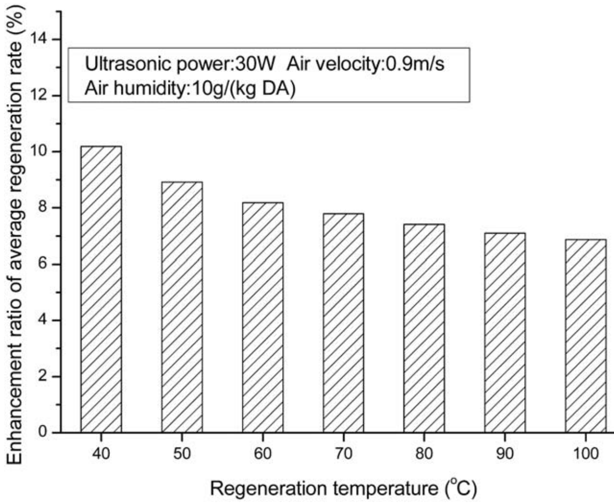


Figure 5. ERARR under different regeneration temperatures.

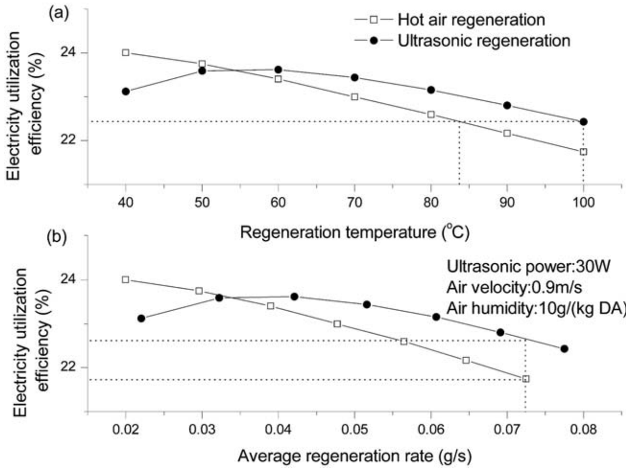


Figure 7. Variation of electricity utilization efficiency under different regeneration temperatures vs. (a) air temperature; (b) average regeneration rate.

temperature. For the regeneration process with ultrasound, the RE brought about by ultrasound is little under lower regeneration temperatures, so the energy utilization efficiency of ultrasound power is small and increases with the regeneration temperature. However, when the regeneration temperature is higher, the power of air heater becomes much larger than that of ultrasonic, and its energy utilization efficiency decreases with the increasing of regeneration power. Therefore, the EE_U first increases and then decreases with the regeneration temperature.

Furthermore, when the regeneration temperature is higher than 55°C, the EE_U becomes higher than the EE_{NU}, and the differences between them grow with the increasing of the regeneration temperature. That is to say, the way of applying ultrasound is more energy-saving at higher regeneration temperature. For example, the EE_U is only about 0.2% higher than the EE_{NU} at the regeneration temperature of 60°C, while the number grows to 0.7% at 100°C. The reason can be explained as that it can produce more RE to intensify heat- and mass-transfer process under higher regeneration temperature.

The electricity utilization efficiency is plotted against average regeneration rate ($R_{r,ave}$) in Figure 7b. It can be found that the EE_U can be almost 0.9% higher than the EE_{NU} when the same average regeneration rate (i.e., 0.072 g/s) is achieved.

Figure 8 shows the temperature of the silica gel at the end of the regeneration process with and without ultrasound. It can be seen that the silica gel temperature regenerated with ultrasound is about 0.2°C lower than that regenerated without ultrasound when the same average regeneration rate is achieved, which is beneficial for the following adsorption process. Therefore, the way of applying ultrasound to the silica gel regeneration process also has its advantages from the perspective of improving the whole dehumidification system performance.

Effects of regeneration air velocity

Figures 9 and 10 present the average regeneration rate and the ERARR under different regeneration air velocities. Obviously, with the regeneration air velocity increasing, the average regeneration rates with and without ultrasound increase

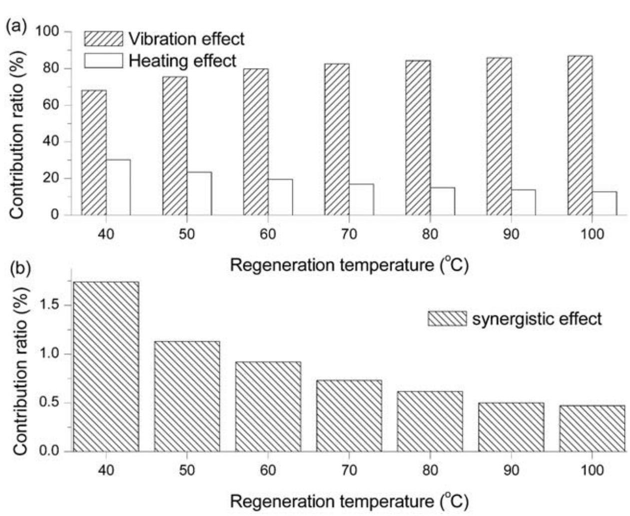


Figure 6. Contribution ratio of (a) vibration and heating effect; (b) synergistic effect; under different regeneration temperatures.

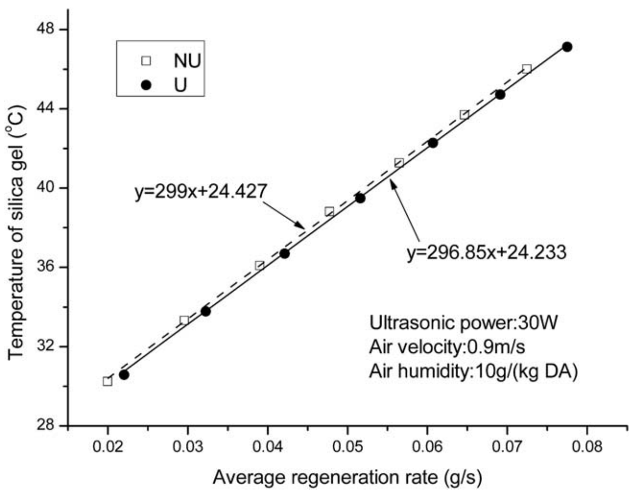


Figure 8. Variation of silica gel temperature under different air temperatures vs. average regeneration rate.

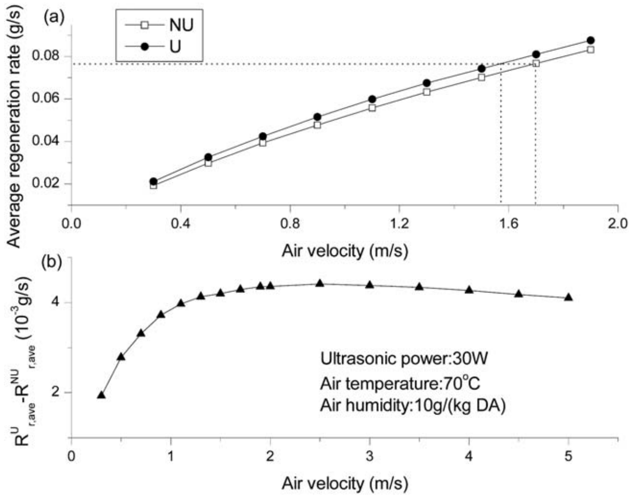


Figure 9. (a) Average regeneration rate; (b) differences between the average regeneration rate with and without ultrasound; under different air velocities.

gradually and the ERARR decreases slowly. Besides, the RE increases rapidly at first, and then decreases slowly. These results may be attributed to the fact that the increase of the regeneration air velocity will bring two influences on the ultrasonic assisted regeneration process: (1) increasing the mass-transfer driving force; (2) decreasing the mass-transfer intensification caused by ultrasound. Under small air speed, the average temperature of silica gel is rather low and the average humidity of the air in equilibrium with silica gel is close to that of regeneration air. As we know, the regeneration rate is proportional to the product of mass-transfer coefficient and mass-transfer driving force (i.e., $R_r = (\rho_a aV)K(w* - w)$). When the driving force is too small, the regeneration rate cannot be greatly improved by enhancing the heat- and mass-transfer process. So, the RE brought by ultrasound is mainly influenced by driving force. Under larger airflow rate, the average temperature of silica gel is higher and the driving force is greater, and the influences of mass-transfer coefficient become more important. The debating of the mass-transfer intensification will decrease the RE

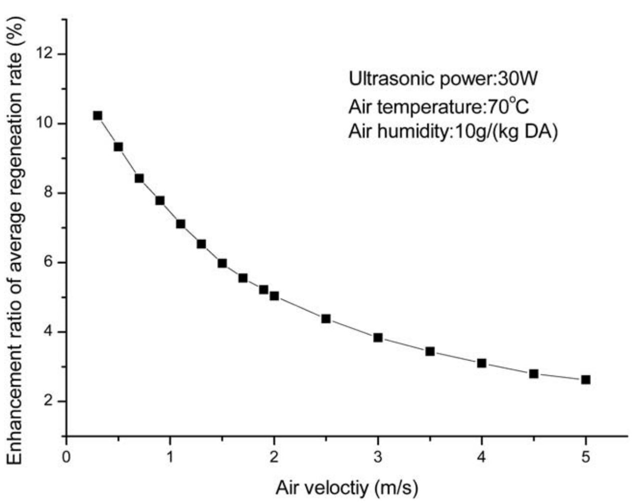


Figure 10. ERARR under different air velocities.

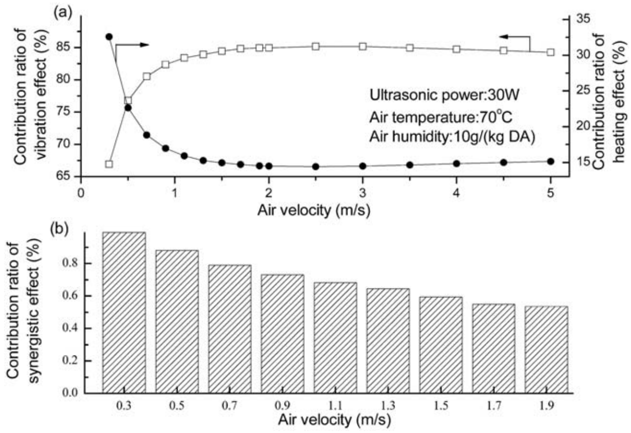


Figure 11. Contribution ratio of (a) vibration and thermal effect; (b) synergistic effect; under different air velocities.

brought by ultrasound. Therefore, the RE brought by ultrasound increases first and then decreases with the increasing of regeneration air velocity.

Figure 11 demonstrates the contribution ratio of the vibration effect, the heating effect, and the synergistic effect to the enhancement of regeneration under different air velocities. We can find that the contribution of the vibration effect dominates when the regeneration air velocity is larger than 0.3 m/s. It increases rapidly from 66.9 to 85.2% when the regeneration air velocity varies from 0.3 to 2.5 m/s, and then declines slowly, whereas the contribution ratio of the heating effect first decreases from 32.1 to 14.4% and then increases slightly (Figure 11a). Under lower air velocity, the improvement of the heat- and mass-transfer coefficients brought by the vibration effect has little influences on the regeneration process, and the heat- and mass-transfer coefficients become the dominant factor affecting the regeneration process under higher air velocity. Therefore, the contribution ratio of the vibration effect increases first and then decreases with the increase of air velocity.

As also seen from Figure 11b, the contribution ratio of the synergistic effect decreases as the air velocity varies from 0.3 to 1.9 m/s. It is known from the above discussion that the temperature of silica gel is the dominant factor that influences the RE brought by vibration effect under lower regeneration air velocity. So, the combination of silica gel temperature rise caused by heating effect and the mass-transfer intensification caused by vibration effect is more effective under lower regeneration air velocity.

The electricity utilization efficiency under different air velocities is shown in Figure 12. It can be found from Figure 12a that the EE_U first increases and then decreases with the regeneration air velocity. The largest EE_U occurs at the velocity of about 0.3 m/s. The change trend of EE_U can be explained easily by Eq. 18.

Moreover, when the air velocity is larger than 0.5 m/s, the EE_U becomes higher than the EE_{NU}, and the differences between them first grow and then dwindle slightly. In fact, the differences depend on the energy utilization efficiency of the ultrasonic energy, which is related to the RE brought by ultrasound. As shown in Figure 9b, the RE brought by ultrasound increases first and then decreases slightly with the air velocity increasing, so does the energy utilization efficiency of ultrasonic energy.

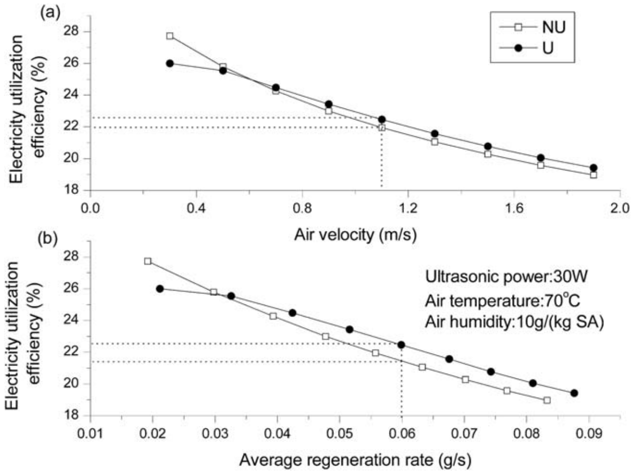


Figure 12. Variation of electricity utilization efficiency under different air velocities vs. (a) air velocity; (b) average regeneration rate.

The electricity utilization efficiency is plotted against the average regeneration rate in Figure 12b to show the energy utilization characteristic with and without ultrasound when the same $R_{r,ave}$ is achieved. It can be found that the EE_U can be over 1% higher than the EE_{NU} at the same $R_{r,ave}$.

Effects of ultrasonic power

The regeneration processes of silica gel assisted by ultrasound are simulated under the ultrasonic power ranging from 30 to 70 W. The ERARR is shown in Figure 13. The results manifest that the ERARR is not linear with ultrasonic power. As the ultrasonic power increases, the exit air humidity will increase, which reduces the mass-transfer driving force. So, the RE brought by the vibration effect is not proportional to the ultrasonic power, and its increase rate becomes smaller gradually.

The contribution ratio of the three effects (vibration effect, heating effect, and synergistic effect) to the enhancement of regeneration is demonstrated in Figure 14. The contribution ratio of the vibration effect decreases with the increase of the ultrasonic power, whereas it reverses for that of the heating effect.

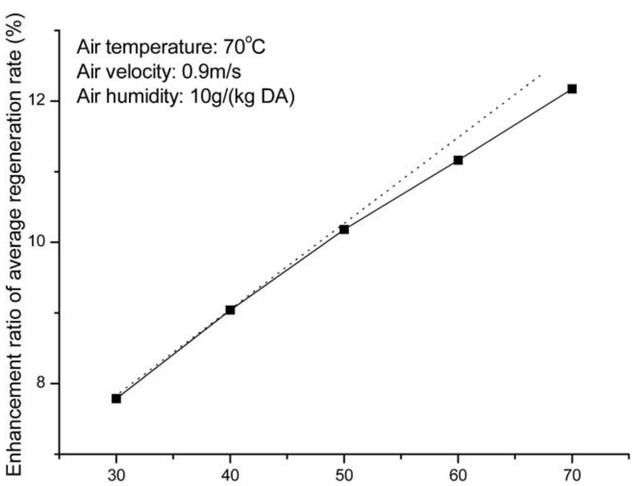


Figure 13. ERARR under different ultrasonic power levels.

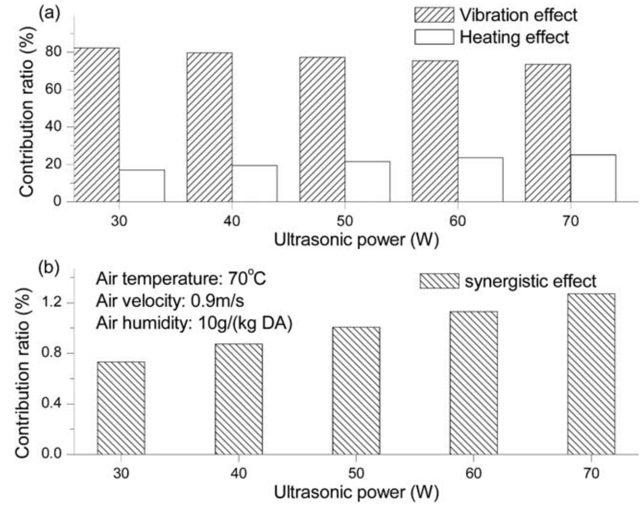


Figure 14. Contribution ratio of (a) vibration and heating effect; (b) synergistic effect; under different ultrasonic power levels.

The contribution ratio of the synergistic effect is shown in Figure 14b, which increases from 0.7 to 1.2% as the ultrasonic power varies from 30 to 70 W. As known from Eq. 16, the contribution ratio of synergistic effect can be expressed as $CR_{syn} = \Delta K/K * CR_{eff}$. ΔK and CR_{teff} increases with the ultrasonic power. Therefore, the contribution ratio of synergism effect increases as the ultrasonic power increases.

Figure 15 presents the electricity utilization efficiency in the silica gel regeneration processes with ultrasound under different ultrasonic power levels. The dotted line in Figure 15 denotes the electricity utilization efficiency in the regeneration without ultrasound. It can be seen that the EE_U decreases with the increasing of ultrasonic power and it becomes lower than EE_{NU} when the ultrasonic power is higher than 55 W. Therefore, from the perspective of energy saving, the ultrasonic power had better be no more than 55 W under the simulation conditions without considering the enhancement of regeneration.

The EE is plotted against average regeneration rate in Figure 15b to show the electricity utilization characteristic with

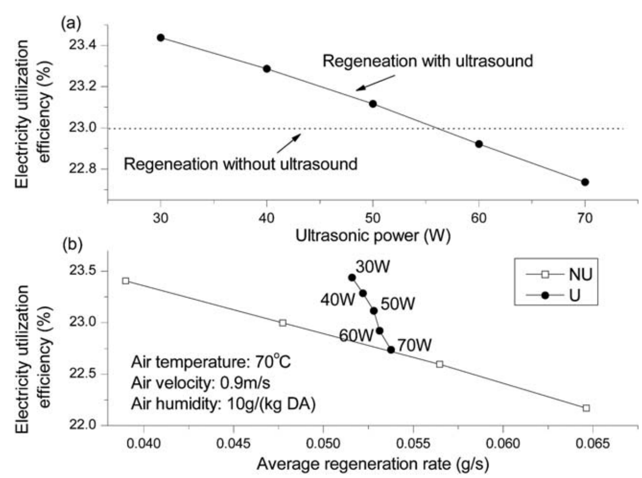


Figure 15. Variation of electricity utilization efficiency under different ultrasonic power levels vs. (a) ultrasonic power; (b) average regeneration rate.

and without ultrasound when the same $R_{r,ave}$ is achieved. It can be found that, when the ultrasonic power is more than 70 W, the gains of applying of ultrasound are even less than increasing regeneration air temperature with the same power under the present simulation conditions.

Effects of air humidity

The regeneration processes of silica gel are simulated under the air humidity ranging from 10 to 22.5 g/(kg DA). The ERARR brought by the power ultrasound is presented in Figure 16. We can find that the ERARR increases very small as the air humidity varies from 10 to 22.5 g/(kg DA).

Figure 17 presents the contribution ratio of the vibration effect, the heating effect, and the synergistic effect to the enhancement of regeneration under different air humidity ratios. As shown in Figure 17a, the contribution ratio of the vibration effect decreases slightly as the air humidity increases, while it reverses for that of the heating effect. The contribution ratio of the synergistic effect, as show in Figure 17b, increases with the rising of the air humidity. To explain this phenomenon, the contribution ratio of the synergistic effect is rewritten as $\mathrm{CR}_{\mathrm{teff}} = \Delta K \Delta w_{\mathrm{eff}}^{*} / \mathrm{RE}$. As discussed before, the RE decreases slightly with the increase of air humidity. Therefore, the contribution ratio of the synergism effect grows when the air humidity become greater.

The electricity utilization efficiencies in the silica gel regeneration processes with and without ultrasound under different air humidity ratios are plotted in Figure 18. Obviously, the electricity utilization efficiency with and without ultrasound both decrease as the air humidity varies from 10 to 22.5 g/(kg DA). Besides the EE_U is about 0.5% higher than the EE_{NU} and the regeneration air humidity makes little influences on the energy-saving characteristics of silica gel regeneration with ultrasound.

Effects of regeneration degree

The regeneration degree, which is reflected by the moisture content of silica gel at the end of regeneration, greatly influences the effect of ultrasound on the silica gel regeneration. The average regeneration rate, RE, and electricity efficiency under different final moisture content of silica gel are presented in Figure 19. As shown in Figure 19, all these parameters change in a similar way as the regeneration degree increases; that is, they first rise to a maximum value and then begin to decline.

At the beginning of regeneration, there will be a process of temperature rise in the silica gel. During this period, the mass-transfer driving force grows gradually with time, which increases the regeneration rate and the RE brought by ultrasonic vibration effect. Therefore, the average regeneration rate and the RE rise in the beginning stage of regeneration. As the overall power input stays unchanged, the electricity utilization efficiency increases as well. However, with the regeneration process going on, the moisture ratio in the silica gel drops, and the mass-transfer driving force becomes smaller. Thus, the average regeneration rate, RE, and electricity efficiency all begin to decline with the increase of degree of regeneration.

As also shown in Figure 19, the gap of electricity efficiency between the case with ultrasonic and without ultrasound increases first and then decreases. It indicates that the energy saving brought by ultrasonic for the regeneration will be affected by the degree of regeneration.

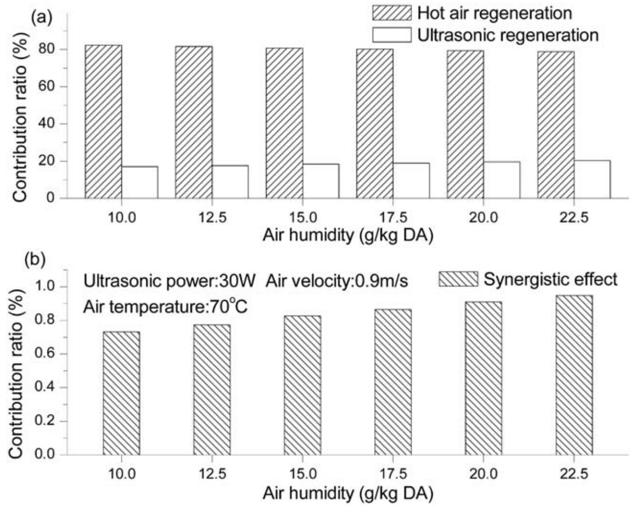


Figure 17. Contribution ratio of (a) vibration and heating effect; (b) synergistic effect; under different air humidity ratios.

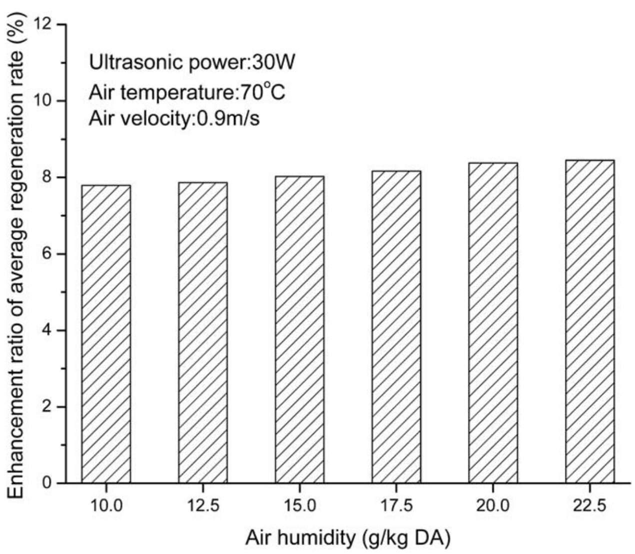


Figure 16. ERARR under different air humidity ratios.

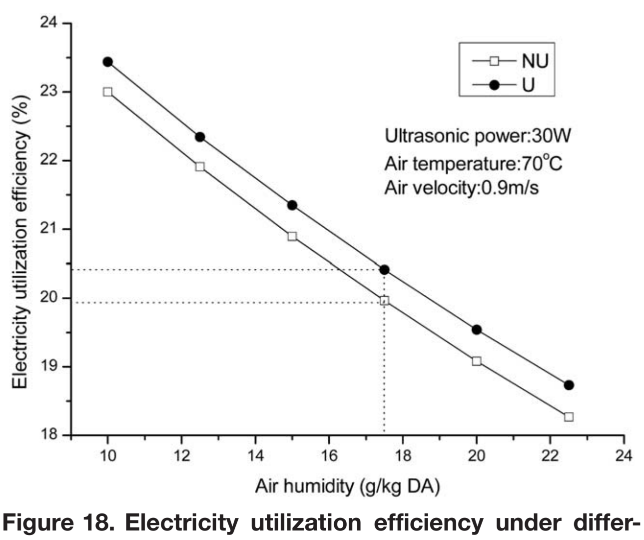


Figure 18. Electricity utilization efficiency under different air humidity ratios.

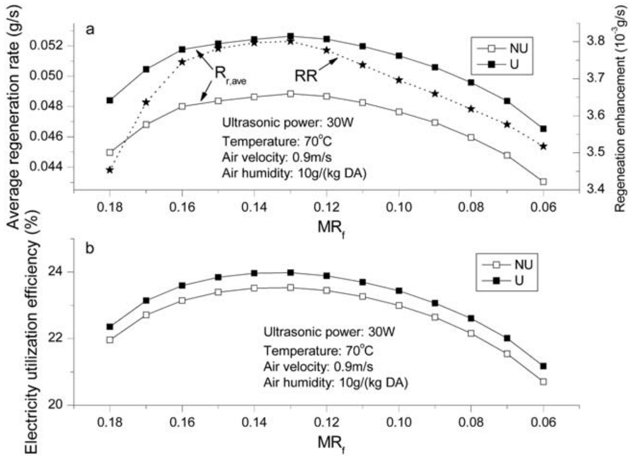


Figure 19. (a) Average regeneration rate and RE; (b) electricity utilization efficiency; under different moisture ratio of silica gel at the end of regeneration (MR_f).

Conclusions

A dynamic mathematical model is built up in this article to predict the regeneration process of the silica gel in the presence of ultrasound under different ultrasonic power and air conditions. The simulated data are validated by several groups of experimental results and the largest error is within ±10%. Therefore, the model can be adopted to investigate the influences of the main parameters of regeneration air and ultrasound on the performance of ultrasonic regeneration. In conclusion, under the simulated conditions, the main results from this article can be summarized as below.

The method of applying ultrasound to the regeneration for silica gel can enhance the regeneration rate and improve the regeneration efficiency. The RE should owe to the vibration effect and the heating effect caused by the power ultrasound. The contribution ratios of the two effects change with the variation of regeneration conditions. For example, the contribution ratio of the microvibration effect dominates and it is larger at higher regeneration temperature, lower air humidity, and lower ultrasonic power level; it increases first and then decreases slightly as the air velocity becomes greater. It is opposite for the contribution ratio of the heating effect.

The RE brought by ultrasound is not a simple sum of the contributions of vibration effect and heating effect. The synergy of the two effects can produce extra RE. The contribution ratio of the synergistic effect increases as the regeneration air humidity and the ultrasonic power increase and the air temperature and velocity decrease.

There exists a suitable regeneration temperature for the ERARR to reach the maximum value, and greater ERARR can be achieved at higher air humidity ratio and velocity.

The electricity utilization efficiency (EE) of the ultrasonic regeneration dwindles as the air humidity and the ultrasonic power grow larger, and there exists an appropriate air temperature and velocity to maximize it. Furthermore, the way of applying ultrasound is more energy-saving for the silica gel regeneration under greater air temperature and velocity, whereas the air humidity has little influences.

The regeneration degree of silica gel should be neither too low nor too high to get greater RE (RR) and better energy-saving effect.

Acknowledgment

This work was sponsored by Shanghai Pujiang Program (2012) and the National Natural Science Foundation of China under contract No.11274279.

Notation

a = area per unit bed volume, m^2/m^3
a_u = absorption coefficient of ultrasonic, dimensionless
A = cross-sectional area, m^2
CR = contribution ratio
c_p = specific heat capacity, kJ/(kg K)
d_m = average diameter of silica gel particles, m
D = mass diffusivity coefficient, m^2/s
DA = dry air
h = convective heat-transfer coefficient, $W/(m^2 \cdot °C)$
G = mass flow rate of air, kg/s
H_{des} = desorption heat of water vapor, kJ/kg
K = thermal conductivity, W/(m°C)
K = mass-transfer coefficient, m/s
m = mass, kg
MR = moisture ratio, kg water/kg silica gel
p_q = saturation vapor pressure, Pa
$P(z)$ = sound pressure, Pa
P_{ove} = overall power input, W
P_t = power of air heater, W
P_{ult} = indicated power of ultrasonic generator, W
RE = regeneration enhancement, kg/s
R_r = regeneration rate, kg/s
S = horizontal cross-section area of bed, m^2
t = temperature, °C
t_{amb} = ambient temperature, °C
u = superficial air speed (that would exist if the bed is empty), m/s
U/NU = with/without ultrasound
V = volume of silica gel bed, m^3
w = absolute humidity of air, kg water vapor/(kg DA)
x = distance from the windward side of bed, m
z = distance from the bottom of bed, m
Z = characteristic acoustic impedance, N s/m^3

Greek letters

δ = working efficiency of ultrasonic transducer, dimensionless
ε = porosity of bed, dimensionless
η = efficiency of air heater, dimensionless
μ = dynamic viscosity, kg/(m·s)
v = sound speed, m/s
ξ = attenuation coefficient, dimensionless
ρ = density, kg/m^3
τ = time, s
τ_f = time taken for MR to arrive at MR_f, s
φ = relative humidity, %

Superscripts

_ = average
* = equilibrium with the silica gel
U/NU = with/without ultrasound

Subscripts

0 = initial
a = air properties
ave = average
f = final
i = inlet
o = outlet
s = silica gel properties
syn = synergistic effect
teff = heating effect
U/NU = with/without ultrasound
v = water vapor properties
veff = vibration effect

Literature Cited

1. Sun J, Besant RW. Heat and mass transfer during silica gel-moisture interactions. *Int J Heat Mass Transfer*. 2005;48:4953–4962.

2. Pramuang S, Exell RHB. The regeneration of silica gel desiccant by air from a solar heater with a compound parabolic concentrator. *Renew Energy*. 2007;32:173–182.
3. White SD, Goldsworthy M, Reece R, Spillmann T, Gorur A, Lee DY. Characterization of desiccant wheels with alternative materials at low regeneration temperatures. *Int J Refrig*. 2011;34:1786–1791.
4. Ohgushi T, Nagae M. Quick activation of optimized zeolites with microwave heating and utilization of zeolites for reusable desiccant. *J Porous Mater*. 2003;10:139–143.
5. Qi RH, Tian CQ, Shao SQ. Experimental investigation on possibility of electro-osmotic regeneration for solid desiccant. *Appl Energy*. 2010;87:2266–2272.
6. Qi RH, Tian CQ, Shao SQ, Tang MS, Lu L. Experimental investigation on performance improvement of electro-osmotic regeneration for solid desiccant. *Appl Energy*. 2011;88:2816–2823.
7. Legay M, Gondrexon N, Person SL, Boldo P, Bontemps A. Enhancement of heat transfer by ultrasound: review and recent advances. *Int J Chem Eng*. 2011;166:1066–1082.
8. Isaza PA, Daugulis AJ, Karan K. Mass transport and thermodynamic analysis of PAHs in partitioning systems in the presence and absence of ultrasonication. *AIChE J*. 2010;56:2717–2726.
9. Gogate PR, Shirgaonkar IZ, Sivakumar M, Senthilkumar P, Vichare NP, Pandit AB. Cavitation reactors: efficiency assessment using a model reaction. *AIChE J*. 2001;47:2526–2538.
10. Gogate PR, Sutkar VS, Pandit AB. Sonochemical reactors: important design and scale up considerations with a special emphasis on heterogeneous systems. *Chem Eng J*. 2011;166:1066–1082.
11. Vichare NP, Gogate PR, Dindore VY, Pandit AB. Mixing time analysis of a sonochemical reactor. *Ultrason Sonochem*. 2001;8(1):23–33.
12. Kumar A, Gogate PR, Pandit AB, Delmas H, Wilhelm AM. Gas−liquid mass transfer studies in sonochemical reactors. *Ind Eng Chem Res*. 2004;43(8):1812–1819.
13. Yao Y, Liu SQ, Zhang WJ. Regeneration of silica gel using high-intensity ultrasonic under low temperatures. *Energy Fuels*. 2008;23: 457–463.
14. Yao Y, Zhang WJ, Liu SQ. Feasibility study on power ultrasound for regeneration of silica gel—a potential desiccant used in air-conditioning system. *Appl Energy*. 2009;86:2394–2400.
15. Yao Y, Zhang WJ, Liu SQ. Parametric study of high-intensity ultrasonics for silica gel regeneration. *Energy Fuels*. 2009;23:3150–3158.
16. Yao Y. Using power ultrasound for the regeneration of dehumidizers in desiccant air-conditioning systems: a review of prospective studies and unexplored issues. *Renew Sustain Energy Rev*. 2010;14:1860–1873.
17. Yang K, Yao Y, Liu SQ. Effect of applying ultrasonic on the regeneration of silica gel under different air conditions. *Int J Therm Sci*. 2012;61:67–78.
18. Guo ZY, Li DY, Wang BX. A novel concept for convective heat transfer enhancement. *Int J Heat Mass Transfer*. 1998;41:2221–2225.
19. *2009 ASHRAE Handbook*. U.S.: ASHRAE, 2009:20–21.
20. Buck AL. New equations for computing vapor pressure and enhancement factor. *J Appl Meteorol*. 1981;20:1527–1532.
21. Shen WD, Tong JG. *Engineering Thermodynamics*. Beijing: Higher Education Press, 2007.
22. Bird RB, Stewart WE, Lightfoot EN. *Transport Phenomena*. New York: Wiley, 1960.
23. Puig A, Perez-Munuera I, Carcel JA, Hernando I, Garcia-Perez JV. Theoretical and experimental investigation on the radial flow desiccant dehumidification bed. *Appl Therm Eng*. 2008;28:75–85.

Appendix

The density of drying air, ρ_a (kg/m^3), is calculated by Eq. A1[19]

$$\rho_a = \frac{1+w}{0.370486(t+459.67)(1+1.607858w)/B} \tag{A1}$$

The specific heat of air at constant pressure, $c_{p,a}$ (kJ/kg DA), is given as

$$c_{p,a} = 1.884w + 1.005 \tag{A2}$$

The saturation vapor pressure of air, p_q (Pa), can be gotten from Eq. A3[20]

$$p_q - 6.1121\exp\left(\frac{18.678t - t^2/234.5}{257.14+t}\right) \tag{A3}$$

and the moisture content of air, w, can be calculated by Eq. A4[21]

$$w = \frac{0.622\cdot\varphi\cdot p_q}{101000-\varphi\cdot p_q} \tag{A4}$$

The heat and mass-transfer coefficients for the gas side in the silica gel bed are presented as

$$h = \frac{\text{Nu}\cdot k_a}{d_m} \tag{A5}$$

$$K = \frac{\text{Sh}\cdot D}{d_m} \tag{A6}$$

where Nu is the Nusselt number and Sh is the Sherwood number. They are calculated by Eqs. A7 and A8, respectively.[22]

$$\text{Nu} = 2+0.6\text{Pr}^{1/3}\cdot\text{Re}^{1/2} \tag{A7}$$

$$\text{Sh} = 2+0.6\text{Sc}^{1/3}\cdot\text{Re}^{1/2} \tag{A8}$$

where Pr is the Prandtl number, Sc is the Schmidt number, and Re is the Reynolds number.

The average velocity of air ($\bar{u}$) is the synthesis speed of apparent horizontal velocity and vertical vibration velocity of air

$$\bar{u} = \sqrt{u^2+\bar{u}_{\text{veff}}^2} \tag{A9}$$

where u_{veff} is the mean value of the vibration velocity $\left(\bar{u}_{\text{vib}} = \frac{1}{10}\sum_{i=1}^{10} u_{\text{vib}}(z=i/100)\right)$.

The vibration velocity, u_{veff}, can be gotten by the equation as below

$$u_{\text{veff}}(z) = P(z)/Z \tag{A10}$$

where $P(z)$ is the sound pressure at the height of z, and Z is the characteristic acoustic impedance. They can be calculated, respectively, by Eqs. A11 and A12

$$P(z) = P_0\exp(-\xi z) \tag{A11}$$

$$Z = \rho_s v_s \tag{A12}$$

The sound pressure,P_0, at the position of $z=0$ is given as

$$P_0 = \sqrt{(P_{\text{ult}}\delta/S)\cdot Z} \tag{A13}$$

The relative humidity of air in equilibrium with silica gel particles, φ^*, can be expressed as a function of the moisture ratio (MR) and surface temperature (t_s) of silica gel

$$\varphi^* = s_1 t_s\text{MR}^2 + s_2 t_s\text{MR} + s_3\text{MR}^4 + s_4\text{MR}^3 + s_5\text{MR}^2 + s_6\text{MR} + s_7 Ln(\text{MR}) \tag{A14}$$

where the empirical constants, s_1, s_2, s_3, s_4, s_5, s_6, and s_7, are specified as 82.9, −4.64, 252148.6, −125044.6, 16001.7, −173.4, and 0.863, respectively.

The desorption heat of water vapor, H_{des}, can be calculated by[23]

$$H_{\text{des}} = 3500-13400\text{MR} \quad \text{MR} \le 0.05 \tag{A15}$$

$$H_{\text{des}} = 2950-1400\text{MR} \quad \text{MR} > 0.05 \tag{A16}$$

Manuscript received Apr. 12, 2013, and revision received Dec. 23, 2013.