Parametric Study of High-intensity Ultrasonics for Silica Gel Regeneration

ARTICLE *in* ENERGY & FUELS · JUNE 2009

Impact Factor: 2.79 · DOI: 10.1021/ef801066m

Parametric Study of High-intensity Ultrasonics for Silica Gel Regeneration

Ye Yao,*,† Weijiang Zhang,† and Shiqing Liu‡

Institution of Refrigeration & Cryogenics at Shanghai Jiao Tong University, Shanghai, 200240, China and Institute of Mathematics and Physics, Zhejiang Normal University, Jinhua, Zhejiang province, 321004, China

Received December 6, 2008. Revised Manuscript Received April 25, 2009

The use of ultrasonic power in the regeneration of silica gel may be very promising because it helps to improve the regeneration efficiency at the lower regeneration temperature. This work is to study experimentally the effects of ultrasonic power and frequency on the regeneration of silica gel using the ultrasound at different regeneration temperatures (i.e., 45, 55, 65, and 75 °C). Three kinds of frequencies (i.e., 21, 26, and 35 kHz) combined with different power (i.e., 0, 20, 40, and 60 W) of ultrasound were employed to perform the experiments. The moisture change in the silica gel during the ultrasonic regeneration was modeled by the Page equation, and the effective moisture diffusivity was estimated through the diffusion equation that is based on the Fick's second law. Three parameters, including the enhanced rate (ER) of regeneration, the conditioned regeneration time (CRT), and the energy-saving rate (ESR), are suggested to evaluate the effect of ultrasonic power and frequency on the regeneration. The results show that the regeneration rate constant (k) in the regeneration model, the ER of regeneration, and the effective moisture diffusivity in silica gel increase with the rising of the ultrasonic power and the lowering of frequency. The higher power and the lower frequency of ultrasound lead to the shorter CRT and the use of less energy for the regeneration. In addition, the effects of ultrasonic parameters (i.e., frequency and power) on the regeneration are more significant at the lower regeneration temperatures.

1. Introduction

Energy efficient air-conditioning systems for both industrial and civilian applications have been increasingly emphasized by people due to the continuing rise in energy demand and the associated environmental problems. In humid and hot climates such as the southern areas of China, the humidity issues are a major contributor to energy inefficiency in HVAC devices. Recently, there is an increasing trend to separate the treatment of sensible and latent load by using an independent humidity control system[1] that integrates liquid/solid desiccant devices with a conventional cooling system. Although the independent humidity control system may bring about potential energy conservation, for example, avoiding excess cooling and heating, being convenient to utilize the waste heat[2] and the solar energy,[3] the energy efficiency of system is still below satisfactory due to the high temperature required for the regeneration of the desiccants in the dehumidification process. As shown in Figure 1, the working cycle of dehumidification using dehumidizer (or desiccants) consists of adsorption (from A to B), regeneration (from B to C) and cooling (from C to A), among which the regeneration occupies the most important position. The employment of the heating regeneration method may be confronted with some dilemmas. The higher regeneration temperature can improve the performance of water vapor adsorption on desiccants and increase the desiccant volume,[4] but it will lead to more energy dissipation in the following cooling process and be disadvantageous to utilize the low-grade energy sources easily available from the nature. However, if the lower regeneration temperature is chosen, the performance of desiccant may be deteriorated and can not satisfy the demand of actual situations. To solve this problem, the method of regeneration using high-intensity ultrasound was first put forward by us.[5] The benefits of the new regeneration method may include: (1) the heat and mass transfer in desiccants can be enhanced by ultrasound, which will improve the regeneration efficiency of desiccants

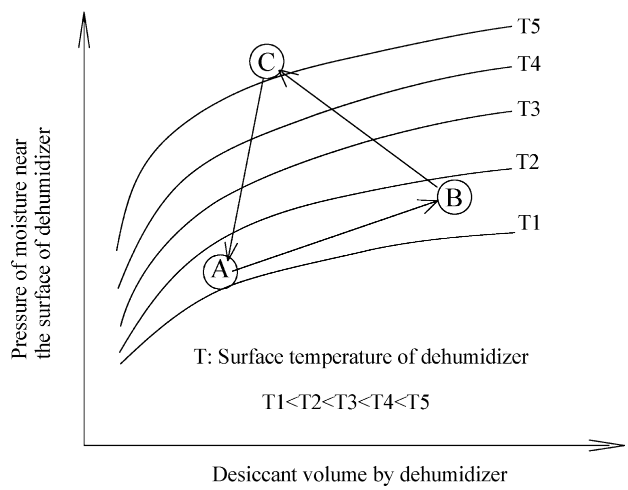
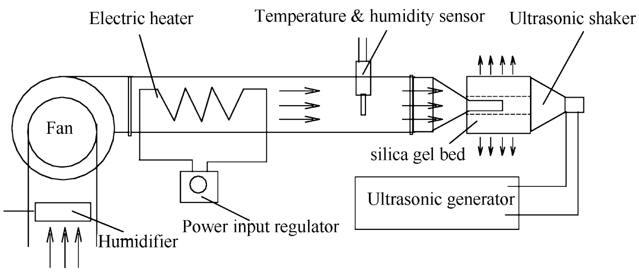


Figure 1. Working cycle of dehumidification using dehumidizer.

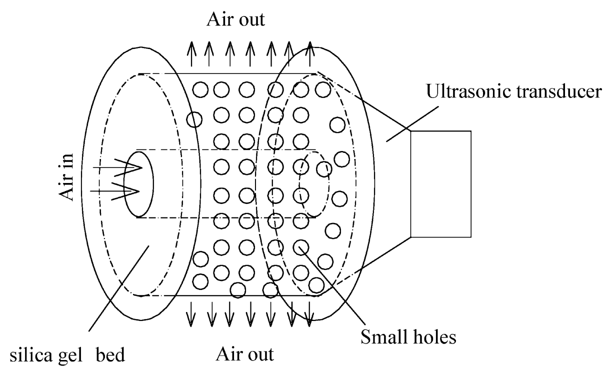
* Corresponding author: E-mail address: yeyao10000@sjtu.edu.cn or yeyao10000@163.com.
† Shanghai Jiao Tong University.
‡ Zhejiang Normal University.

(1) Zhang, L. Z. *Energy* **2006**, *31* (8−9), 1228–1242.
(2) Cowie, M.; Liao, X. H.; Radermacher, R *ASHRAE Transactions* **2003**, *109* (2), 572–579.
(3) Techajunta, S.; Chirarattananon, S.; Exell, R. H. B. *Renewable Energy* **1999**, *17* (4), 549–568.
(4) Kuei-Sen, C.; Hui-Chun, W.; Tsair-Wang, C. *Appl. Therm. Eng.* **2004**, *24* (5−6), 735–742.
(5) Ye, Y.; Shiqing, L.; Weijiang, Z. *Energy Fuels* **2009**, (1), 457–463.

10.1021/ef801066m CCC: $40.75
Published on Web 05/06/2009



(a) The experimental setup



(b). The silica gel bed

Figure 2. Schematic diagram for the experimental system and the silica gel bed.

and make it possible for the desiccants to be regenerated under lower temperatures; (2) the ultrasonic energy will be utilized with a higher efficiency in the regeneration compared with the thermal energy because the former can penetrate through the entire mass in no time; and (3) ultrasound can shorten regeneration time and improve the working efficiency of desiccants.

In our previous paper,[5] the regeneration of silica gel (a kind of desiccant) assisted by high-intensity ultrasound has been investigated in terms of different regeneration temperatures and different moisture ratio in sample. This paper is mainly to discuss how the ultrasonic parameters, that is, power and frequency, impact the regeneration and the moisture transfer in silica gel.

2. Materials and Methods

2.1. Raw Materials. The silica gel used in this study has the particle size distribution of 3.5 ± 0.5 mm in diameter. The physical properties, as provided by the manufactory, mainly include the following aspects: specific surface area ≥ 600 m^2/g; pore diameter = 20−30 Å; pore volume = 0.35−0.45 mL/g; bulk density = 750 g/L.

2.2. Experimental Setup. The schematic diagram for the experimental system is shown in Figure 2a. The system mainly consists of a silica gel bed, an ultrasonic generator, an ultrasonic transducers, an air duct, a fan, an electric heater (rated power: 400 W), a humidifier, and the other testing instruments, including an integrated temperature and humidity sensor (type: HMT100; measurement errors: ±2% in relative humidity and ±0.2 °C in temperature), a dry−wet bulb thermometer (precision: ±0.5 °C), an electronic balance (precision: ±0.1 g), and a digital anemometer (measurement errors: ±3% of reading data).

As shown in Figure 2b, the silica gel bed with a height of 95 mm is assembled by two concentric steel cylindrical shells with numerous small orifices in the surface and two steel circular plates. The inner and the outer cylindrical shell, whose diameters are, respectively, about 20 and 50 mm, are concentrically fixed between the two circular plates and form an empty space for filling the silica gel. The ultrasonic transducer, which is driven by the ultrasonic generator, is clung tightly to one circular plate through which the ultrasonic waves propagate into the silica gel in the bed. There opens a hole with a diameter of 20 mm in the center of the other circular plate through which the hot air first enters into the inner cylindrical shell, then passes through the silica gel in the bed, and finally exhausts outside from the orifices of the outer cylindrical shell.

The ultrasonic transducer, which is made from one special magnetostrictive material that changes in dimension upon the application of a changing magnetic field, is responsible for the conversion from the electric energy into ultrasonic fields. Three ultrasonic transducers, as shown in Figure 3a, with 21, 26, and 35 kHz, respectively, in the harmonic frequency are used for this study. The ultrasonic generator, as shown in Figure 3b, can provide high-intensity electrical signals with the power range of 0∼100 W and the frequency range of 10∼100 kHz.

The electric heater is placed in the upward stream of the air duct. A power controller is used to adjust the input power of the electric heater to create the target temperatures of air for the experiments. The temperature and humidity sensors, used for checking the inlet conditions of regeneration air, are placed near the inlet of the silica gel bed. The digital anemometer and the dry−wet bulb thermometer are used to measure the flow rate of regeneration air in the air duct and the states of ambient air, respectively, during the experiments. The humidifier is used to wet the silica gel to certain initial moisture ratio before the regeneration experiments.

2.3. Experimental Process. The experiments were done at different regeneration temperatures (45, 55, 65, and 75 °C), combined with ultrasound with different parameters (20, 40, and 60 W in power; 21, 26, and 35 kHz in frequency) or without ultrasound (0 W). Some other conditions were kept consistent in all the experiments, for example, the temperature and relative humidity of the ambient air were identically measured, respectively, as 28 ± 1 °C and (80 ± 5)%; the air speed in the air duct was identically as about 0.3 ± 0.05 m/s. All the experiments were carried out in the same procedure. The basic steps were listed as follows:

To begin with, the bed together with the ultrasonic transducer was weighed. A certain amount of fresh silica gel (about 175.1 g) was filled tightly into the bed.

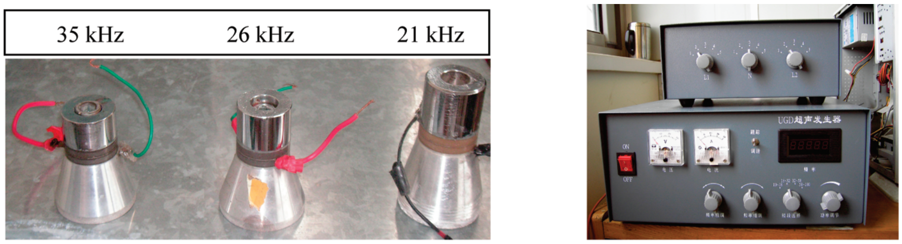
Then, the silica gel in the bed was wetted by the humidifier to the same initial moisture ratio, identically as 200.4 g in the weight, for the following step of regeneration.

And then, the regeneration air with an experimental temperature (e.g., 45 °C) was created through adjusting the power of the electric heater.

Afterward, the regeneration using ultrasound with an experimental frequency and power was performed. The moisture changes in the sample (silica gel) during the regeneration were observed by weighing the bed for every 8 min. The regeneration lasted until no measurable weight loss was observed in the sample.

After the regeneration, the silica gel in the bed was fully dried by an electronic oven with a baking temperature of 300 °C to acquire the dry basis of the sample. In this study, the dry basis of the sample was weighed as about 150.8 g.

2.4. Analytical Methods. *2.4.1. Moisture Change in Silica Gel.* The regeneration in this study is a diffusion-controlled process and may be represented by Fick's law. The simplified solution to the diffusion equation has been success-



(a) Ultrasonic transducers with different frequency **(b). Ultrasonic generator**

Figure 3. Photographs for the ultrasonic generator and ultrasonic transducers in this study.

fully used to depict the moisture transport of biological materials.[6,7] Since the Page model has been proved to get better results than the simple exponential models in quantifying the dehydrating kinetics of various grains and some seeds,[8] it is employed to model the moisture change in silica gel during the regeneration using ultrasound.

The Page model is presented as:

$$\mathrm{MR} = \frac{M - M_e}{M_{ini} - M_e} = \exp(-k\tau^{\beta}) \quad (1)$$

where, MR represents the dimensionless moisture content, M is the instantaneous moisture content during the regeneration (g/g of dry sample), M_{ini} is the initial moisture content (g/g of dry sample), M_e is equilibrium moisture content (g/g of dry sample), τ is the time (s), and k and β are the regeneration rate constant and the dimensionless exponent, respectively.

The form of normalized Page equation is written as:

$$\ln(-\ln(\mathrm{MR})) = \ln(k) + \beta \ln(\tau) \quad (2)$$

where, the empirical constants k and β are determined, respectively, from the intercept and slope of the ln (−ln (MR)) versus ln(τ) curve that is obtained based on the experimental data.

2.4.2. Moisture Diffusivity. Since the pore diameter of silica gel is about 20−30 Å, the kinetics could possibly be pore-diffusion controlled. The regeneration of silica gel is actually a drying process in the falling rate period[5] (the dehydrating rate drops with the dying time). It has been established that drying of porous materials in the falling rate period when the internal resistance is dominant can be approximated by Fick's second law no matter what mechanisms is involved.[9] Under the assumptions of one-dimensional moisture movement, no volume change, uniform initial moisture distribution throughout the sample, negligible external mass transfer resistance, and final equilibrium moisture content close to zero, the analytical solutions to the equations representative of mass transfer of a spherical adsorbent particle of radius, r, in terms of Fick's law has been given by Crank:[10]

$$\mathrm{MR} = \frac{M - M_e}{M_{ini} - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2 D_e \tau}{r^2}\right) \quad (3)$$

where, D_e denotes effective diffusivity (which is defined as "the amount of a particular substance that diffuses across a unit area in one second under the influence of a gradient of one unit[10]"), m^2/s; and τ is the drying time (i.e., regeneration time in this study), s. In spite of many theoretic restrictions on eq 3, the moisture diffusivity D_e in porous medium can be still determined from it (eq 3) based on the experimental data[9,11]

When the time, τ, is sufficiently long, eq 3 could be simplified to a linear equation as:[12]

$$\ln(\mathrm{MR}) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_e}{r^2}\right)\tau \quad (4)$$

The effective diffusivity (D_e) can be obtained according to a straight line of ln (MR) versus time that is plotted by the experimental data. Using the slope of the straight line, κ, the effective diffusivity (D_e) can be calculated by:

$$D_e = \frac{\kappa r^2}{\pi^2} \quad (5)$$

In the following calculation of D_e, the particle radius (r) is assumed as 0.001 75 m, the mean size of the sample in this experimental study.

2.4.3. Evaluation Indexes. To evaluate the effect of ultrasonic on regeneration, three parameters, including the enhanced rate of regeneration, the conditioned regeneration time, and the energy-saving rate, are suggested in this study.

The enhanced rate of regeneration (ER, %) assisted by ultrasonic is evaluated by:

$$\mathrm{ER} = \frac{(\mathrm{MRS})_U - (\mathrm{MRS})_{NU}}{(\mathrm{MRS})_{NU}} \times 100\% \quad (6)$$

where, MRS denotes the mean regeneration speed (g/[min ·(g of dry sample)]), which is defined as the mass decrement of moisture per minute in unit mass of dry sample during regeneration. The subscripts "U" and "NU" denotes with ultrasonic and without ultrasonic, respectively.

The conditioned regeneration time (CRT, min) refers to the time required for making the sample achieve certain regeneration degree. Regeneration degree (RD) is determined as the ratio of the loss of moisture (M_{loss}, g/g of dry sample) to the initial moisture content (M_{ini}, g/g of dry sample) in sample.

$$\mathrm{RD} = \frac{M_{loss}}{M_{ini}} \quad (7)$$

The energy-saving rate (ESR, %) brought by power ultrasound is defined as:

$$\mathrm{ESR} = \frac{E_U(\mathrm{RD})}{E_{NU}(\mathrm{RD})} \times 100\% \quad (8)$$

(6) Simal, S.; Benedito, J.; Sanchez, E. S.; Rossello, C *J. Food Eng.* **1998**, *36* (3), 323–336.
(7) Sogi, D. S.; Shivhare, U. S.; Garg, S. K.; Bawa, A. S. *Biosyst. Eng.* **2003**, *84* (3), 297–301.
(8) Roberts, J. S.; Kidd, D. R.; PadillaZakour, O *J. Food Eng.* **2008**, *89* (4), 460–465.
(9) Zogzas, N. P.; Maroulis, Z. B. *Drying Technol.* **1996**, *14* (7−8), 1543–1573.
(10) Crank J. *The Mathematics of Diffusion*, 2nd ed.; Clarendon Press: Oxford, 1979.
(11) Hassini, L.; Azzouz, S.; Belghith, A. Estimation of the moisture diffusion coefficient of potato during hot-air drying. *Drying* 2004; Proceedings of the 14th International Drying Symposium (IDS 2004) São Paulo, Brazil, August 22−25, 2004; Vol. B, pp 1488−1495.
(12) Doymaz, I. *J. Food Eng.* **2005**, *69* (3), 275–279.

Table 1. Empirical Constants of the Page Model in the Ultrasonic Regeneration

regeneration temperature (° C)	UF = 21 kHz, UP = 20 W			UF = 21 kHz, UP = 40 W			UF = 21 kHz, UP = 60 W		
	k (min^{-1}) × 10^{-3}	β	R^2	k (min^{-1}) × 10^{-3}	β	R^2	k (min^{-1}) × 10^{-3}	β	R^2
45	4.087	1.338	0.9874	6.069	1.317	0.9546	8.131	1.337	0.9643
55	8.539	1.179	0.9754	9.764	1.175	0.9678	10.739	1.169	0.9876
65	10.834	1.256	0.9466	11.481	1.230	0.9886	12.013	1.221	0.9662
75	13.038	1.299	0.9678	13.4507	1.210	0.9756	13.700	1.184	0.9586
	UF = 26 kHz, UP = 20 W			UF = 26 kHz, UP = 40 W			UF = 26 kHz, UP = 60 W		
45	3.987	1.390	0.9623	5.070	1.390	0.9832	7.132	1.391	0.9487
55	8.439	1.268	0.9856	9.176	1.234	0.9743	10.174	1.261	0.9894
65	10.783	1.228	0.9598	11.048	1.257	0.9532	11.801	1.206	0.9723
75	12.904	1.300	0.9356	13.095	1.263	0.9583	13.270	1.202	0.9476
	UF = 35 kHz, UP = 20 W			UF = 35 kHz, UP = 40 W			UF = 35 kHz, UP = 60 W		
45	3.872	1.362	0.9845	4.472	1.340	0.9459	5.717	1.349	0.9475
55	7.835	1.368	0.9634	8.395	1.326	0.9623	8.605	1.359	0.9876
65	10.375	1.387	0.9723	10.651	1.360	0.9654	10.813	1.366	0.9812
75	12.690	1.335	0.9364	12.790	1.302	0.9399	12.904	1.292	0.9523

Table 2. The Slope (κ) Estimation of the Straight Lines of ln(MR) versus Time τ for the Determination of D_e

regeneration temperature (° C)	UF = 21 kHz, UP = 20 W		UF = 21 kHz, UP = 40 W		UF = 21 kHz, UP = 60 W	
	κ (× 10^{-4})	R^2	κ (× 10^{-4})	R^2	κ (× 10^{-4})	R^2
45	−3.862	0.9973	−5.095	0.9956	−7.313	0.9829
55	−5.804	0.9834	−8.074	0.9735	−9.799	0.9628
65	−8.385	0.9723	−10.111	0.9836	−11.343	0.9728
75	−10.867	0.9913	−12.592	0.9726	−13.332	0.9682
	UF = 26 kHz, UP = 20 W		UF = 26 kHz, UP = 40 W		UF = 26 kHz, UP = 60 W	
45	−3.788	0.9686	−4.734	0.9983	−6.857	0.9725
55	−6.050	0.9829	−8.103	0.9782	−9.553	0.9836
65	−8.632	0.9519	−10.230	0.9725	−11.137	0.9894
75	−11.193	0.9682	−12.839	0.9793	−13.524	0.9593
	UF = 35 kHz, UP = 20 W		UF = 35 kHz, UP = 40 W		UF = 35 kHz, UP = 60 W	
45	−3.665	0.9685	−4.355	0.9785	−6.115	0.9838
55	−5.609	0.9737	−6.543	0.9729	−7.980	0.9724
65	−7.892	0.9835	−8.829	0.9902	−9.170	0.9538
75	−10.231	0.9599	−11.113	0.9743	−11.606	0.9677

where, E(RD) denotes the energy (MJ) used for the regeneration as certain RD of silica gel is achieved.

3. Results and Discussion

The empirical constants in the Page model for the ultrasonic regeneration at each temperature, estimated by the experimental dada, are given in Table 1. The coefficients of determination (R^2) for the empirical constants are above 0.93 for all values, with most being above 0.95. It indicates that the Page equation is fairly good in modeling the moisture changes in the silica gel during the regeneration assisted by ultrasound. The slopes (κ) of the straight lines of ln(MR) versus time τ at each temperature, used for the determination of the effective diffusivity (D_e), are given in Table 2. The high coefficients of determination (R^2) for κ (above 0.95 for all, most being above 0.97) indicates the validity of D_e calculated by κ. In the following sections, the effects of ultrasonic power and frequency on the constant, k, in the Page model, the effective diffusivity (D_e), as well as the indexes used to evaluate the benefit brought by ultrasound in the regeneration, are discussed.

3.1. Influence of Ultrasonic Power. In Figure 4, the regeneration rate constant (k) is plotted versus the ultrasonic power. It can be seen that k will increase with the rising of ultrasonic power level applied. The degree of effect of the ultrasonic power on the parameter k is markedly influenced by other factors, for example, the ultrasonic frequency and the regeneration temperature. As shown in Figure 4, under the same frequency, the change curves of k at lower regeneration temperature are obviously steeper than that at higher temperatures. Taking 21 kHz for example, the change gradient of k at 45 °C is about 0.1 per watt, which is higher than that at 55 °C (about 0.06 per watt), 65 °C (about 0.03 per watt), and 75 °C (about 0.02 per watt). Under the same regeneration temperature, the change gradient of k becomes smaller with the rising of ultrasonic frequency. When the frequency arrives at 35 kHz, the values of k have almost no change with the variations of ultrasonic power at the regeneration temperatures over 65 °C. It indicates that the ultrasonic power will make less influence on k as the ultrasonic frequency or the regeneration temperature goes higher. As the parameter k is directly proportional to the regeneration rate, it can be inferred that the equal increase of ultrasonic power would contribute more to the regeneration rate in the case of lower frequencies or lower regeneration temperatures.

The changing trend of the effective diffusivity (D_e) against the ultrasonic power is plotted in Figure 5, which manifests that the values of D_e will increase greatly with the rising of ultrasound power input. It convincingly proves that the high-intensity ultrasound can enhance the moisture transfer in silica gel. The mechanism can be explained by the nature of ultrasound that will produce a series of rapid compressions and expansions (known as the special "high-frequency microvibration" effect) in material when propagating through the solid medium.[6] Mainly owe to such effect caused by ultrasound, the internal and external resistance of mass transfer taking place in the medium can be reduced, and the mass diffusion rate can be enhanced.

There might be a threshold of power above which the effect of ultrasound on the moisture transfer becomes significant. Taking the ultrasound with 35 kHz for example, the ultrasound hardly brings about an obvious increase in the effective

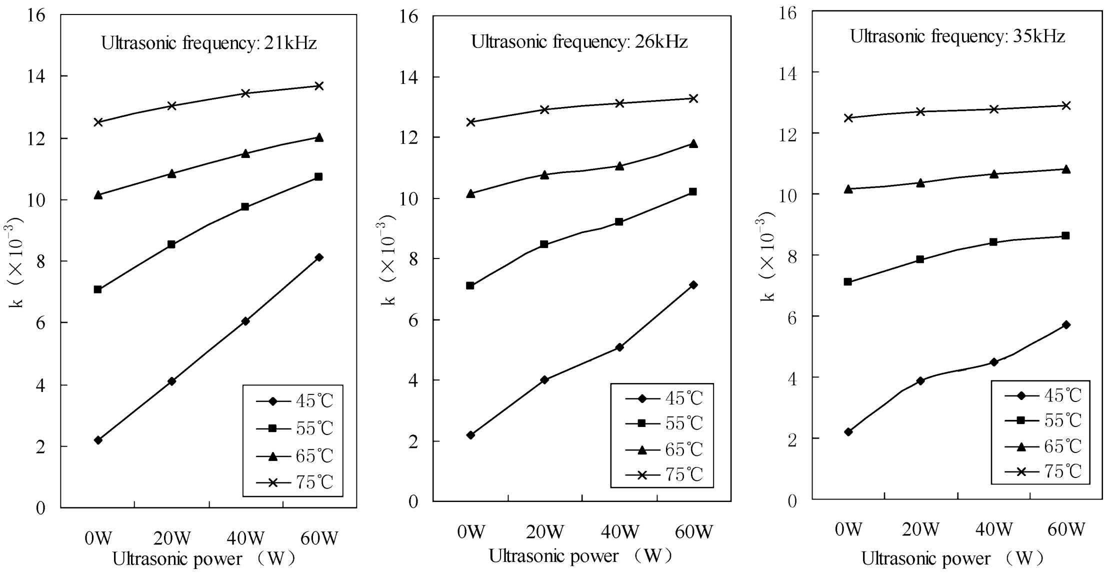


Figure 4. Influence of power on *k* in the kinetic model at different regeneration temperatures.

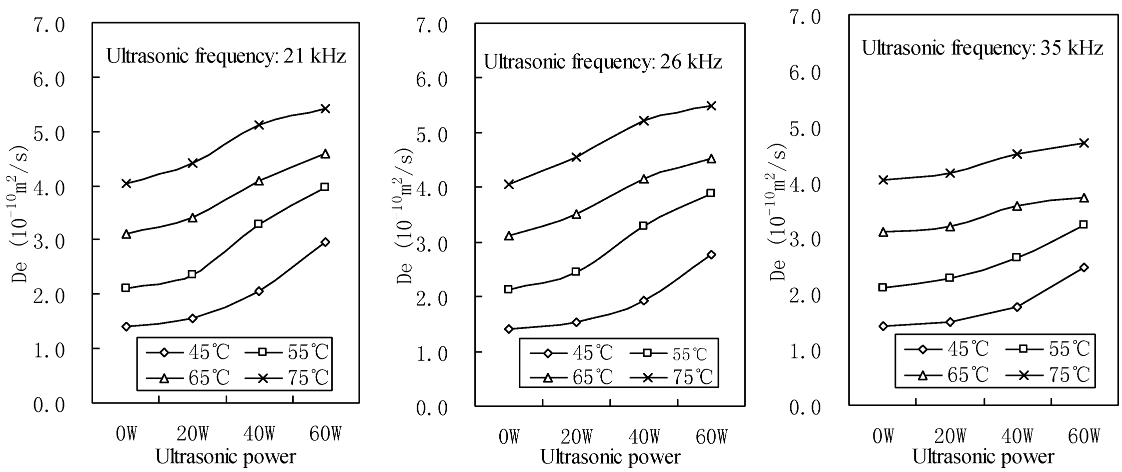


Figure 5. Influence of ultrasound power on D_e of moisture in silica gel during the regeneration.

diffusivity (D_e) until the power reaches above 20 W. It can also be found from Figure 5 that the ascend gradients of D_e become increasingly steeper with the rising of ultrasonic power under the relatively lower regeneration temperatures (e.g., 45 °C), while it is adverse for the cases when the regeneration temperature is higher (e.g., 75 °C). Besides, the effects of ultrasonic power on the moisture transfer in silica gel will be synchronously influenced by the frequency of ultrasound. The slopes of D_e against the ultrasonic power at 21 kHz are obviously steeper than that at 35 kHz. The phenomenon may be explained by the fact that the attenuation of ultrasonic energy will increase with the rising of frequency as the ultrasound propagates through the medium.

Figure 6 shows the influence of ultrasonic power on the enhanced rate (ER) of regeneration during the first 16 min regeneration. As can be seen from Figure 6, higher ER assisted by the ultrasound will be achieved at the lower regeneration temperature. Taking 21 kHz for example, the ultrasound with 20 W in power brings about 60% in ER at the regeneration temperature of 45 °C, whereas the ER brought by the same power of ultrasonic decreases with the increase of regeneration temperature, for example, the ER drops to about 45, 30, and 20%, respectively, at 55, 65, and 75 °C. It may be explained by the following two reasons: first, the higher regeneration temperature means more thermal energy being put into the regeneration, which results in a smaller proportion of ultrasonic energy in the total energy applied to the regeneration. Therefore, the role of ultrasound in the enhancement of regeneration will be weakened. The second may be that the higher regeneration temperature leads to a higher working temperature of ultrasonic transducer that will decrease the working efficiency of the machine. Another interesting phenomenon can be found from Figure 6, in that the curves of ER versus the ultrasonic power bend upward at the regeneration temperature over 65 °C and downward below 55 °C. It indicates that the increase of ultrasonic power will be more efficient in the enhancement of regeneration under lower regeneration temperatures.

Conditioned regeneration time (CRT) is a particularly important factor that impacts the operation performance of desiccant system. Clearly, the desiccant system will be of higher regeneration time can be shortened. As shown in Figure 7, the ultrasound can markedly reduce the regeneration time of silica gel. As far as 45 °C (the regeneration temperature) is concerned, the CRT (RD = 0.5) under the ultrasound with 21 kHz in frequency and 20 W in power, which was determined as about 65 min by the experimental data, is about 40 min less than that under no ultrasonic radiation. The CRT will be further reduced as the ultrasonic power applied to the regeneration increases. In such case (45 °C in the regeneration temperature, RD = 0.5), the time required for the regeneration drops about to 45 and 38 min, respectively, as the ultrasonic power rises to 40 and 60 W. In addition, the effect of ultrasonic power on CRT may be

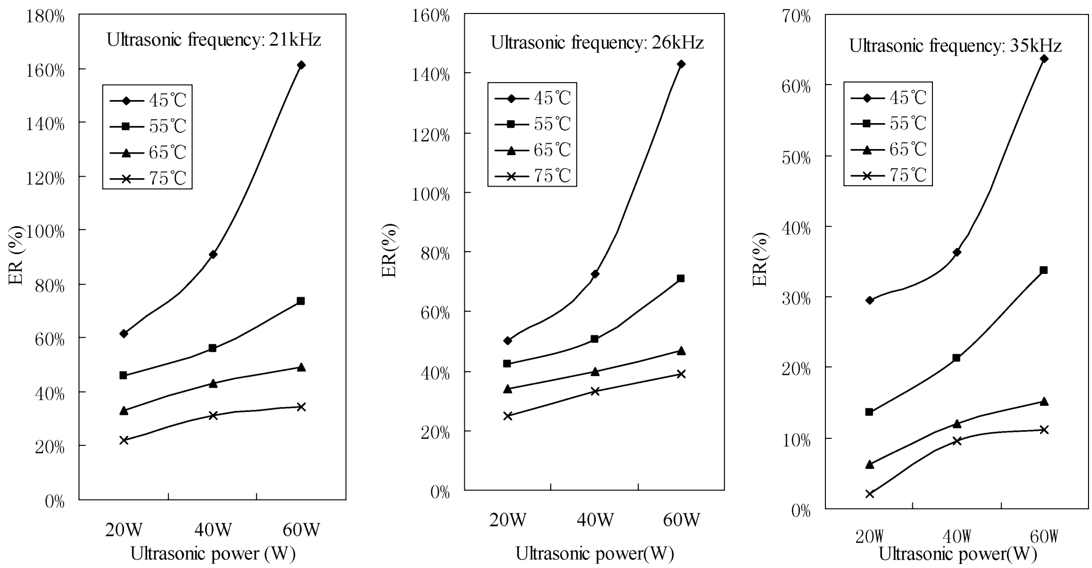


Figure 6. Influence of ultrasonic power on ER during the first 16 min regeneration.

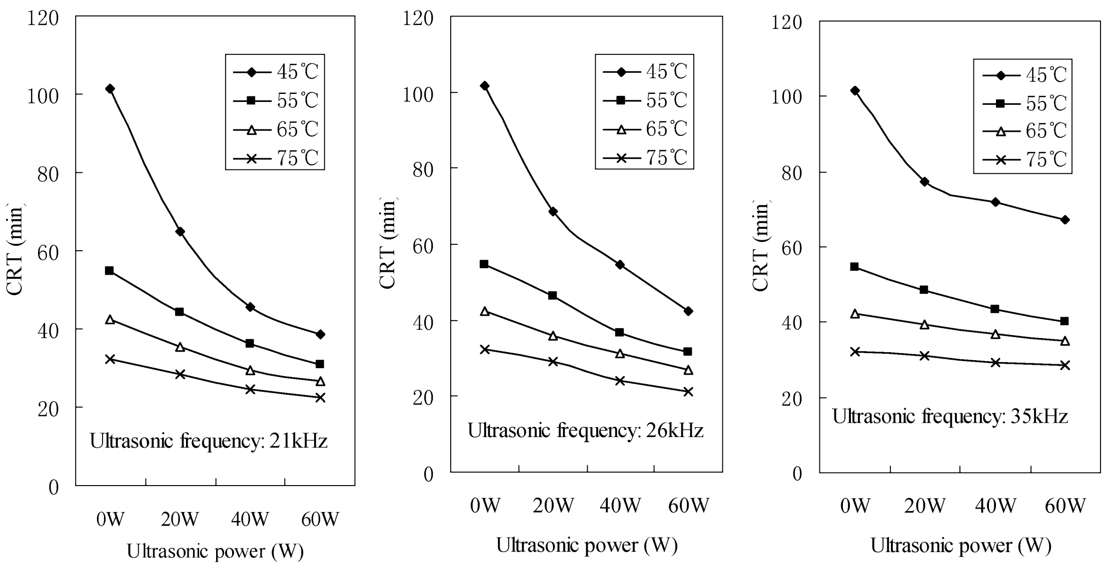


Figure 7. Influence of ultrasonic power on CRT at RD = 0.50.

influenced as well by the regeneration temperature and the ultrasonic frequency. Comparing the curves of CRT versus ultrasonic power in Figure 7, it can be found that the equal increase of power in ultrasound will bring about shorter CRT in the case of lower regeneration temperatures or lower ultrasonic frequency.

3.2. Influence of Ultrasonic Frequency. Frequency is another important parameter considered in the ultrasonic application. Different frequencies used will result in different kinetic models for the ultrasonic regeneration. As presented in Figure 8, the value of k in the kinetic model (eq 1) declines with the increase of ultrasonic frequency, and the decline gradient becomes more significant as the ultrasonic power rises. As mentioned above, bigger value in k means more rapid regeneration rate. Therefore, lower frequency may be in favor of ultrasonic in the regeneration, especially when the ultrasonic power is high. The similar patterns can be reflected as well by Figure 9 in which the values of D_e in the silica gel under the radiation of 21 kHz ultrasound are distinctly bigger than that under the 35 kHz ultrasound with identical power, and the slopes of D_e against the ultrasonic frequency also increase with the rising of ultrasonic power applied.

The ER against the ultrasonic frequency under different regeneration temperatures are plotted in Figure 10. The general trend can be got from Figure 10 is that the ER decreases with the rising of the ultrasonic frequency, especially when the frequency changes from 26 to 35 kHz. Although some abnormal cases occur under the regeneration temperature of 75 °C, in which the ER at 21 kHz is smaller than that at 26 kHz, the study still insists that the ultrasound with lower frequency should be the favorable choice in the regeneration.

The CRT is also related to the ultrasonic frequency. Taking RD = 0.5 (the regeneration degree arrives at 0.5) for example, the CRT versus the ultrasonic frequency is given in Figure 11. Overall, the CRT increases with the ultrasonic frequency going up. The CRT at 35 kHz is obviously longer than that at the other two frequencies (21 and 26 kHz).

Known from the above analyses, the lower frequency will be favorable for the ultrasound to play a greater positive role in the regeneration of silica gel, including the higher D_e and ER as well as the shorter CRT. The reason may be that higher frequency results in an increase of energy dissipation in the porous medium[13] and, as a consequence, the ultrasonic wave

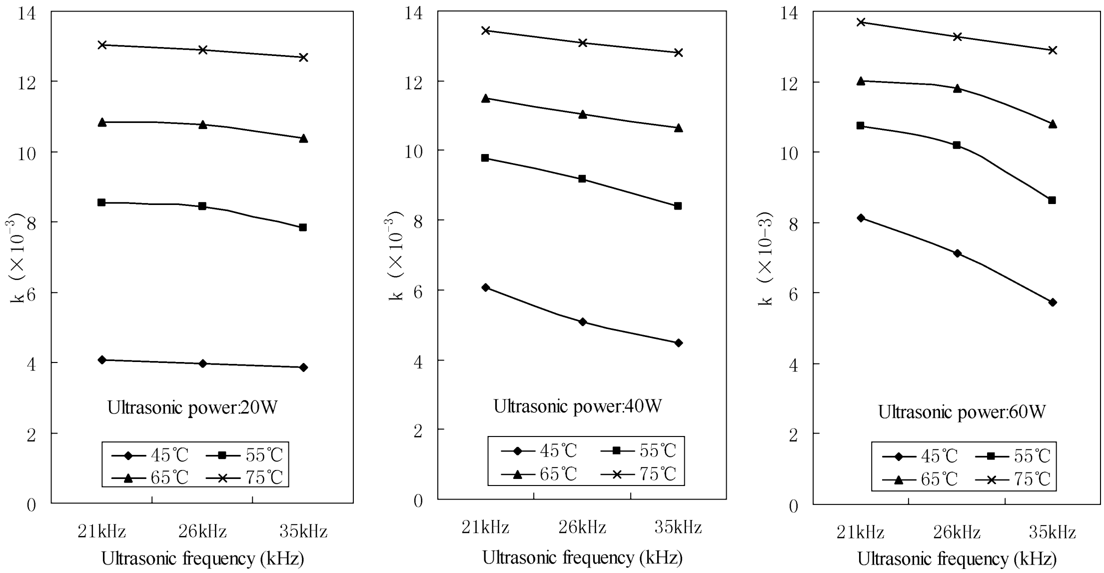


Figure 8. Influence of frequency on k in the kinetic model at different regeneration temperatures.

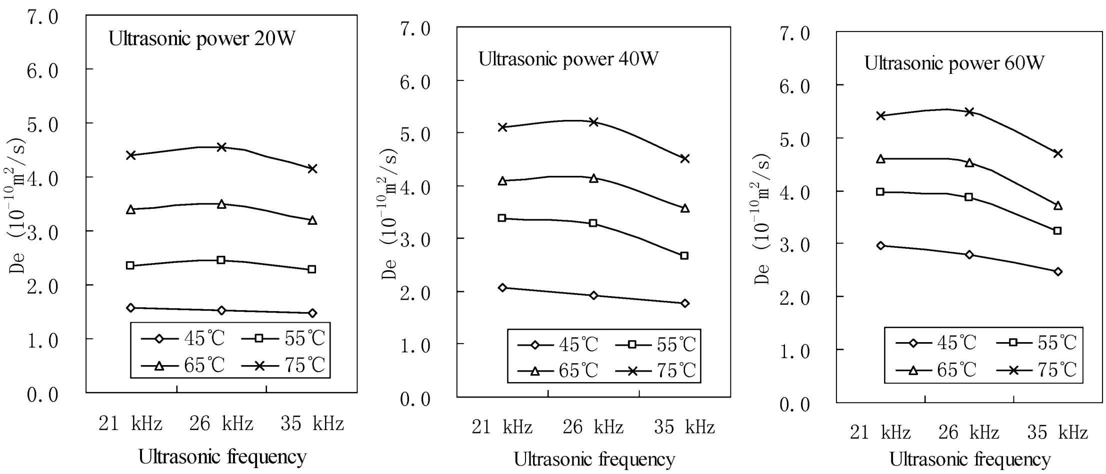


Figure 9. Influence of ultrasound frequency on D_e of moisture in silica gel during the regeneration.

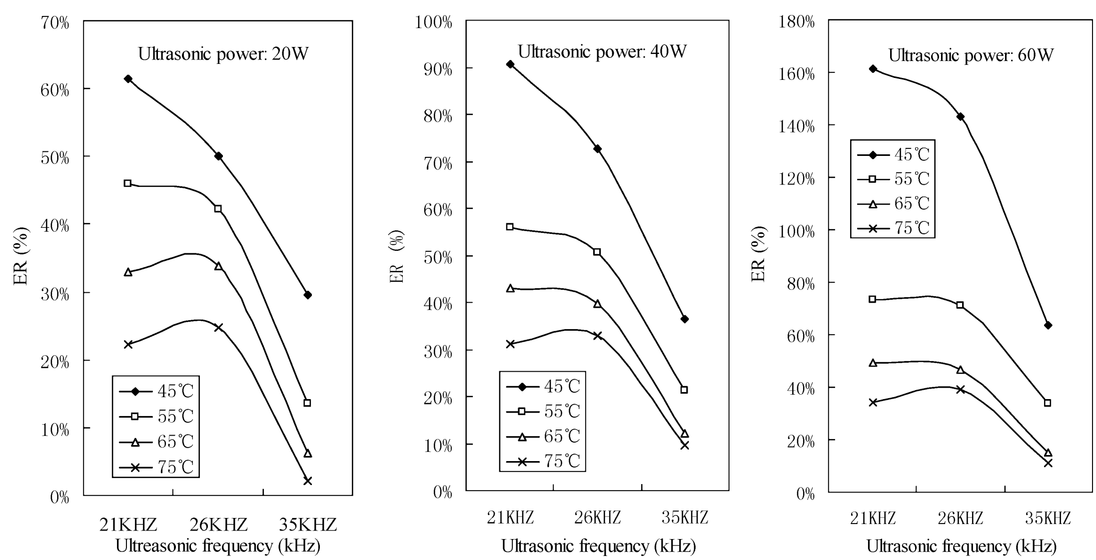


Figure 10. Influence of ultrasonic frequency on ER during the first 16 min regeneration.

does not penetrate into the silica gel deeper. The similar result can be found in the other study[14] that confirmed the ultrasonic with 20 kHz will achieve better effect than that with 40 kHz in the product drying process. However, too low frequency, for example, lower than 16 kHz, may cause big noise that is actually

(13) OBrien, R. W. *Phys. Chem. Chem. Phys.* **2006**, *8* (43), 5115–5123.

(14) Jambrak, A. R.; Mason, T. J.; Paniwnyk, L.; Lelas, V. *J. Food Eng.* **2007**, *81* (1)), 88–97.

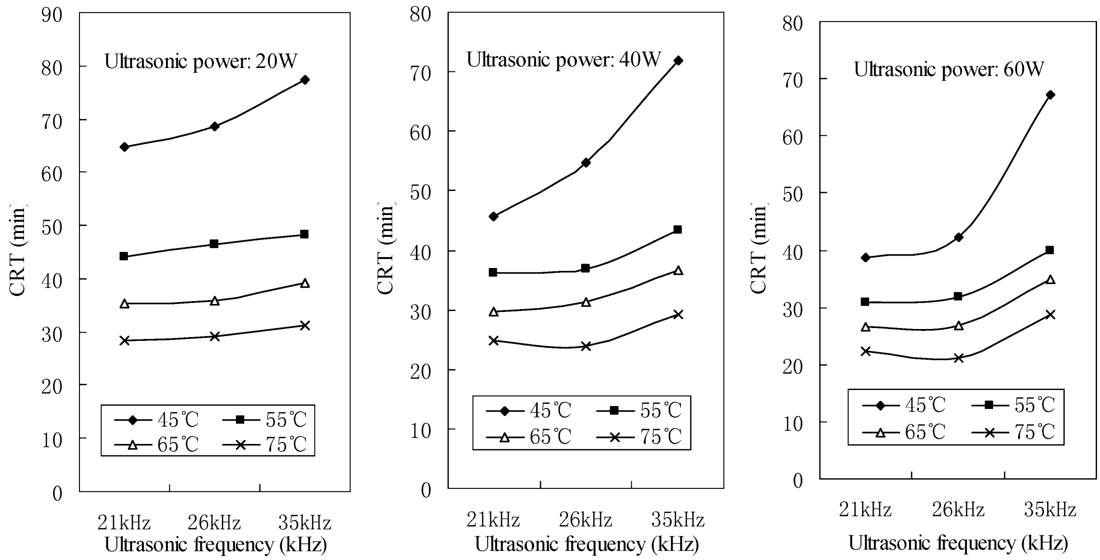


Figure 11. Influence of ultrasonic frequency on CRT at RD = 0.50.

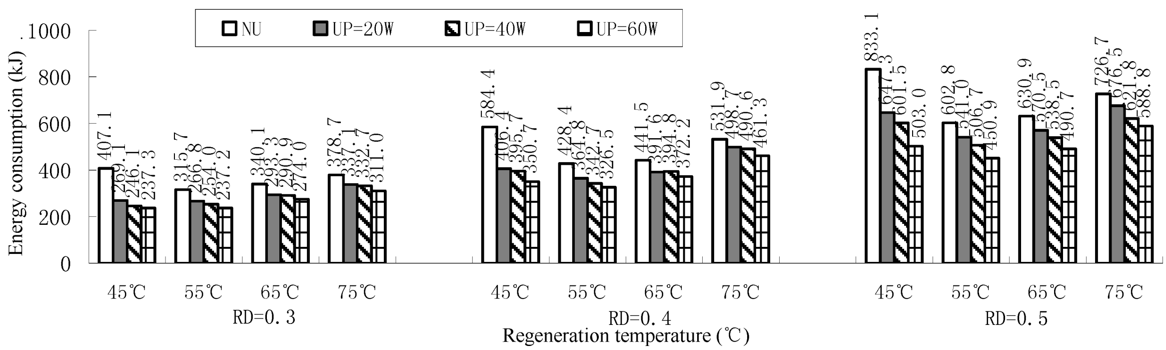


Figure 12. Comparisons of energy consumption between the NU and U cases (UF = 21 kHz).

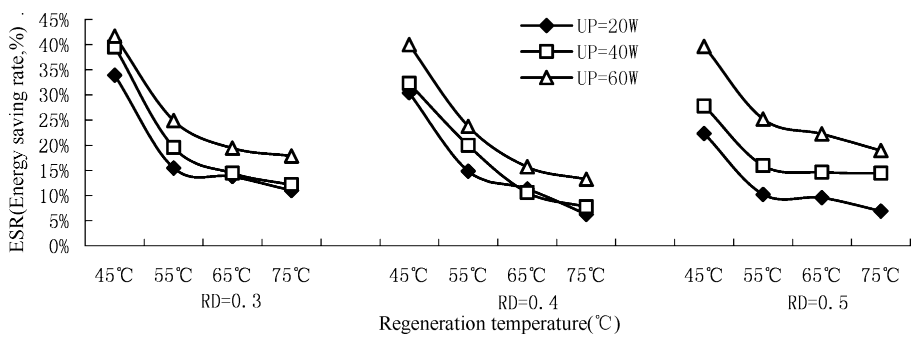


Figure 13. ESR brought by the ultrasound (UF = 21 kHz) in the regeneration.

not permitted in most occasions. Hence, around 20 kHz is suggested for the ultrasonic regeneration.

3.3. Energy Analysis. The energy consumptions are compared between the NU (no ultrasound) case and U (ultrasound existing) cases under different conditions. Since the lower frequency does better for the ultrasonic regeneration, the 21 kHz study is focused on for the energy analysis. The energy consumption required for different RD achieved (RD = 0.3, 0.4, and 0.5) is calculated, respectively, based on the CRT and the total power used by the heater and the ultrasonic producer. The results of energy consumption and the ESR brought by the ultrasound in different cases are shown, respectively, in Figures 12 and 13. Obviously, the regeneration energy can be reduced after the ultrasonic power is put into the regeneration. Several reasons lead to the energy savings. First, the mass transfer in the medium can be enhanced by the ultrasound, which may improve the utilization efficiency of heating energy during the regeneration. Second, the CRT can be shortened due to the presence of ultrasound, and hence, less heat loss will be caused in the regeneration. Lastly, the ultrasonic energy is capable of penetrating through the entire mass immediately once the ultrasound begins to work in the regeneration. Therefore, a higher efficiency of energy utilization will be achieved by the ultrasonic regeneration compared with the heating method in which the heat energy only works on the medium surface.

The higher ultrasonic power tends to gain the higher energy saving rate (ESR) for the same regeneration degree (RD). As can be seen from Figure 13, the ultrasound with 60 W in power achieves the higher ESR than that with the lower power (40 W and 60 W) under the same regeneration temperature and the same RD. Besides, the ESR increases with the dropping of regeneration temperature. Taking RD = 0.3 (i.e., the final regeneration degree of the silica gel arrives at 0.3) for example, the ESR brought by the ultrasound with 60 W exceeds 40% at the regeneration temperature of 45 °C, whand the ESR drops to 24.9, 19.4, and 17.9%, respectively, as the regeneration temperature rises to 55, 65, and 75 °C. It indicates that the ultrasound will play a larger role in the energy saving of regeneration under the lower regeneration temperature.

4. Conclusions

From this study, it can be concluded that the ultrasound can effectively enhance the effective diffusivity of moisture in silica gel, improve the regeneration speed, and reduce the conditioned regeneration time (CRT) as well as the energy consumption. The benefits of ultrasonic use in the regeneration mainly depend on the power and the frequency of ultrasound, and meanwhile, are influenced by the regeneration temperature. The ultrasonic power applied should have a threshold value above which the effects of ultrasound in the regeneration become apparent. The lower frequency is favorable for the ultrasound to be used in the silica gel regeneration. The frequency of around 20 kHz is recommended by this paper for the application of the ultrasonic regeneration. The effects of ultrasonic parameters (i.e., frequency and power) on the regeneration are more significant at the lower regeneration temperatures. Besides, the role of the ultrasound played in the regeneration of silica gel will increase with the dropping of the regeneration temperature.

The Page equation can be used to establish the moisture change model of silica gel during the ultrasonic regeneration. The regeneration rate constant (k) in the model generally increases with the rising of ultrasonic power and the lowering of ultrasonic frequency. However, the Page model is completely empirical and may be difficult to generalize. A better model mostly based on the mechanism should be developed in the future study.

Acknowledgment. This work was supported by The National Natural Science Foundation of China under contract No. 50708057 and The Specialized Research Fund for the Doctoral Program of Higher Education of China under contract No. 2007024811.

Note Added after ASAP Publication. There was an error in reference 12 of the version of this paper published ASAP May 6, 2009; the corrected version published ASAP May 12, 2009.

EF801066M