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Modeling of Silica Gel Dehydration Assisted by Power Ultrasonic

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ABSTRACT

Regeneration of dehumidizers (a typical drying process) is the most important stage in the working cycle of desiccant system. Lowering the regeneration temperature is one of the most effective way to improve the energy efficiency of the system. Ultrasonic technology, as a non-heating method, may help improve mass transfer in materials and accomplish the drying process under a lower temperature. In the present work, the dehydration of silica gel assisted by power ultrasonic was experimentally studied under different drying air temperatures (i.e. 45℃, 55℃, 65℃ and 75℃). Three kinds of frequencies (i.e. 21 kHz, 26 kHz and 35 kHz) combined with three power levels (20W, 40W and 60W) of ultrasonic were employed to investigate the affects of acoustic frequency and intensity on the dehydration process. Moreover, the characteristics of ultrasonic drying were modeled, respectively, by different drying models, i.e. the Page, the Lewis, the Henderson & Pabis, the Logarithmic and the Weibull model. Meanwhile, the suitability of these models for the ultrasonic regeneration was evaluated by the following indexes: the root mean square error (RMSE) and the relative percent error (PE).
Keywords: ultrasonic, silica gel, drying, modeling

1. INTRODUCTION

Silica gel, as a type of dehumidizer, has found its major application in desiccant-based air-conditioning systems (Chang et al., 2005) and cooling systems (Baker, 2008) due to its high moisture adsorption capacity. Regeneration (i.e. dehydration of moist silica gel) may be the core process of the silica gel application in these systems. In general, the regeneration is made through heating, The higher regeneration temperature will bring about the larger desiccant volume of silica gel, but it is adverse to the energy efficiency of desiccant systems because the higher temperature will, on the one hand, cause bigger energy dissipation; on the other hand, it is inconvenient to utilize the low-temperature energy sources widely existed in the nature (Yao and Liu, 2008). Therefore, decreasing the regeneration temperature with non-heating method may be an effective method to improve energy efficiency of desiccant systems using silica gel. Recently, power ultrasound has been proved to become a promising dehydration method for silica gel regeneration (Yao and Liu, 2008; Yao et al., 2009). The supporting principle may be that the ultrasound will produce micro-oscillation and acoustic streaming when it transmits through the medium [7], which can enhance heat and mass transfer process occuring in the dehydration of silica gel.

The objectives of this work include the following two aspects: (1).Qualitative analysis on the affects of power ultrasound on the dehydration process under different acoustic frequency (i.e. 21 kHz, 26 kHz and 35 kHz) and energy power levels (i.e. 20W, 40W and 60W); (2). Modelling the kinetics of ultrasonic dehydration by different drying models (i.e. the Page model, the Lewis model, the Henderson & Pabis model, the Logarithmic model and the Weibull model) from which the best one is found out to predict the behaviour of silica gel dehydration process.

2. MATERIALS AND METHODS

2.1 Experimental setup

The experimental setup (see Fig.1) mainly consists of the silica gel bed, the ultrasonic transducer (i.e. ultrasonic shaker), the ultrasonic generator, the fan, the duct and the electric heater with a power controller. The silica gel bed (the key component of the experimental system), as shown in Fig.2, is a cylindrical container with the height of about 95 mm. It is made of two steel cylindrical shells with numerous orifices (about 2.5 mm in size) in the surface and two round steel plates. The two cylindrical shells, about 20 mm and 50 mm, respectively, in diameter, are concentrically placed and fixed by the two plates at both ends. The sample (i.e. silica gel: 3.5±0.5 mm in diameter; Specific surface area$\geqslant$600m^2/g; Pore diameter=20-30Å (angstrom); pore volume=0.35- 0.45 *ml*/g; bulk density=750*g/l.*) is then filled in the space enveloped by the two cylindrical shells and the two plates. The ultrasonic transducer is clung tightly to one plate through which the ultrasound propagates into the silica gel in the bed. During experiments, the hole is connected with the outlet of the air duct. The hot air from the duct firstly 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 positive/negative electrode of the ultrasonic transducer is of active connection with the positive/negative output of the ultrasonic producer that can produce high-energy ultrasound with the power range of 0～300 W and different frequency ranging from 16 kHz to 100 kHz. The electric heater, which is used for creating different experimental temperatures of hot air, is installed in the upward stream of the air duct. A temperature-and-humidity sensor (type: HMT100; measurement precision: ±2% in humidity and ±0.2℃ in temperature) is placed at the outlet of the air duct to monitor the conditions of regeneration air during the experiments. A humidifier used to wet the silica gel in the bed to the initial moisture ratio for the experiment, is placed at the inlet of the fan. The other instruments include an electronic balance (measurement precision: ±0.1g) for measuring the moisture change in silica gel, a dry-wet bulb thermometer (measurement precision: ±0.5℃) for monitoring the ambient air conditions and a digital anemometer (measurement precision: ±3% of reading data) for testing the airflow rate in the air duct.

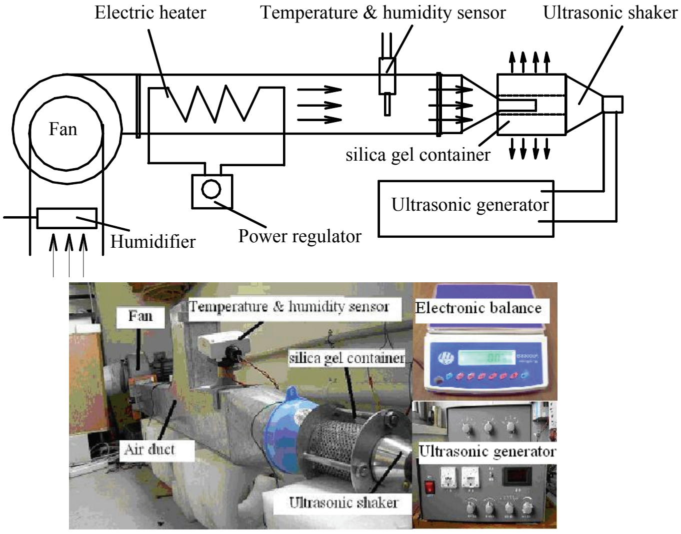


Figure 1 Schematic diagram for the experimental setup

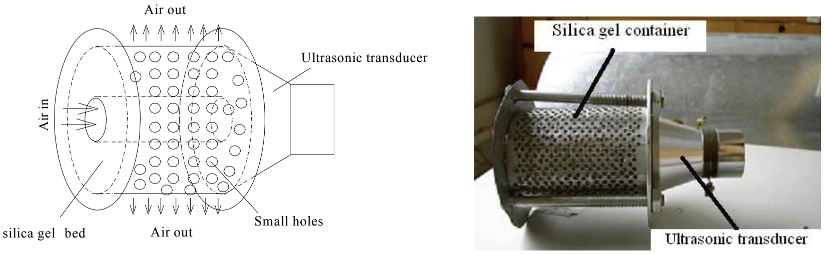


Figure 2 Schematic diagram for the silica gel bed

2.3 Procedure

Experiments were done at a series of regeneration temperatures, i.e. 45℃, 55℃, 65℃ and 75℃, to investigate the effect of ultrasound in the regeneration. Three kinds of acoustic frequencies (i.e. 21 kHz, 26 kHz and 35 kHz) combined with three power levels (20W, 40W and 60W) of ultrasonic were employed for this study. During the experiments, the environmental conditions were kept basically stable, i.e. the air temperature and relative humidity was at about 27±2℃ and 70±10%，respectively. And the airflow rate in the air duct was checked as about 0.3±0.05m/s.

The basic procedure of experiment was as follows:

Firstly, certain amount of fresh silica gel (175.1±0.1 grams) was tightly filled in the bed. The total weight of the bed together with silica gel and the ultrasonic transducer was measured and recorded.

Secondly, the bed was connected with the air duct through a funneled connection. The silica gel in the bed was humidified by the humidizer till the experimental moisture ratio. In this study, the initial weight of the moisted silica gel before regeneration was identically 200.4±0.1 grams.

Thirdly, the bed was temporarily moved away from the air duct. The humidifier was turned off, and the heater was turned on. The experimental regeneration temperature (e.g. 45℃) was created by adjusting the power controller that controls input power of the electric heater.

Afterwards, the bed was reconnected with the air duct and the experiment with or without ultrasound at the experimental temperature was performed. During the period of experiment, the bed was weighed by the electronic balance for every eight minutes to observe moisture change of the silica gel inside. The total experimental time for each condition lasted until no measurable weight loss was observed in the sample.

Finally, silica gel in the bed was fully dried to get the dry sample. In this study, the nearly dry sample, whose mass was measured as about 150.8±0.1 grams, was acquired by an electronic oven with the baking temperature of 300℃.

2.4 Method of analysis

The statistical model of ANalysis Of VAriance (or **ANOVA**) is employed to evaluate the significance of influence of ultrasound on silica gel dehydration under different regeneration conditions. In this work, the drying air temperature and power levels were chosen as the independent variables, and the moisture change in silica gel (ΔM) was chosen as the dependent variable. The analysis of data (ΔM) can be obtained according to the experimental data in different regeneration stages (i.e., the first 8 min, the first 16 min, the first 24 min, etc.), and totally eight samples are analyzed for each regeneration condition. The LSD (least significance difference) intervals ($p < 0.05$) are used to distinguish the significant differences among different regeneration conditions. Statistical analysis is performed by means of the SPSS 14.0 software package (Zhu and Yin, 2007) . To analyze the effect of acoustic frequency on the dehydration assisted by ultrasound, the enhanced raito (ER) brought by the ultrasound is suggested, which is defined as below:

$$ER = \frac{\Delta M_{(-US)} - \Delta M_{(+US)}}{\Delta M_{(-US)}} \times 100\% \qquad (1)$$

where, $\Delta M_{(-US)}$ is the change of moisture mass in silica gel during the regeneration without ultrasound, kg; $\Delta M_{(+US)}$ is the change of moisture mass in silica gel during the regeneration assisted by ultrasound, kg.

2.5 Drying models

Some semi-theoretical drying models, e.g. the Page (Eq.(2)), the Lewis (Eq.(3)), the Henderson & Pabis (Eq.(4)), the Logarithmic (Eq.(5)) as well as the Weibull (Eq.(6)), have been used to quantify drying kinetics of different agricultural products, such as seeds and grains (Midilli and Kucuk, 2003; Sogi et al., 2003; TogrulI and Pehlivan, 2004; Akpinar et al., 2006).

$$WR = \frac{W_\tau - W_e}{W_o - W_e} = \exp(-Kt^n) \qquad \text{Page model} \qquad (2)$$

$$WR = \frac{W_{\tau} - W_e}{W_o - W_e} = \exp(-Kt) \qquad \text{Lewis model} \qquad (3)$$

$$WR = \frac{W_{\tau} - W_e}{W_o - W_e} = A\exp(-Kt) \qquad \text{Henderson \& Pabis model} \qquad (4)$$

$$WR = \frac{W_{\tau} - W_e}{W_o - W_e} = A\exp(-Kt) + C \qquad \text{Logarithmic model} \qquad (5)$$

$$WR = \frac{W_{\tau} - W_e}{W_o - W_e} = \exp(-\left(\frac{t}{\beta}\right)^{\alpha}) \qquad \text{Weibull model} \qquad (6)$$

where, W_{τ} is moisture ratio in material at any time (τ) of drying, kg/kg drysample; W_o, W_e is initial and equilibrium moisture ratio, respectively; $A, C, K, n, \alpha, \beta$, are obtained by fitting the experimental drying curves.

These models are examined in this study to see whether they are suitable for depicting the drying process of silica gel assisted by ultrasound. The predicted WR is compared to the experimental one, and the goodness of fit for each model is evaluated by the relative percent error (PE) shown as below (McMinn, 2006; Roberts and David, 2008):

$$PE(\%) = \frac{100}{n}\sum_{i=1}^{n}\left[\frac{\left|WR_{\exp eriment,i} - WR_{\bmod el,i}\right|}{WR_{\exp eriment,i}}\right] \qquad (7)$$

It’s easy to understand that the lower the RMSE and PE are, the better the model will be. The experimental data for every condition are divided into two equal groups, the first group are used to determine the empirical constants of these models, and the second group are used for the model validation.

3. RESULTS AND DISCUSSION

3.1 Influence of acoustic parameters

In our previous study (Yao et al., 2009), the influence of acoustic parameters on silica gel dehydration has been quantitatively analyzed. In this work, the statistical method is used to analyse the influence qualitatively. Table 1 shows the multiple comparisons of ΔM (the moisture change in silica gel) among different acoustic power levels (i.e. 0W, 20W, 40W and 60W). The results show that the impact of acoustic power on the dehydration will be influenced by the dry air temperature and the acoustic frequency. Under the lower drying air temperature, the threshold power level of ultrasound required for the significant effect on the dehydration will be lower than that under the higher temperature. Taking 21kHz for example, in the case of 35℃, only 20W in acoustic power can result in significant difference of ΔM compared with the circumstance of no ultrasonic radiation (0W in acoustic power). But when the drying air temperature rises to 45℃, the ultrasound with 20W in power level produces little effect on ΔM , only after the power increases to certain level (e.g., 40W) can the ultrasound cause a significant effect on the silica gel dehydration. For 55℃ and 65℃ (in the drying air temperature), however, the threshold power level of ultrasound may increase to 60W, and will be higher when the temperature is 75℃. It can be inferred as well from Table 1 that the acoustic frequency is another key factor influencing the effect of ultrasonic dehydration for the silica gel regeneration. As shown in Table 1, at 45℃ in the drying air temperature, the differences of ΔM between 0W and 40W or 60W are insignificant when the ultrasound with 38kHz is employed, while it is reverse in the case of 26kHz and 21kHz. It indicates that for the same power level, the better effect of dehydration will be achieved by the ultrasound with the lower frequency. To further illustrate this point, the comparisons of enhanced raito (ER) of dehydration brought by the ultrasound with different acoustic frequencies at the drying temperature of 45℃ are shown in Fig.3, which manifests the benefit of lower frequency of ultrasound applied in the silica gel dehydration. This can be explained by the reason that higher frequency results in an increase of energy dissipation in the porous medium (O’Brien, 2006) and, as a consequence, the ultrasonic wave does not penetrate into the silica gel deeper.

Table 1 Multiple comparisons of ΔM among different acoustic power levels

Drying air temperature	*f=21kHZ*			*f=26kHZ*			*f=38kHZ*		
	0W			0W			0W		
	20W	40W	60W	20W	40W	60W	20W	40W	60W
35℃	*	*	*	*	*	*	.113	*	*
45℃	.213	*	*	.328	*	*	.524	.398	.261
55℃	.695	.314	*	.772	.398	*	.892	.746	.549
65℃	.609	.355	*	.877	.430	.316	.860	.740	.597
75℃	.410	.217	.123	.449	.267	.213	.732	.515	.413
'*'denotes significant difference; values indicate non-significant difference.									

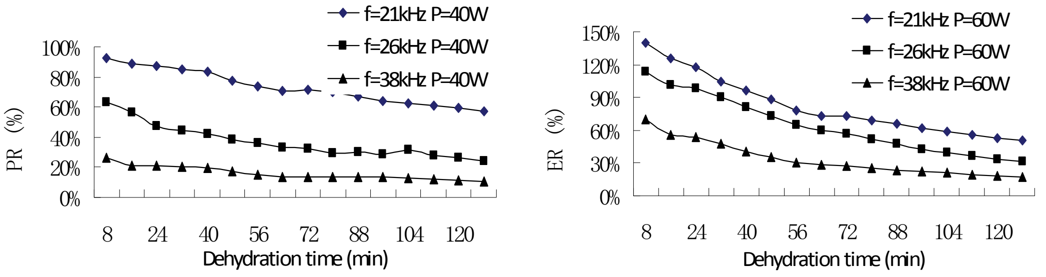


Figure 3 Enhanced ratio brought by the ultrasound with different acoustic frequencies (Drying air temperature: 45℃)

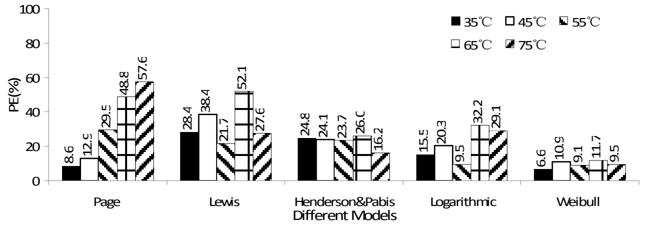
3.2 Model analysis

Table 2 shows the empirical constants in different models that are got by fitting the experimental data with the Least Squares method. In the Page, the Lewis, the Henderson & Pabis and the Logrithmic model, the constant k (also called the drying rate constant) is directly related to the drying rate, and the constant β in the Weibull model is inversely linked to the drying rate. It is reasonable to suppose that the higher dehydration rate would lead to the bigger value of k or the smaller value of β. Therefore, the value of k under the higher drying air temperature will be larger than that under the lower temperature, and it is reverse for the constant β. The effect of acoustic power level and frequency on the silica gel dehydration can be also indicated by the constant k and β. It can be known from the values of k and β in Table 2 that the higher acoustic frequency is not favorable for the ultrasonic dehydration.

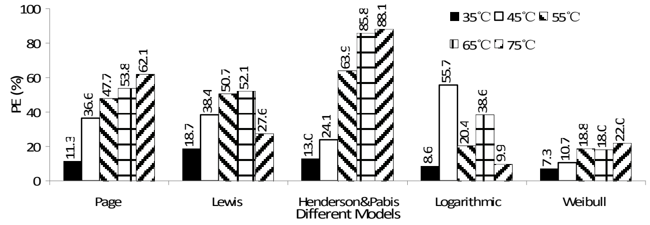
Fig.4 gives the results of the PE for these models under different dehydration conditions. It can be easily found that among these models, the Weibull model will have the best prediction (the lowest PE) for the behaviour of silica gel dehydration assisted by ultrasound, and the second favorable model for that is the Logarithmic model. The Page and the Henderson & Pabis model are the worst. Many values of PE of the two models exceed 50% , some are even close to 100%. Hence, the Page and the Henderson & Pabis model may be not suitable for describing the dehydration process of silica gel assisted by ultrasound. Nevertheless, the Weibull model does not always have good prediction. For example, in the case of 65℃ and under the ultrasonic parameter of 26kHz and 20W, the PE of Weibull model reaches 30%. Still, the Weibull model can be employed to analyze the drying kinetics of dehydration assisted by ultrasound (de la Fuente Blanco et al., 2006).

Table 2 Empirical constants of the models focused in this study

Acoustic parameters		Drying air temp.	Page model		Lewis model	Henderson & Pabis model		Logarithmic model			Weibull model	
Frequency	Power Level		K	n	K	A	K	A	K	C	α	β
21 kHz	20 W	35℃	0.0036	1.3341	0.0126	1.0450	0.0138	1.7232	0.0064	-0.7232	1.2847	66.4141
		45℃	0.0056	1.3471	0.0201	1.0571	0.0217	1.9371	0.0086	-0.9159	1.3343	47.9401
		55℃	0.0144	1.1910	0.0284	1.0331	0.0295	1.2210	0.0207	-0.2111	1.3041	35.1434
		65℃	0.0177	1.1542	0.0304	1.0270	0.0313	1.1590	0.0237	-0.1528	1.2316	33.3451
		75℃	0.0183	1.2421	0.0387	1.0410	0.0402	1.1360	0.0315	-0.1171	1.1962	27.2231
	40 W	35℃	0.0063	1.2344	0.0150	1.043	0.0162	1.6311	0.0084	-0.6081	1.2909	61.6412
		45℃	0.0073	1.2982	0.0218	1.0510	0.0232	1.6381	0.0111	0.6218	1.3256	41.7921
		55℃	0.0123	1.2511	0.0306	1.0404	0.0320	1.2231	0.0223	-0.2089	1.2754	32.7421
		65℃	0.0177	1.1790	0.0331	1.0311	0.0341	1.1721	0.0251	-0.1651	1.2125	30.3402
		75℃	0.0205	1.2021	0.0403	1.0341	0.0415	1.1081	0.0341	-0.0913	1.2136	25.2212
	60 W	35℃	0.0111	1.1281	0.0177	1.0290	0.0185	1.1681	0.0149	-0.1483	1.1445	55.0241
		45℃	0.0117	1.2251	0.0263	1.0381	0.0275	1.3560	0.0164	-0.3487	1.2256	37.1421
		55℃	0.0127	1.3752	0.0336	1.0620	0.0357	1.3021	0.0225	-0.2738	1.3521	29.7421
		65℃	0.0175	1.1970	0.0346	1.0361	0.0358	1.1431	0.0279	-0.1269	1.1925	28.5211
		75℃	0.0202	1.2271	0.0427	1.0350	0.0441	1.1141	0.0355	-0.0976	1.2066	24.2211
26 kHz	20 W	35℃	0.0037	1.2891	0.0112	1.0421	0.0122	1.804	0.0053	-0.8041	1.3481	72.9403
		45℃	0.0068	1.2651	0.0180	1.0501	0.0195	1.5081	0.0109	-0.4812	1.3034	51.2431
		55℃	0.0134	1.2012	0.0276	1.0371	0.0287	1.2311	0.0201	-0.2171	1.2641	36.7421
		65℃	0.0141	1.1971	0.0271	1.0211	0.0277	1.0841	0.0242	-0.0747	1.1225	35.5211
		75℃	0.0151	1.2771	0.0363	1.0490	0.0395	1.2120	0.0274	-0.1923	1.1621	28.2711
	40 W	35℃	0.0074	1.1801	0.0146	1.0350	0.0155	1.3721	0.0101	-0.3512	1.2255	64.9401
		45℃	0.0096	1.2781	0.0211	1.0490	0.0225	1.5801	0.0114	-0.5610	1.2872	45.2413
		55℃	0.0141	1.2110	0.0296	1.0371	0.0308	1.2031	0.0221	-0.1891	1.2124	35.0412
		65℃	0.0161	1.2151	0.0319	1.0310	0.0332	1.1471	0.0256	-0.1361	1.1725	30.5212
		75℃	0.0177	1.2290	0.0390	1.0370	0.0404	1.0851	0.0352	-0.0595	1.2302	26.1203
	60 W	35℃	0.0104	1.1321	0.0171	1.0321	0.0179	1.1801	0.0142	-0.1604	1.2993	57.9421
		45℃	0.0093	1.2871	0.0261	1.0490	0.0028	1.4461	0.0151	-0.4313	1.3182	38.2431
		55℃	0.0169	1.2073	0.0329	1.0451	0.0348	1.2471	0.0231	-0.2329	1.2824	31.0412
		65℃	0.0189	1.1541	0.0338	1.0281	0.0342	1.0921	0.0292	-0.0772	1.1825	29.5231
		75℃	0.0238	1.1550	0.0412	1.0461	0.0431	1.1231	0.0357	-0.0944	1.2602	26.0192
38 kHz	20 W	35℃	0.0027	1.3451	0.0102	1.0440	0.0113	2.5215	0.0034	-1.5215	1.2843	80.9402
		45℃	0.0044	1.3521	0.0166	1.0571	0.0181	2.3951	0.0058	-1.3721	1.2532	56.2413
		55℃	0.0096	1.2740	0.0252	1.0481	0.0252	1.3641	0.0164	-0.3449	1.2324	38.8412
		65℃	0.0164	1.1320	0.0262	1.0291	0.0271	1.1141	0.0228	-0.0966	1.1725	36.7211
		75℃	0.0192	1.1981	0.0362	1.0401	0.0390	1.0891	0.0342	-0.0607	1.2303	30.8210
	40 W	35℃	0.0056	1,2311	0.0133	1.0391	0.0144	1.7810	0.0068	-0.7603	1.2543	68.9411
		45℃	0.0061	1.2890	0.0174	1.0471	0.0186	1.9890	0.0073	-0.9723	1.4232	54.2401
		55℃	0.0105	1.2621	0.0268	1.0460	0.0282	1.3251	0.0177	-0.3084	1.2924	37.7412
		65℃	0.0170	1.1631	0.0301	1.0340	0.0313	1.1241	0.0257	-0.1046	1.1825	33.2201
		75℃	0.0192	1.1981	0.0375	1.0410	0.0390	1.0891	0.0342	-0.0607	1.1893	28.1214
	60 W	35℃	0.0062	1.2340	0.0145	1.0381	0.0155	1.8571	0.0069	-0.8421	1.2746	61.9412
		45℃	0.0094	1.1890	0.0189	1.0340	0.0198	1.4361	0.0116	-0.4244	1.3233	47.6402
		55℃	0.0101	1.2951	0.0285	1.0481	0.0301	1.3790	0.0174	-0.3655	1.2659	35.0421
		65℃	0.0185	1.1560	0.0319	1.0341	0.0331	1.0961	0.0285	-0.0737	1.1562	32.2201
		75℃	0.0169	1.2541	0.0396	1.0441	0.0413	1.1221	0.0337	-0.0957	1.2402	27.1211



Ultrasound parameter: *f=21 kHz; P=20W*



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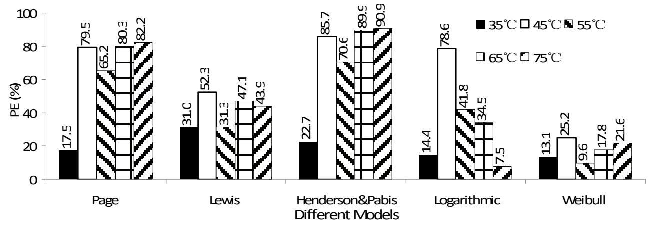
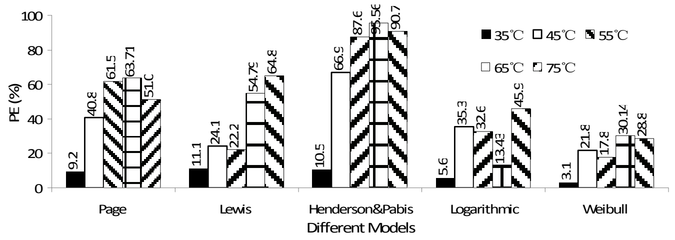


Ultrasound parameter: *f=21 kHz; P=60W*



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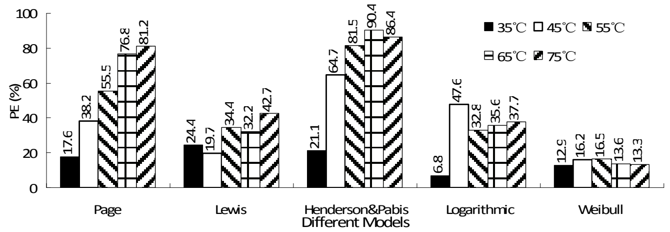
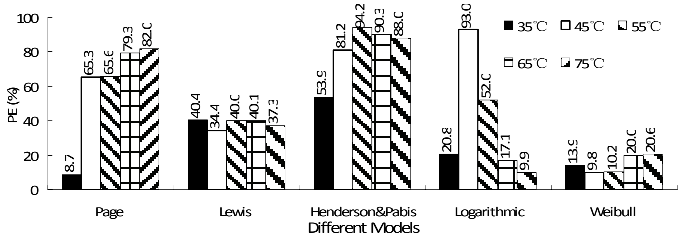
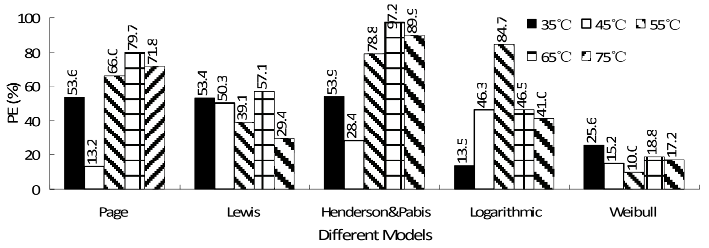


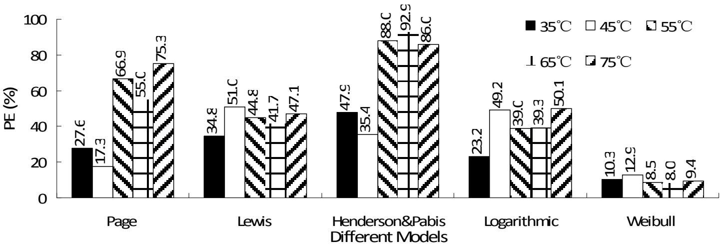
Ultrasound parameter: *f=26 kHz; P=40W*



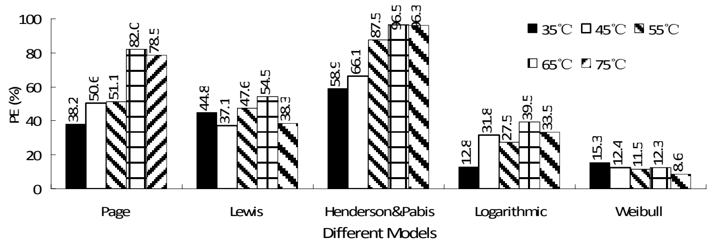
Ultrasound parameter: *f=26 kHz; P=60W*



Ultrasound parameter: *f=35 kHz; P=20W*



Ultrasound parameter: *f=35 kHz; P=40W*



Ultrasound parameter: *f=35 kHz; P=60W*

Figure 4 Model analysis under different dehydrating conditions

4. CONCLUSION

The silica gel dehydation assisted by ultrasound was experimentally studied under different drying air temperatures and acoustic parameters. The statistical method was used to analyze the effects of acoustic level and frequency on the silica gel dehydration. It manifests that the lower acoustic frequency is favorable for the ultrasonic dehydration of silica gel, which is consistent with the results achieved by our previous publication [6]. In particular, the five semi-empirical models (i.e., the Page, the Lewis, the Henderson & Pabis, the Logarithmic and the Weibull model) were studied to model the drying kinetics of ultrasonic dehydration. It was found that among these models, the Weibull model would be an overall better prediction model for the drying behaviour of silica gel assisted by ultrasound.

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