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Experimental and predictive study on the performance and energy consumption characteristics for the regeneration of activated alumina assisted by ultrasound

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ABSTRACT

Activated alumina used in dehumidification should be regenerated at more than 110 °C temperature, resulting in excessive energy consumption. Comparative experiments were conducted to study the feasibility and performance of ultrasonic assisted regeneration so as to lower the regeneration temperature and raise the efficiency. The mean regeneration speed, regeneration degree, and enhanced rate were used to evaluate the contribution of ultrasound in regeneration. The effective moisture diffusivity and desorption apparent activation energy were calculated by theoretical models, revealed the enhanced mechanism caused by ultrasound. Also, we proposed some specific indexes such as unit energy consumption and energy-saving ratio to assess the energy-saving characteristics of this process. The unit energy consumption was predicted by artificial neural network (ANN), and the recovered moisture adsorption of activated alumina was measured by the dynamic adsorption test. Our analysis illustrates that the introduction of power ultrasound in the process of regeneration can reduce the unit energy consumption and improve the recovered moisture adsorption, the unit energy consumption was decreased by 68.69% and the recovered moisture adsorption was improved by 16.7% under 180 W power ultrasound compared with non-ultrasonic assisted regeneration at 70 °C when initial moisture adsorption was 30%. Meanwhile, an optimal regeneration condition around the turning point could be obtained according to the predictive results of ANN, which can minimize the unit energy consumption. Moreover, it was found that a larger specific surface area of activated alumina induced by ultrasound contributed to a better recovered moisture adsorption.

1. Introduction

Activated alumina, as a commonly used solid desiccant, has a high specific surface area and good moisture adsorption, which has been widely applied in petrochemical industry, food industry and air-conditioning industry [1]. It has a high specific surface area ($\geq 300 \text{ m}^2/\text{g}$), and its moisture adsorption is greater than 50% [2]. In specific industrial applications, activated alumina can be professionally developed to enhance relevant performance, making it cost-efficient solutions to many pressing environmental problems [3,4]. Compared with silica gel, activated alumina has advantages in higher stability and stronger affinity for halides [5]. Activated alumina could recover moisture adsorption ability through regeneration which is also called desorption. Dupont et al. [6] studied the adsorption and desorption properties of silica gel and activated alumina and reported that the regeneration temperature of activated alumina is higher than silica gel.

Abd-Elrahman et al. [7] tested the transient desorption characteristics of activated alumina using radial flow desiccant bed at different regeneration temperatures (110–198 °C). Hamad et al. [8] stated that the high regeneration temperatures (110–198 °C) may limit the applications of activated alumina. Abou-Ziyan et al. [1] studied the adsorption and regeneration performance of thin-multilayer activated alumina bed. It was found that the activated alumina had higher COP and faster dynamic response compared with silica gel. Thus, activated alumina has different characteristics from silica gel on account of own special properties.

However, more energy dissipation will occur due to the higher regeneration temperature. Using low-temperature energy to regenerate the activated alumina can not only reduce the energy dissipation, but also potentially utilize solar energy and waste heat. To solve with this problem, some techniques have been proposed such as using vacuum and hot water [9,10], hot air combined with hot water [11], etc. These

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techniques are aimed to use low-grade energy to regenerate desiccants, but require additional equipment, such as hot water tanks, vacuum pumps, water coils, etc. And also, a major problem needs to be considered that the operation procedure and initial investment are complex and large.

The regeneration of activated alumina is essentially a drying process. Related studies [12–16] proposed the technique of power ultrasound assisting the drying process. Ultrasound can produce ‘thermal effect’ and ‘non-thermal effects’ (mechanics, cavitation and sponge effects) when propagating through solid media [17–19]. Based on these effects, activated alumina has the potential to be regenerated with ultrasonic irradiation. But activated alumina has not been tested using power ultrasound since silica gel has been the mainstay desiccant in industry and laboratory use for a long time. There still lacks a relevant research on the performance and energy consumption characteristics of ultrasound-assisted regeneration of activated alumina so far. Meanwhile, the parametric study is very helpful to further understand the enhanced mechanism of ultrasound, and provide some guidance for the optimal design of ultrasound-assisted regeneration system. Although a few scholars have studied the performance of ultrasound-assisted drying and regeneration, the performance was only reported for particular range of ultrasonic power [14–16]. The prediction of unit energy consumption at different conditions will be very essential for optimal design of the system. In addition, the recovered moisture adsorption of activated alumina after ultrasound-assisted regeneration is very important for its reuse in the system and the further development of this technology.

Thus, the objective of the present work is to investigate the performance and energy consumption characteristics for the regeneration of activated alumina assisted by ultrasound. The content mainly concerns about the following four aspects:

- (1) Investigation about the effects of ultrasound on the mean regeneration speed (*MSR*), regeneration degree (*RD*) and enhanced rate (*ER*) of activated alumina regeneration under different conditions.
- (2) Analysis on the enhanced mechanism induced by ultrasound by calculating the effective moisture diffusivity (D_{eff}) and desorption apparent activation energy (E_a) of activated alumina during regeneration.
- (3) Report and prediction on the unit energy consumption (*UEC*) and energy-saving ratio (*ESR*) of the system at different ultrasonic power levels.
- (4) Discussion about the recovered moisture adsorption of activated alumina after regeneration by dynamic adsorption test.

2. Material and methods

2.1. Materials

The sample of activated alumina used in this experiment was provided by Sinopharm Chemical Reagent Co., Ltd (China). The physical properties were given as follows: specific surface area ≥ 200 m²/g, pore diameter = 30–40 Å (angstrom), pore volume = 0.38–0.42 ml/g, bulk density ≤ 0.75 g/ml, particle size distribution = 3.5 ± 0.5 mm in diameter, and dynamic adsorption capacity of equilibrium water (100% RH, 20 °C) $\geq 25.0\%$.

2.2. Experimental set up

The schematic diagram of experimental set up is depicted in Fig. 1. The apparatus consists of two parts: a constant temperature and humidity system and an ultrasonic generation and transduction system. The constant temperature and humidity system is mainly composed of a constant temperature and humidity chamber (HS: 150L, China), including dehumidifier, a heating device, a fan, etc., a temperature sensor

(pt100-A), a humidity sensor (AM2322), and a wind speed measuring instrument (NENGZHAO; VS50B, China) and an electronic balance (LICHEN; FA1004, China), etc. The ultrasonic generation and transduction system consists of an ultrasonic generator (XIANOU; 600D, frequency: 15–60 kHz), an ultrasonic transducer (20 kHz, 180 W) and an activated alumina thin layer bed (80 mm \times 80 mm).

2.3. Experimental program

Different regeneration conditions, i.e. 70, 90 and 110 °C in hot air temperature combined with 0, 45, 90, 135 and 180 W in ultrasonic power, were designed for the experimental study. The activated alumina with initial moisture adsorption of 20%, 30% and 40% were regenerated under above conditions. The environmental conditions were kept basically stable, i.e. the air temperature was 25 ± 1 °C and relative humidity was $70 \pm 5\%$.

The mass change of moisture in the activated alumina was measured by weighing method. The experimental procedure was as follows:

- (1) First, a certain amount of activated alumina with certain initial moisture adsorption was completely filled into the thin layer bed, the total weight of activated alumina bed and ultrasonic transducer was measured and recorded.
- (2) Then, the activated alumina was pretreated by different ultrasonic power for 8 min.
- (3) And then, the constant temperature and humidity system was started up to reach a stable environment, put the activated alumina thin layer bed and the ultrasonic transducer into the chamber, and the ultrasonic system was set up to assist at the same time.
- (4) During the regeneration process, the weight of thin layer bed was weighed with the electronic balance after every 60 s in order to observe the moisture change in the activated alumina.
- (5) Finally, the regeneration experiment for each condition was finished when the mass change rate was less than 0.01% in 10 min.
- (6) In order to obtain the drying base mass of activated alumina, the activated alumina used in the experiment was fully dried by vacuum drying machine at 300 °C.

Each experimental condition was run 5 times so as to ensure the reproducibility. The results showed that the maximum relative deviation of the experimental results under the same condition was about 2.0%, indicating the good reproducibility. The repetitive experiments of activated alumina with 30% initial moisture adsorption at 90 °C of air temperature and 90 W of ultrasonic power are shown in Fig. 2.

2.4. Error sources and uncertainty analysis

The error mainly comes from the measurement process of the sample in this experiment. The measurement range of the electronic balance is 0–8.1 kg, with an accuracy of 0.001 g. The measurement error of temperature is 0.5 °C, and the humidity measurement error is 2% RH. The uncertainties of the measured parameters were estimated by using the method in reference [20,21], and listed in Table 1.

2.5. Evaluation indicators

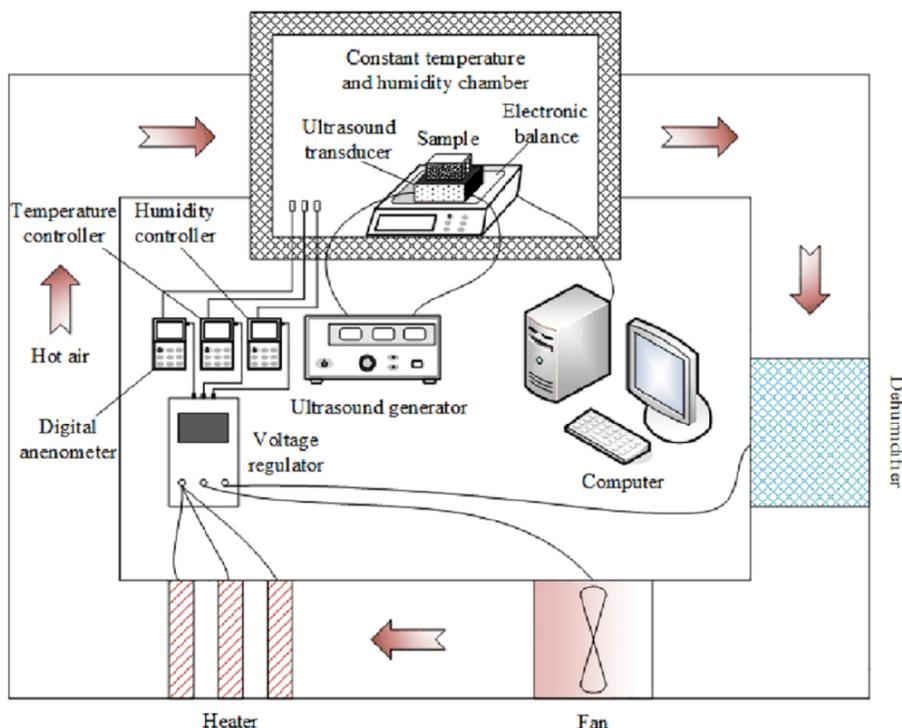
To evaluate the performance of activated alumina regeneration assisted by ultrasound, some indicators are suggested here.

The dry base moisture ratio (*X*) can be expressed as:

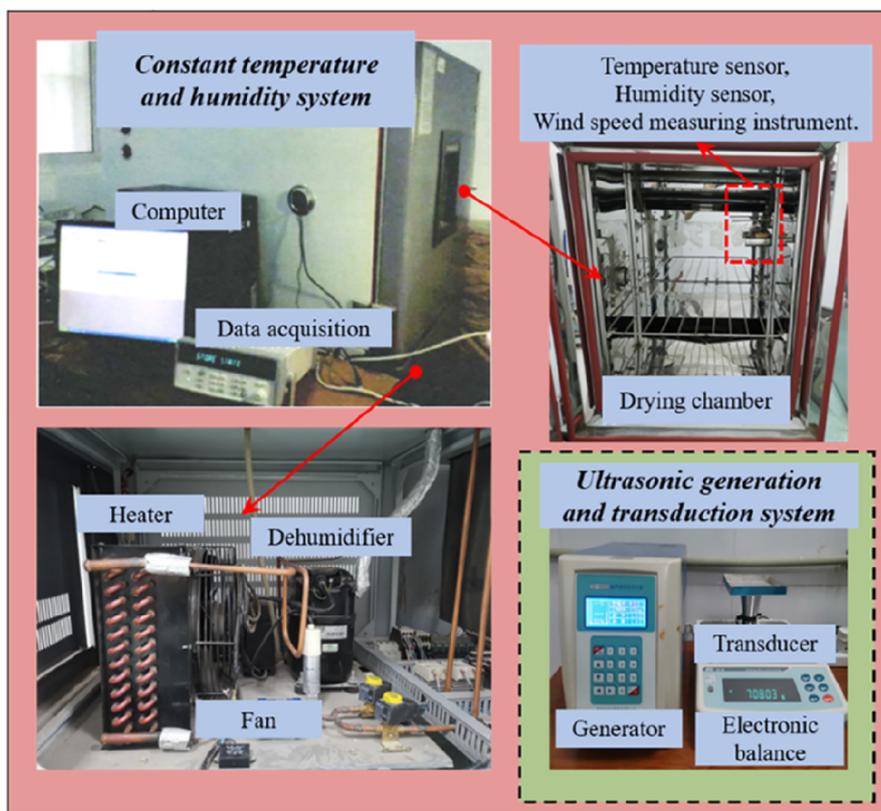
$$X_t = \frac{m_{a,t} - m_{a,dry}}{m_{a,dry}} \quad (1)$$

where $m_{a,t}$ is the mass of activated alumina at any time during the regeneration process (kg), $m_{a,dry}$ is the mass of the dry activated alumina (kg).

The dimensionless moisture ratio (*MR*) implies changes occurring in



(a). The schematic diagram of experimental set up



(b). The field photo of experimental set up

Fig. 1. Schematic diagram and field photo of experimental set up.

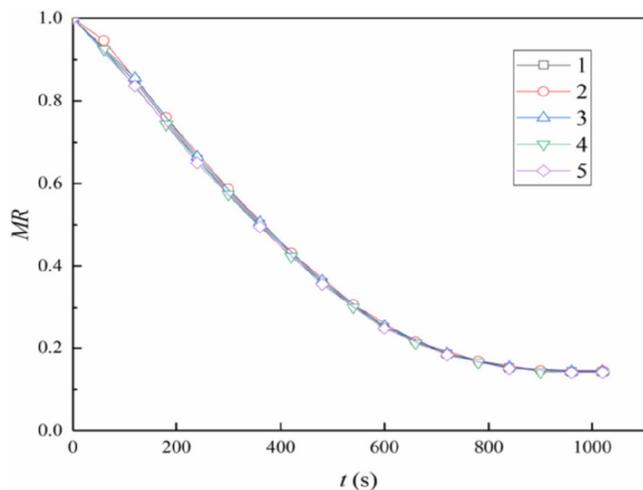


Fig. 2. Repetitive experiments at 90 °C of air temperature and 90 W of ultrasonic power.

Table 1
Uncertainty analysis of measurement parameters.

Parameter	Uncertainty analysis
Temperature	$\pm \frac{\delta T}{T} = \pm \sqrt{\left(\frac{0.35/\sqrt{3}}{70}\right)^2 + \left(\frac{0.1/2\sqrt{3}}{70}\right)^2} = \pm 0.29\%$
Mass	$\pm \frac{\delta m}{m} = \pm \frac{0.001/2\sqrt{3}}{50} = \pm 0.0006\%$
Length	$\pm \frac{\delta l}{l} = \pm \frac{0.1/2\sqrt{3}}{80} = \pm 0.04\%$

the moisture content of activated alumina. Based on the literature [22], the calculation of MR is defined as:

$$MR = \frac{X_t - X_e}{X_i - X_e} \quad (2)$$

where X_t , X_i and X_e refer to the moisture content at specific time (% d.b.), the initial moisture content (% d.b.) and the equilibrium moisture content (% d.b.), correspondingly.

Regeneration degree (RD) is defined as the ratio of the mass of moisture desorption to the initial mass of moisture in the sample [23].

$$RD = \frac{m_{a,i} - m_{a,t}}{m_{a,i} - m_{a,dry}} \quad (3)$$

where $m_{a,i}$ is the mass of activated alumina at the beginning of the regeneration.

Enhanced rate (ER) of activated alumina regeneration assisted by ultrasound is evaluated by [23]:

$$ER = \frac{MRS_U - MRS_{NU}}{MRS_{NU}} \quad (4)$$

where MRS denotes the mean regeneration speed ($\text{kg}\cdot\text{s}^{-1}$), that is, the average moisture desorption rate in a period of regeneration time. The subscript "U" and "NU" denote the case in the presence and absence of ultrasonic irradiation, respectively.

Energy-saving ratio (ESR) brought by ultrasound is defined as [23]:

$$ESR = \frac{EC_{NU} - EC_U}{EC_{NU}} \quad (5)$$

where EC denotes the energy consumption (kWh) used for regeneration.

2.6. Calculation of D_{eff} and E_a

The correlation of effective moisture diffusivity (D_{eff}) of activated alumina, MR and drying time (t) can be calculated by [19,22]:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{L^2} \quad (6)$$

where L means the radius of particle (m), t means the drying time (s). The plotting $\ln MR$ vs. t can be used to evaluate D_{eff} .

Desorption apparent activation energy (E_a) of activated alumina during regeneration can be obtained according to the Arrhenius equation [24,25]:

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{RT} \quad (7)$$

where, D_0 is the pre-exponential factor of Arrhenius equation ($\text{m}^2\cdot\text{s}^{-1}$); E_a is the apparent activation energy ($\text{kJ}\cdot\text{mol}^{-1}$); T is the drying temperature (K) and R is the gas constant ($\text{kJ}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$).

3. Results and discussion

3.1. MR and MRS

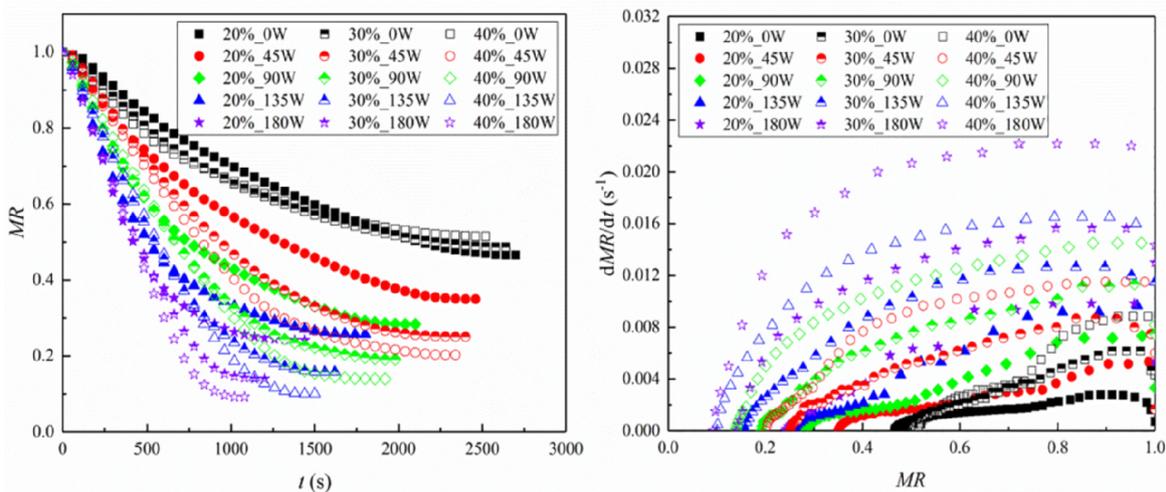
The dimensionless moisture ratio (MR) curve directly reflects the proportion of residual water in the activated alumina during the regeneration process. As observed from Fig. 3, the MR of activated alumina after ultrasonic assisted regeneration was far lower than that after non-ultrasonic assisted regeneration. Such results also suggested that, power ultrasound could be adopted to enhance the regeneration of activated alumina. Meanwhile, a higher regeneration temperature also promoted the regeneration of activated alumina. It was also discovered that, at the beginning of regeneration, MR decreased at a faster rate in the presence of ultrasound, and ultrasound had significant enhancement effect at this stage, as seen from the mean regeneration speed (MRS) curve. To be specific, with the decrease in MR , the difference in MRS between with and without ultrasound gradually decreased.

As can be seen from the MRS curve, with the decrease in MR , MRS gradually declined. Thus, the activated alumina regeneration process can be divided into three stages according to the value of MRS , including initial stage, 1st falling rate stage and 2nd falling rate stage. The MRS rapidly increased within a short time at the initial stage. Hence, the environmental conditions governed the MRS , like the regeneration temperature and ultrasonic power. There's a decrease of the moisture within the activated alumina as the regeneration proceeds, leading to low moisture migration rate. At the 1st falling rate stage, MRS decreased at a slower rate than that at the 2nd falling rate stage, and the duration of the former was also longer than that of the latter. The MRS increased with the increases of regeneration temperature and ultrasonic power. Meanwhile, at the high initial moisture adsorption, the greater difference in MRS between ultrasonic and non-ultrasonic treatment indicated the more significant effect of ultrasound on MRS .

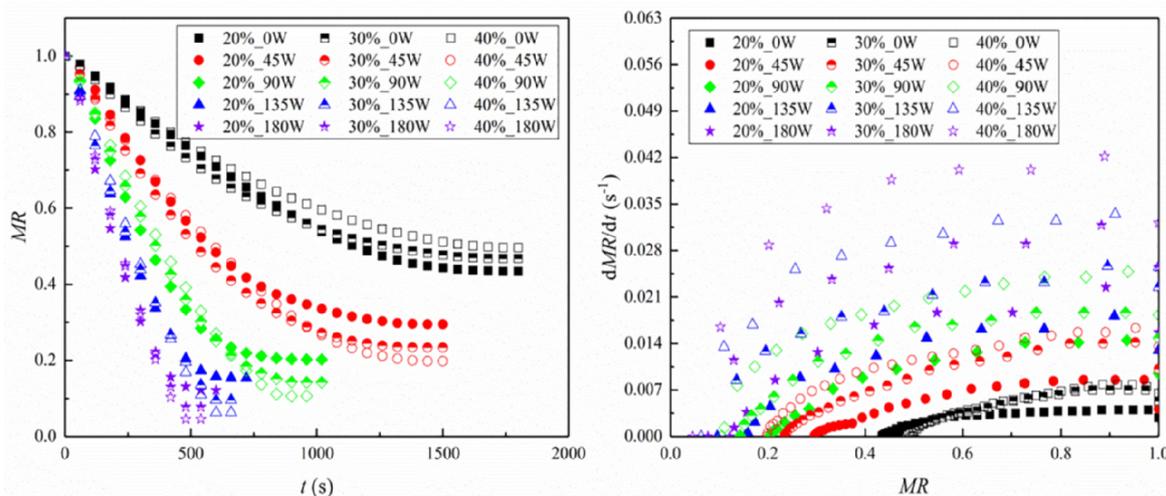
3.2. ER and RD

Fig. 4 displays the impact of ultrasound on the enhanced rate (ER) within the first 8 min. ER increased with the increase of ultrasonic power, and that at 70 °C was much lower than those at 90 °C and 110 °C. This is because that, the regeneration temperature of activated alumina is generally at above 110 °C. At the same regeneration temperature, ER increased with the increase of activated alumina initial moisture adsorption. This indicates that, a higher initial moisture adsorption promotes the enhancement effect of ultrasound during the regeneration process.

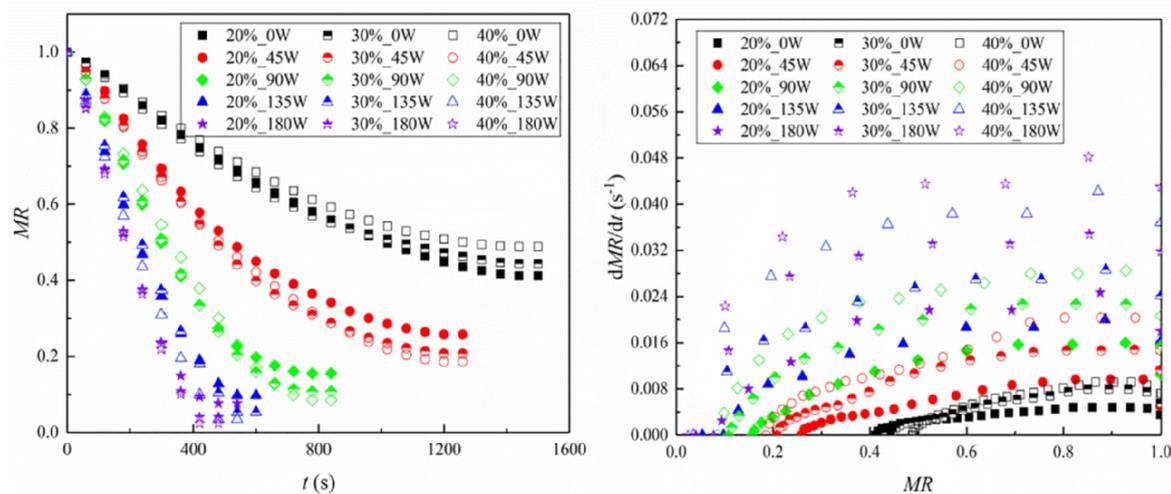
Equilibrium regeneration time, which refers to the time required to maintain the unchanged MR within a certain period of time during the regeneration process. In this study, equilibrium regeneration time was used to compare the decrease in regeneration time under ultrasonic irradiation. As observed from Fig. 5, power ultrasound significantly reduced the regeneration time of activated alumina. Taking activated alumina with the initial moisture adsorption of 20%, for example, at



(a) Regeneration temperature: 70°C



(b) Regeneration temperature: 90°C



(c) Regeneration temperature: 110°C

Fig. 3. Evolutions of MR and MRS with the change in ultrasonic power at different regeneration temperatures.

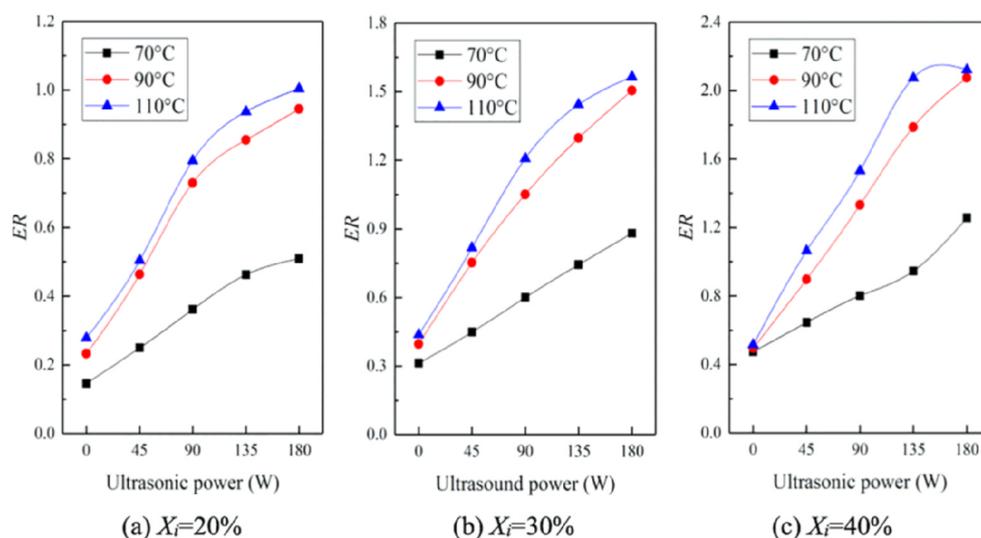


Fig. 4. ER versus ultrasonic power for the first 8-minute regeneration.

70 °C, the equilibrium regeneration time under 45 W power ultrasound was 5 min shorter than that without ultrasound, and those at the regeneration temperatures of 90 °C and 110 °C reduced by about 4.5 and 4 min, respectively. Besides, the equilibrium regeneration time further decreased with the increase in ultrasonic power, and those reduced by 21, 20 and 16 min, respectively, at the 180 W power ultrasound. The reduction in equilibrium regeneration time decreased with the increase of regeneration temperature. The presence of ultrasound had more significant effect on reducing the regeneration time at 70 °C. Moreover, the reduction of equilibrium regeneration time of activated alumina elevated as the initial moisture adsorption increased.

The evolution of the regeneration degree (RD) against the ultrasonic power is plotted in Fig. 6, which can well prove the superior effect of ultrasound on activated alumina regeneration. As shown in Fig. 6, RD increased with the increase of regeneration temperature, ultrasound had better effect on enhancing RD at a higher regeneration temperature. Similarly, a higher initial moisture adsorption contributed to a better effect of ultrasound on enhancing RD . Taking $X_i = 40\%$ and $T = 70$ °C, for example, the RD in the presence of 45 W power ultrasound improved by 79.7% compared with that in the absence of ultrasound, while those at 90, 135 and 180 W improved by 86.0%, 89.9% and 90.8%, respectively.

3.3. D_{eff} and E_a

The influence of ultrasonic power on the effective moisture diffusivity (D_{eff}) is depicted in Fig. 7, which shows that D_{eff} increases significantly with ultrasonic power increasing. Taking $X_i = 40\%$, for example, the values of D_{eff} in the absence of ultrasound were 2.74E-10, 3.65E-10 and 4.56E-10, respectively, at the regeneration temperatures of 70, 90 and 110 °C; while those increased to about 1.91E-9, 2.10E-9 and 2.19E-9 at the 180 W power ultrasound. It convincingly proves that power ultrasound can enhance the moisture transfer in activated alumina, which is ascribed to the ultrasonic “thermal effect” [2]. It should be noted that the D_{eff} elevated slightly with the increase of initial moisture adsorption, especially at a higher ultrasonic power level.

Table 2 lists the values of desorption apparent activation energy (E_a) of activated alumina under different conditions. Taking 20% as the initial moisture adsorption, for example, the E_a values of activated alumina decreased from 0.812 kJ·mol⁻¹ to 0.237 kJ·mol⁻¹ from 0 to 180 W power ultrasound. Less E_a means lower thermodynamic temperature required for the regeneration [14]. Hence, the presence of ultrasound can reduce the regeneration temperature. Yao et al. [14] stated that, the reason responsible for such phenomenon is that, the reduced desorption apparent activation energy can be substituted by

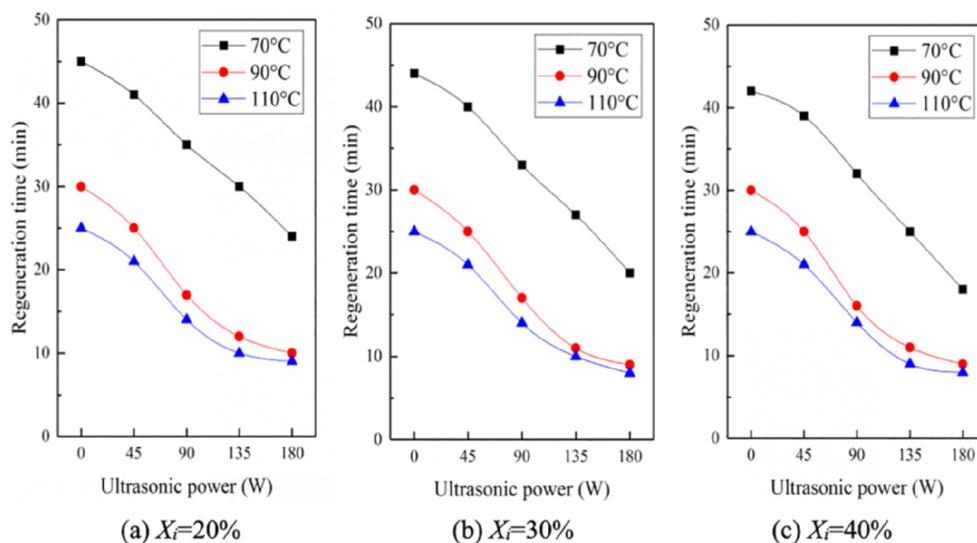


Fig. 5. Equilibrium regeneration time versus ultrasonic power.

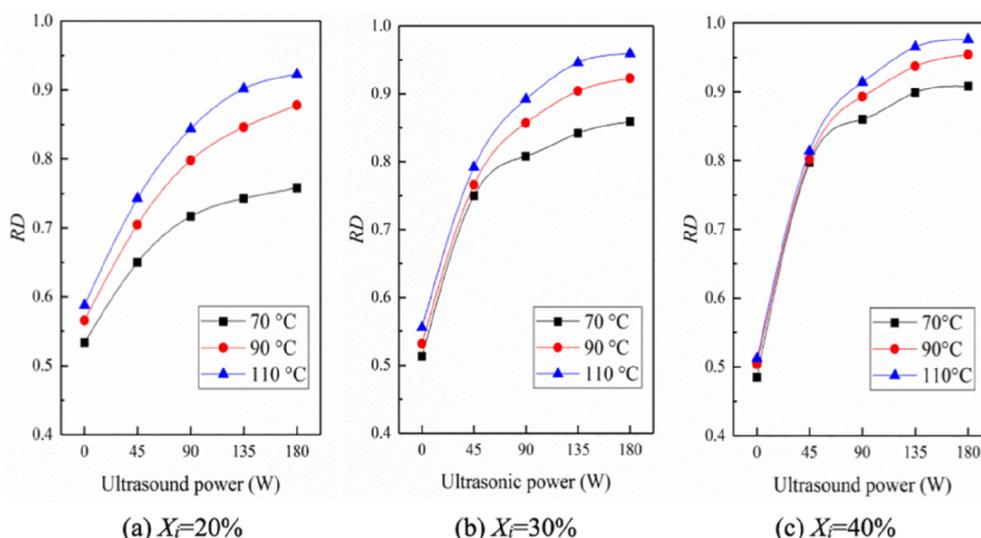
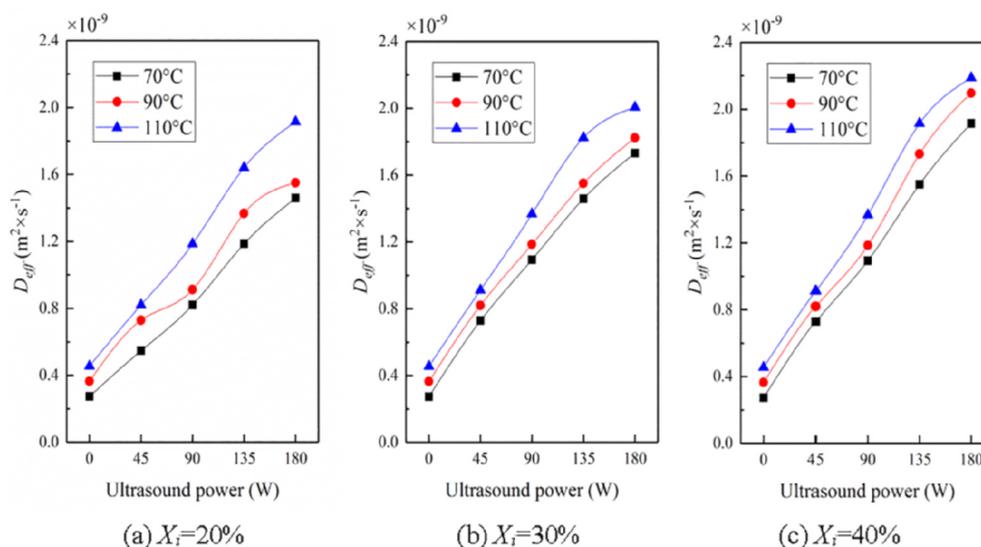


Fig. 6. Equilibrium RD versus ultrasonic power.

Fig. 7. Influence of ultrasonic power on D_{eff} in activated alumina.

the ultrasonic energy, while the “thermal effect” and “non-thermal effect” of ultrasound will lower the E_a .

3.4. UEC and ESR

The unit energy consumption (UEC) during the regeneration (the energy consumption required for desorption of 1 g water from the activated alumina) can be estimated based on the equilibrium regeneration time and the total power used in the system. Fig. 8 shows the comparisons of UEC at different ultrasonic power levels, which

confirms that the energy dissipation can be significantly reduced after the application of ultrasound. Yao et al. [14] also reported similar phenomenon in the silica gel regeneration. Notably, higher initial moisture adsorption was conducive to the reduction of UEC in regeneration as shown in Fig. 8.

Fig. 9 presents the energy-saving ratio (ESR) brought by ultrasound. Within a certain range of ultrasonic power, the higher the ultrasonic power was applied, the higher ESR was obtained in the regeneration. At the initial moisture adsorption of 20% and the regeneration temperature of 70 °C, the ESR acquired at 45, 90, 135 and 180 W power

Table 2

E_a of activated alumina under different conditions.

Ultrasonic power (W)	20%		30%		40%	
	E_a (kJ·mol ⁻¹)	R^2	E_a (kJ·mol ⁻¹)	R^2	E_a (kJ·mol ⁻¹)	R^2
0	0.812	0.997	0.812	0.997	0.812	0.997
45	0.353	0.988	0.353	0.991	0.353	0.991
90	0.344	0.970	0.344	0.969	0.344	0.959
135	0.339	0.962	0.339	0.959	0.334	0.991
180	0.237	0.959	0.237	0.994	0.216	0.994

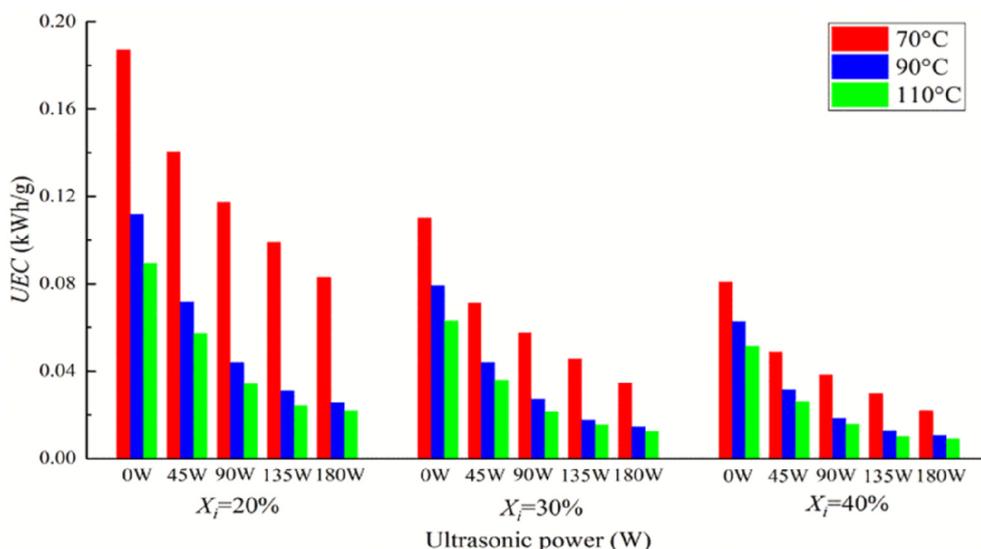


Fig. 8. Comparisons of UEC at different ultrasonic power levels.

ultrasound were 0.22, 0.39, 0.48 and 0.58, respectively. Activated alumina with higher initial moisture adsorption (40%) achieves a higher ESR than that with lower levels (20% and 30%) in the regeneration. Consequently, the ultrasound-assisted regeneration technique can be evaluated and optimized based on the results of ESR, which is consistent with the “specific energy consumption” concept proposed by Zhang et al. [15] during the silica gel regeneration process.

In order to obtain large-scale and high-density results of energy consumption, the artificial neural network (ANN) has been introduced into the prediction of the UEC, which is widely adopted in relevant studies [26–28]. Selecting the appropriate network is of crucial importance to the accuracy and efficiency of the prediction of the UEC. Through massive sample learning, the Back Propagation (BP) network can map any unknown non-linear relation between input and output, which has been extensively applied in various fields at present, such as in predicting and optimizing [29–31]. Thus, the BP network was selected in this paper. The structural design of BP network mainly includes the determination of network layer, determination of the node numbers in input, hidden, and output layers, and the determination of excitation function and the initial weight value [30]. In this network,

the input layer nodes included the initial moisture adsorption of activated alumina, regeneration temperature and ultrasonic power. The output layer nodes directly adopted the UEC as the only output node. The designed network architecture (a secondary BP network consisting of three layers) is shown in Fig. 10, in which the hidden layer is a single layer.

The flow chart of the ANN used for UEC prediction is given in Fig. 11. It was made in MATLAB (R2018a). About 50% experimental data at different conditions have been used to train the network, and the rest is used for the test set. Three standard criteria (*RMS*, *COV*, and R^2) were used to evaluate the ANN network quality, and indicated that the ANN predictions used in this paper has high accuracy. The results of UEC predicted by ANN were presented in Fig. 12. At $X_i = 20\%$, the UEC tended to be stable when the ultrasonic power was greater than 180 W; at $X_i = 30\%$, the UEC slightly increased with the gradual increase in ultrasonic power (greater than 135 W); at $X = 40\%$, the UEC increased as the ultrasonic power increased (greater than 90 W). This reveals that, there is a turning point of ultrasonic power under different initial moisture adsorption. The UEC markedly reduces before the turning point, while the UEC hardly changes after the turning point. It should be noticed that the UEC was the lowest around the turning point.

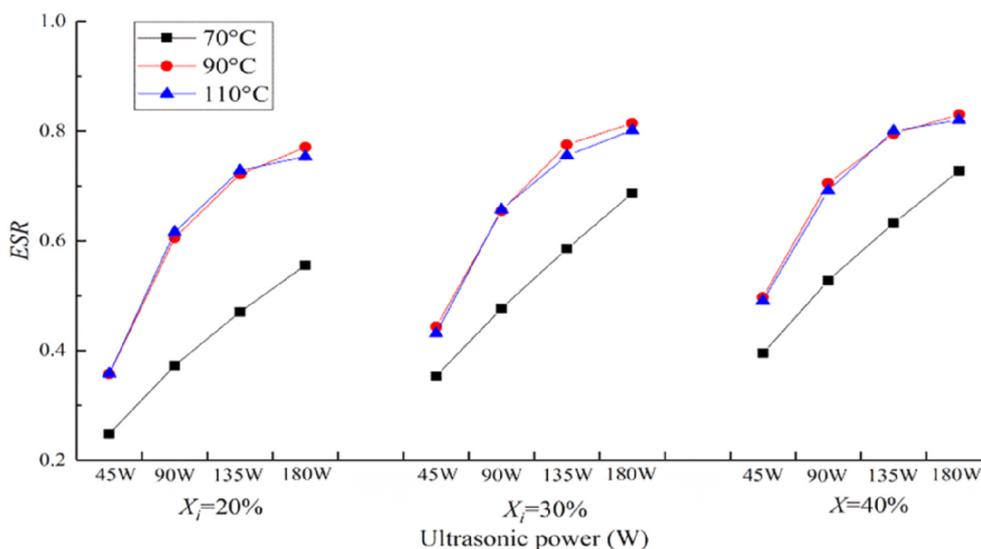


Fig. 9. ESR brought by ultrasound in the regeneration.

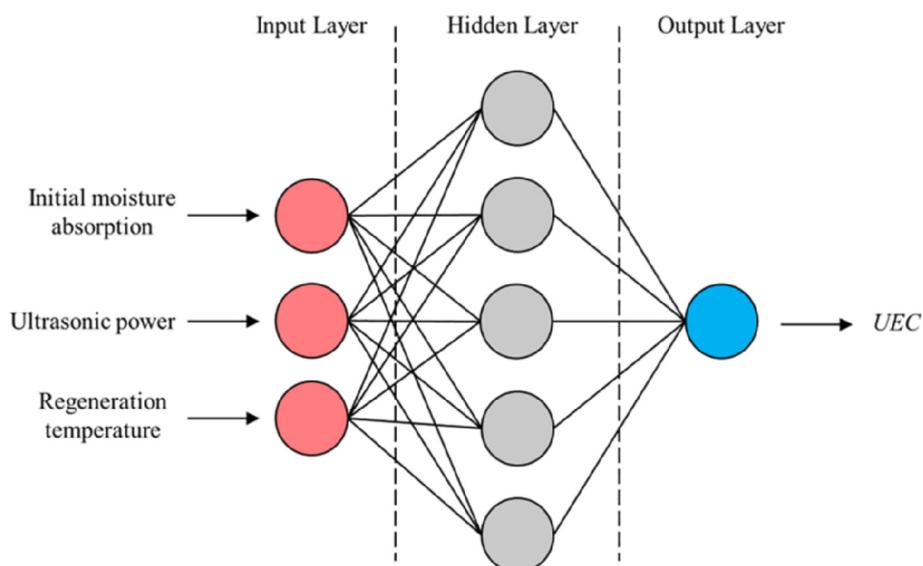


Fig. 10. Architecture of the ANN used for energy consumption prediction.

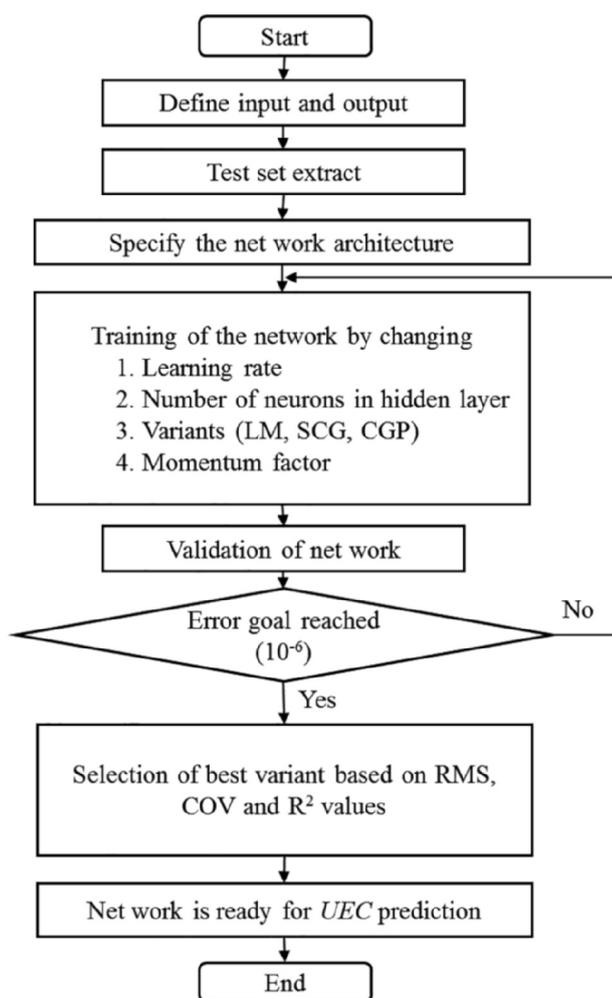


Fig. 11. Flow chart of the ANN used for UEC prediction.

Meanwhile, the ultrasonic power at the turning point decreased with the increase of initial moisture adsorption, which suggested that only lower ultrasonic power is required to rapidly reduce the UEC at a higher initial moisture adsorption. Besides, a higher regeneration temperature led to the lower UEC before the turning point, while the situation is

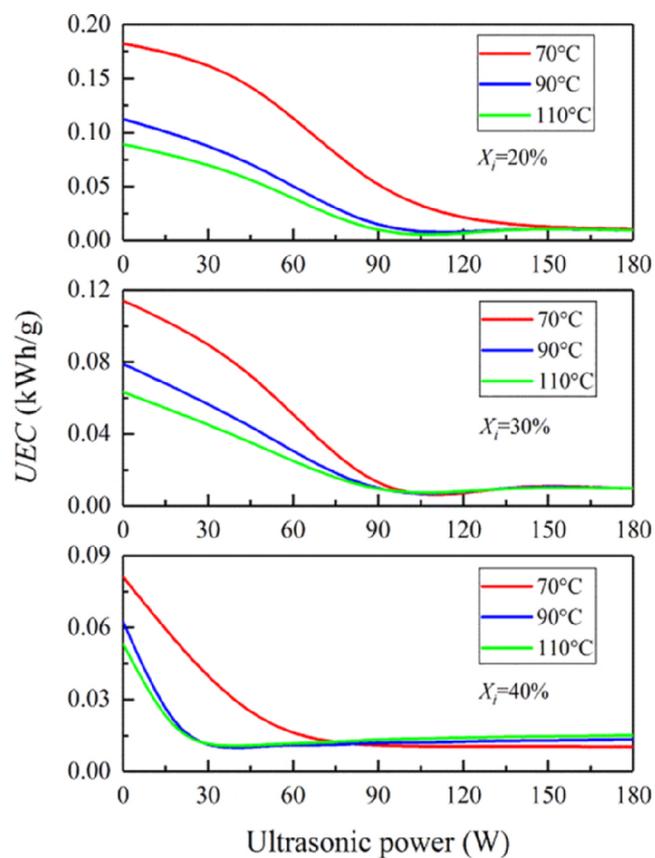


Fig. 12. Prediction of UEC under different conditions.

opposite after the turning point. Therefore, the ultrasonic power at the turning point is the importance reference when optimizing the regeneration process parameters.

3.5. Recovered moisture adsorption from regeneration

Activated alumina is recycled in the dehumidification process. Thus, the recovered moisture adsorption of activated alumina from regeneration is an important evaluation index, which is usually ignored in previous studies. Consequently, the dynamic adsorption tests were

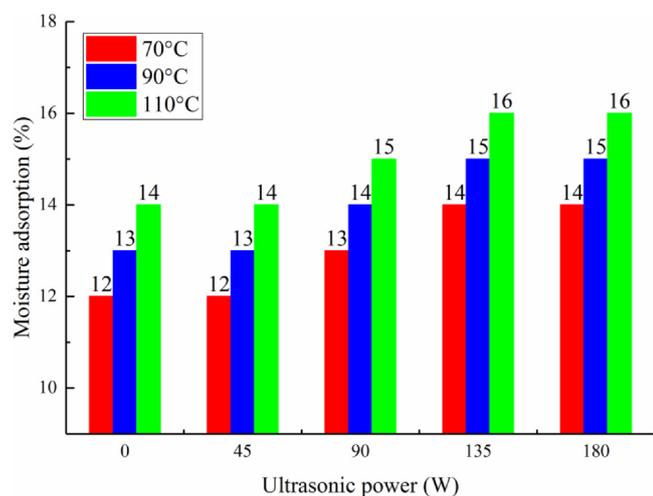


Fig. 13. Comparisons of recovered moisture adsorption of activated alumina regenerated at different conditions.

carried out to detect the moisture adsorption of activated alumina regenerated under different conditions. The environmental conditions for detection were as follows, temperature = 25 °C and relative humidity = 40%, and the moisture adsorption of the fresh activated alumina was 18% under such condition. Fig. 13 presents the comparisons of recovered moisture adsorption of activated alumina regenerated at different conditions. It can be summarized that the moisture adsorption of activated alumina declined to varying degrees after regeneration. A higher regeneration temperature led to a better moisture adsorption recovered from regeneration. Meanwhile, a higher ultrasonic power also contributed to a better recovered moisture adsorption. At 70 °C, the recovered moisture adsorption was improved by 16.7% under 180 W power ultrasound compared with non-ultrasonic regeneration.

Specific surface area is one of the most important indexes to evaluate the adsorption capacity of the solid desiccant, and a greater specific surface area indicates the stronger adsorption capacity. To intuitively analyze the changes in surface morphology of activated alumina during the regeneration process, the optical electron microscope (OLYMPUS; ZOOM-650E, Japan) was used for the microscopic observation of the fixed region on activated alumina surface at different stages, as shown in Fig. 14. In order to obtain the degree of fluctuations on the surface of the extracted region clearly, the MATLAB software was employed to process the extracted region images and the Contour

Table 3

The specific surface area of activated alumina.

	Specific surface area (m ² /g)
Fresh	254.0696
Non-ultrasonic regeneration	241.7082
Ultrasonic regeneration (45 W)	242.1981
Ultrasonic regeneration (90 W)	246.4745
Ultrasonic regeneration (135 W)	249.8332
Ultrasonic regeneration (180 W)	250.2671

function was utilized to display the surface morphology contour map, as can be seen from Fig. 14. The X-axis and Y-axis of the contour map represent the length of extracted region image from the microscopic observation. The particle surface of the fresh activated alumina fluctuated slightly, which became relatively flat after moisture adsorption. After the ultrasonic pretreatment, the surface was smooth, since tiny droplets were adhered onto the surface. The surface of activated alumina regenerated without ultrasound restored the roughness, while those regenerated with ultrasound had even more rough surface.

Meanwhile, we have performed Brunauer-Emmett-Teller (BET) specific surface area analysis using 'Micromeritics ASAP 2460 V3.01' equipment manufactured in the USA for the activated alumina with and without ultrasonic regeneration. The samples were analyzed under nitrogen atmosphere (adsorption-desorption isotherms at 77.3 K) in a volumetric working device. The moisture content in the samples was removed by drying them at 300 °C for 8 h prior to analysis. Results are shown in Table 3. It can be seen that the specific surface area of activated alumina increased with ultrasonic power. Consequently, the presence of ultrasound is conducive to the recovered moisture adsorption of activated alumina from regeneration.

4. Conclusions

In this paper, a series of comparative experiments were performed, and related evaluation indexes were proposed and utilized to comprehensively explore the performance and energy consumption characteristics for the regeneration of activated alumina assisted by ultrasound. The following conclusions can be summarized:

- (1) Power ultrasound can significantly enhance the regeneration of activated alumina. A higher initial moisture adsorption promotes the enhanced effects of ultrasound during the regeneration process.
- (2) The regeneration temperature of activated alumina can be lowered by ultrasound, which can be ascribed to the increase of effective moisture diffusivity (D_{eff}) and the reduction of desorption apparent

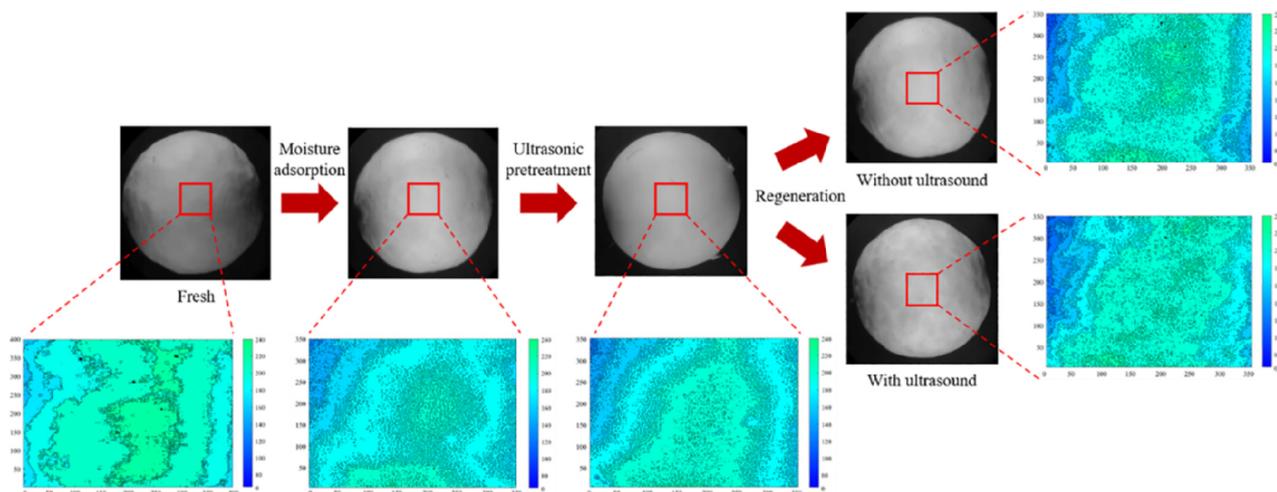


Fig. 14. Surface morphologies of activated alumina during regeneration process.

activation energy (E_a).

- (3) Within a certain range of ultrasonic power, the presence of ultrasound can reduce the energy consumption. The predicted results by ANN proved that there was an optimal regeneration condition around the turning point, which could minimize the unit energy consumption (UEC).
- (4) The presence of ultrasound is conducive to the recovered moisture adsorption of activated alumina from regeneration. A greater specific surface area induced by ultrasound resulted in a stronger adsorption capacity.

Thus, the initial moisture adsorption of activated alumina should be considered when adopting ultrasound-assisted low-temperature energy for the regeneration. Thereafter, related indexes can be used in the evaluation of the system, in order to realize the energy saving well while recovering the best moisture adsorption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ultsonch.2020.105314>.

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