Ultrasound-Assisted Regeneration of Zeolite / Water Adsorption Pair

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ABSTRACT
The use of ultrasound to enhance the regeneration of zeolite 13X was investigated as a substitute to conventional heating methods. The effects of ultrasonic power and frequency on the desorption of water from zeolite 13X were analyzed to optimize the desorption efficiency. To determine the effectiveness of incorporating ultrasound, an approach of constant overall input power of 20 or 25 W was adopted. To measure the extent of the effectiveness of using ultrasound, the ultrasonic-power-to-total power ratios of 0.2, 0.25, 0.4 and 0.5 were investigated and the results compared with those of no-ultrasound (heat only) at the same total power. To analyze the effect of ultrasonic frequency, identical experiments were performed at three ultrasonic frequencies of ∼28, 40 and 80 kHz. The experimental results showed that using ultrasound enhances the regeneration of Zeolite 13X at all the aforementioned power ratios and frequencies. With regard to ultrasonic power, the highest energy-saving power ratio was observed at 0.25 and with an increase in ultrasonic power, i.e. an increase in acoustic-to-thermal power ratio, the effectiveness of applying ultrasound decreased drastically. In terms of ultrasonic frequency, lower frequencies resulted in higher efficiency and energy savings, and it was concluded that the effect of ultrasonic radiation becomes more significant at lower ultrasonic frequencies.

KEY WORDS: Ultrasound; Zeolite; Desorption; Regeneration; Thermal storage; Sorption cooling.

1. Introduction
Desiccants consisting of solid porous materials are increasingly gaining attention for various applications including thermal energy storage, sorption cooling, dehumidification processes, water purification, desalination, and water harvesting. One of the significant drawbacks of using desiccant materials is the lengthy and energy-inefficient process of regeneration of the material, which calls for novel and more efficient desorption processes instead of conventional regeneration processes namely direct heating and application of hot air [1]. Zeolite 13X is porous crystalline Alumina Silicate with maximum water adsorption capacity of 12% - 36 % by mass [2], [3]. As a desiccant material, zeolite 13X has various applications including sorption cooling [3]–[7] and thermal storage [8]–[10]. Wang et al. [5] reported the heat of adsorption of the zeolite-water pair to be about 3300 - 4200 kJ/kg and the regeneration temperature to be about 250 – 300 °C. The high values of heat of adsorption and regeneration temperature of the zeolite/water pair, compared to other adsorption pairs like silica gel/water or activated carbon/ammonia, makes it both a curse and a blessing for sorption cooling and thermal storage applications, respectively. In recent years researchers have attempted to resolve the issue of inefficiencies caused by inadequate heat and mass transfer in desiccant materials by introducing alternative energy sources to assist in the desorption process along with low-grade heating [11], [12]. One such energy source is ultrasound [1], [13]–[17]. Ultrasound has been used to not only assist desorption of adsorbates in sorption cooling, but also desorption of many other chemicals as well as the drying of food and
The use of ultrasound on adsorbents has been recently studied as a means of overcoming insufficient heat and mass transfer during the regeneration of the adsorbents. Conventional heating of adsorbents is the primary contributor to the long time required for regeneration and the energy-consuming nature of the desorption process. In the relatively sparse amount of research available on ultrasonic regeneration, there have been investigations on the effect of the input power and frequency of the sound waves as well as on how those inputs perform under different thermal power input, e.g., regeneration temperature [1], [16], [17]. Zhang et al. [17] investigated the effects of different levels of ultrasonic power and regeneration temperature on moisture removal from silica gel and found that higher ultrasonic power and regeneration temperature results in higher desorption. Zhang et al. [16], on the other hand, investigated the effects of ultrasonic frequency on moisture removal from silica gel. They reported that desorption decreases with an increase in ultrasonic frequency. These studies have attributed numerous theories on ultrasonic interaction with silica gel for a fundamental explanation as to why desorption is enhanced. But, as discussed below, the fundamental mechanisms behind why the application of ultrasound improves desorption are still not clear.

2. Material and experimental setup

2.1. Zeolite 13X

The zeolite 13X beads used in this study were procured from SORBENT SYSTEMS IMPAK Inc. The physical properties and specifications provided by the supplier are presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Physical Properties of zeolite 13X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bead diameter (mm)</td>
</tr>
<tr>
<td>Pore diameter (nm)</td>
</tr>
<tr>
<td>Specific surface area (m^2/g)</td>
</tr>
<tr>
<td>Porous volume (ml/g)</td>
</tr>
<tr>
<td>Density (kg/m^3)</td>
</tr>
</tbody>
</table>

2.2. Experimental procedure

The main components of the experimental equipment used in this study are the desorption bed, an ultrasonic transducer, a function generator (Siglent Technologies SDG1032X), a high frequency-low slew rate amplifier (AALABSYSTEMS A-303), a cartridge heater, and a power supply (PROTEK P6000). A detailed schematic of the experimental setup is shown in Fig. 1. The bed is of hollow cylindrical shape machined out of aluminum 6061 rod. The ultrasonic transducers used are of low-heat piezoceramic type procured from APC INTERNATIONAL. Incorporating a combination of function generator and amplifier instead of fixed power - frequency ultrasonic generator makes it possible to drive the transducer at any desirable power level and frequency. The desorption bed is attached to the transducer with resin epoxy. Drying of the zeolite sample was achieved by heating it in an oven at 280 °C and measuring the mass until no change in mass was observed. The drying process of the sample was validated using a vacuum oven. The mass of the dried sample was controlled to be 48.31 ± 0.01 g in all experiments. The dried sample was then saturated to 27% moisture ratio using an ultrasonic humidifier. The moisture ratio (MR), representing the mass of water adsorbed by zeolite 13X, is used to describe the desorption process and is defined as:

\[
MR = \frac{M_{\text{measured}} - M_{\text{dry}}}{M_{\text{dry}}}
\]

where \( M_{\text{measured}} \) is the measured mass of the sample and \( M_{\text{dry}} \) the measured mass of the dry sample.
The resonant frequency of the transducers was determined using an oscilloscope (Rigol DS 1054Z) and a shunt resistor. The ultrasonic transducer and the shunt resistor were connected in series and with the help of four voltage probes, the impedance of the transducer based on the voltages across the transducer and across the shunt resistor was calculated. The resonant frequency corresponds to the lowest impedance (also the phase difference between the voltage and current is zero) [21]. The resonant frequencies of the unloaded transducers provided by the supplier, 28 kHz (APC 90-4040), 40 kHz (APC 90-4050), and 80 kHz (APC 90-4040) kHz were validated and the resonant frequency of the transducer-bed assembly was measured to be 24.3, 31.5, and 75.5 kHz, respectively.

![Figure 1 Schematic diagram of experimental setup.](image)

Identically, for each frequency, experiments at two levels of 20 and 25 W of total power ($P_{\text{Total}}$) were carried out. The experimental ultrasonic ($P_{\text{US}}$) – thermal power ($P_{\text{TH}}$) combinations are presented in Table 2.

<table>
<thead>
<tr>
<th>$P_{\text{Total}}$ (W)</th>
<th>$P_{\text{TH}}$ (W)</th>
<th>$P_{\text{US}}$ (W)</th>
<th>$P_{\text{US}} / P_{\text{Total}}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>5</td>
<td>0.25</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>10</td>
<td>0.50</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>5</td>
<td>0.20</td>
</tr>
<tr>
<td>25</td>
<td>15</td>
<td>10</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Thermal power was regulated through a power supply connected to the cartridge heater shown in Fig. 1. The ultrasonic power was regulated using a shunt resistor, an oscilloscope and voltage probes. The ultrasonic power was determined as:

$$P_{\text{US}} = V_{\text{rms}} I_{\text{rms}} \cos \theta$$  \hspace{1cm} (2)
where $V_{rms}$ is the root mean square value of voltage across the transducer, $I_{rms}$ the root mean square value of alternating current passing through the transducer, and $\theta$ the phase angle between the voltage and current. Since zeolite 13X is a poor heat conductor, the regeneration temperature was measured at three different locations using OMEGA T type thermocouples (wire diameter = 0.571 mm), referred to as reference, axial, and radial temperatures, and a NATIONAL INSTRUMENTS data acquisition device NI 9212. The reference and axial thermocouples are positioned at the same radial distance (20 mm) from the center of the bed and at 5 mm and 45 mm axial distance from the inner bottom surface of the bed, respectively. The radial thermocouple is positioned at the same axial height (5 mm) as the reference thermocouple and at a radial distance of 15 mm from the center of the bed. The placement of thermocouples is such that an approximated average desorption bed temperature can be measured, but the positional accuracy of the thermocouples is not sufficient to determine radial and axial temperature gradients. The experimental period is limited to 50 minutes and the mass and temperatures are measured at 5-minute intervals. For each measurement, all wires are disconnected from the bed and the mass of the bed is measured using an electronic scale (My Weigh SCMIM01) with a capacity of 1000 ±0.1 g.

2.3. Ultrasonic desorption enhancement

The ultrasonic desorption enhancement $UDE$ indicates the percent improvement in removing the adsorbate (here, water) using ultrasound compared to a heat-only desorption process and is defined as:

$$UDE = \frac{\Delta m_{removed,US} - \Delta m_{removed,non\ US}}{\Delta m_{removed,non\ US}}$$

(3)

where $\Delta m_{removed,US}$ is the mass of adsorbate (water) removed in a desorption process involving ultrasound and $\Delta m_{removed,non\ US}$ is the mass of adsorbate (water) removed in a heat-only desorption process.

2.4. Ultrasonic desorption efficiency enhancement

The ultrasonic desorption efficiency enhancement $UDEE$ is an indicator of the amount of energy saved in desorbing adsorbate (water) from the adsorbent (zeolite 13X) by using ultrasound compared to a heat-only desorption process and is defined as:

$$UDEE = \frac{P_{Total} \Delta t \Delta m_{removed,non\ US}}{P_{Total} \Delta t \Delta m_{removed,non\ US}}$$

(4)

where $\Delta t$ is the total time of the experiment (50 minutes).

2.5. Uncertainty analysis

The thermocouple – data acquisition device was calibrated using a HONEYWELL HIH 6130 Silicon bandgap temperature sensor with an accuracy of ±1°C. The accuracies of the mass and temperature measurements are provided in Table 3.

<table>
<thead>
<tr>
<th>Measured variable</th>
<th>Accuracy</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>±1.00</td>
<td>°C</td>
</tr>
<tr>
<td>Mass</td>
<td>±0.01</td>
<td>g</td>
</tr>
<tr>
<td>Voltage</td>
<td>2</td>
<td>%</td>
</tr>
<tr>
<td>Phase angle</td>
<td>0.1</td>
<td>minute</td>
</tr>
</tbody>
</table>
The uncertainties of the calculated variables were determined using [22]

\[ w_f = \left( \left( w_1 \frac{\partial f}{\partial x_1} \right)^2 + w_2 \left( \frac{\partial f}{\partial x_2} \right)^2 + w_3 \left( \frac{\partial f}{\partial x_3} \right)^2 + \cdots \right)^{0.5} \]  

(5)

where \( w_f \) is the uncertainty of calculated variable \( f(x_1, x_2, x_3, \ldots) \) and \( w_1, w_2, w_3, \ldots \) the uncertainties involved in the measured variables \( x_1, x_2, x_3, \ldots \) respectively. For instance, the uncertainty associated with the calculated variable \( MR \) is obtained using

\[ w_{MR} = \sqrt{w_{m_{measured}}^2 \left( \frac{1}{m_{dry}} \right)^2 + w_{m_{dry}}^2 \left( \frac{m_{measured}}{m_{dry}^2} \right)^2} \]  

(6)

The maximum values of uncertainty of the calculated variables are provided in Table 4.

<table>
<thead>
<tr>
<th>Calculated variable</th>
<th>Maximum uncertainty</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( MR )</td>
<td>±0.21</td>
<td>%</td>
</tr>
<tr>
<td>( T_{reg} )</td>
<td>±1.7</td>
<td>°C</td>
</tr>
<tr>
<td>( UDE )</td>
<td>±0.45</td>
<td>%</td>
</tr>
<tr>
<td>( UDEE )</td>
<td>±1.98</td>
<td>%</td>
</tr>
</tbody>
</table>

### 3. Conceptualization of ultrasound-enhanced desorption

In recent years there have been several efforts to conceptualize the principle of ultrasound-enhanced desorption. This improved desorption process can be described using heat and mass transfer governing relations while also incorporating ultrasonication effects into them to analyze this improvement [23]. In the literature, there are several contributing factors cited proposing why improved desorption occurs due to the introduction of an acoustic field, but the most common factor discussed in previous studies is surface cavitation [19], [23]–[28]. The alternating, locally established compressions and rarefactions induced by ultrasound waves at the surface of the adsorbent material subject the solid-gas interface to successive negative and positive pressures. Experimentally, for plant based material, it has been shown that the effect of expansion dominates that of compression at the interface, which results in surface cavitation that breaks the boundary layer and overcomes the adsorption forces (van der Waals forces) [24]. Another important effect of ultrasound that improves desorption that has been discussed is ultrasonic-induced, locally established partial vacuum. When an adsorbent is under ultrasonic radiation, a pulsating partial vacuum is created at the same frequency of the ultrasonic field that in turn reduces the gas pressure at the gas-solid interface and enhances vapor transport by canceling or prevailing over the present adsorption field and thus promoting surface evaporation [19], [24], [26]. Based on findings from previous studies, another factor shown to play a significant role in ultrasound-assisted desorption is circulating fluid currents. Induced by high-intensity ultrasonic radiation at the adsorbent surface, circulating currents enhance desorption of adsorbate from the surface [29]. The movement of the adsorbate molecules is achieved when acoustic forces dominate the viscous and surface forces allowing molecules to move more freely. This phenomenon is also reported as microstreaming, which occurs at the desiccant material surface resulting in a reduction in the diffusion boundary layer hence an increase in diffusion and mass transfer [25]. Another explanation proposed is that the alternating pressure creates local vapor bubbles, which force liquid molecules to move around forming currents [19]. It has also been postulated that the flow of the fluid in porous media is accelerated in an ultrasonic field [19], [30]. Turbulence is another factor contributing to ultrasound-enhanced desorption. Turbulence induced at the gas phase will partially reduce the gas pressure and consequently increase the diffusivity at the gas-solid interface [24]. Viscosity and diffusivity are important factors governing the heat and mass transfer and must be considered in any discussion of enhanced desorption.
Ultrasonic radiation reduces the adsorbate viscosity, which will have the effect of increasing its diffusivity [28], [31]. The temperature rise due to dissipation of ultrasonic energy is a controversial factor. In some studies, the application of ultrasonic waves has been considered as a contributing factor to enhanced mass transfer, while in others dismissed as a contributing factor compared to other factors [24], [28], [32]. At this point, however, the precise mechanisms by which ultrasound enhances desorption from porous media are not firmly established.

4. Results and discussion

4.1. Moisture ratio

Figure 2 shows the reduction in moisture ratio (i.e. desorption) of zeolite 13X for all six power combinations and at all three ultrasonic frequencies, including no applied ultrasound (heat-only). It can be observed from the figure that with constant power level, replacing some portion of thermal power with ultrasound enhances moisture removal from the adsorbent. In previous studies [1], [16], [17], the ultrasound was added to the thermal power such that the total power increased from the heat-only experiments to the ones with ultrasound. Although this approach confirms that applying ultrasound enhances desorption, the fact that heat-only and ultrasound-assisted experiments were not performed with the same level of total power makes it impossible to justify the use of ultrasound in terms of energy savings. The novelty of the present study is the constancy of total power in both heat-only and ultrasound-integrated experiments that justifies the use of ultrasound to enhance the desorption process. Since the total input power is constant, the enhancement in desorption must be ultrasound related.

The highest moisture ratio in this study is 27% meaning that the total mass of adsorbed water is 13.04 g. Using water molar mass and Avogadro’s number; there are a total of $4.36 \times 10^{23}$ water molecules present. Assuming a uniform adsorptive distribution (water molecules tend to adhere to the zeolite surfaces rather than to other water molecules), and considering a water molecule effective radius of 0.097 nm, the total surface occupied by water molecules is $12.64 \times 10^3 \text{ m}^2$. The mass of dry zeolite sample is 48.31 g, and using the sample’s specific area of 726 m$^2$/g, the total surface of the zeolite sample is $35.07 \times 10^3 \text{ m}^2$. The surface coverage is therefore obtained as

$$\text{Surface coverage} = \frac{A_{\text{water,Total}}}{A_{\text{zeolite,Total}}} = \frac{12.64 \times 10^3}{35.07 \times 10^3} = 0.36 = 36\%$$

(7)

Considering that in this study the highest level of surface coverage is 36%, i.e. the relative absence of liquid or liquid film, the effects of ultrasonication involving liquid including the viscosity effect, capillary effect, sonic currents, microstreaming, circulating flow and surface cavitation can be disregarded. The observed ultrasound-assisted enhancement in desorption is perhaps due to ultrasound-induced establishment of local partial vacuum and alternating zones of compression and rarefaction resulting in enhanced mass diffusivity. Another potential mechanism worth mentioning is the effect of turbulence. The ultrasound-triggered pressure alteration causes turbulence resulting in an increase in mass diffusivity. The same effect is observed in Henry’s constant in acoustic fields [28].

4.1.1. Effect of ultrasonic power

Although ultrasonic radiation apparently improves the desorption process, the amount of ultrasonic power to be used in order to achieve the highest desorption at the lowest total power input is of major concern. A closer look at Figure 2 reveals that at any frequency, for the 20-W total power experiments, the highest desorption was achieved with a power combination of 15 W thermal power and 5 W of ultrasonic power, i.e., a ratio of ultrasonic to total power of 0.25. In addition, with an increase in this power ratio to 0.50, there is still a slight enhancement in desorption compared to the heat-only experiment but it is relatively
The greatest enhancement in desorption occurred at a power combination of 20 W thermal and 5 W of ultrasonic power (ratio of ultrasonic to total power of 0.20). Again, at a higher ultrasonic-to-total power ratio, desorption rates were significantly higher compared to the control experiment without ultrasonics.
ratio of 0.40, there is a modest improvement in desorption over the heat-only experiment. This suggests that there is an optimal value for ultrasonic-to-thermal-power ratio resulting in maximal adsorbate removal per constant total power.

4.1.2. Effect of ultrasonic frequency

The values of ultrasonic desorption enhancement $UDE$ relative to heat-only desorption are plotted in Figure 3. It can be concluded from the figure that for any total power level and with any ultrasonic – thermal power combination, with an increase in ultrasonic frequency $f_{US}$, the ultrasonic desorption enhancement decreases.

![Figure 3](image)

*Figure 3 Ultrasonic desorption enhancement for zeolite / water at different frequencies and total power levels. The Uncertainty of the UDE is provided in Table 4.*

The same trend of deterioration in desorption enhancement with an increase in $f_{US}$ has been observed in some previous studies [16]. The reduction is somehow proportional to the increase in $f_{US}$. With a slight shift from 24.3 kHz to 31.5 kHz, there is a slight drop in $UDE$. However, with an increase from 24.3 kHz to 75.7 kHz, there is a significant reduction in $UDE$. The inverse proportionality between $f_{US}$ and $UDE$ in some ways appears to confirm the ultrasound-induced desorption improvement through partial vacuum and zones of alternating pressure. At higher frequencies, the rarefaction, compression, and partial vacuum are established and demolished so fast that there may not be enough time for the mass-transfer-enhancing effects to be fully developed. The same phenomena can be observed in ultrasonic-induced cavitation [33].

4.2. Regeneration temperature

Figure 4 shows the average regeneration temperature, taken as the average of the three thermocouples shown in Fig. 1, for all experiments. It is worth mentioning that at any frequency, the highest desorption
occurred at the highest regeneration temperature, confirming the importance of temperature in desorption regardless of using ultrasound.

In addition, for all three frequencies and both total power levels, ultrasound-enhanced experiments showed higher temperatures than the non-ultrasonic ones. Specifically, at any frequency, the highest

Figure 4 Desorption curves for zeolite / water. (a) at 24.3 kHz and 20 W; (b) at 24.3 kHz and 25 W; (c) at 31.5 kHz and 20 W; (d) at 31.5 kHz and 25 W; (e) at 75.7 kHz and 20 W; (f) at 75.7 kHz and 25 W.
temperature was achieved at the lowest ultrasonic-to-total power ratio. This could be due to the fact that zeolite 13X, being a porous medium with low thermal conductivity (about 0.1 - 0.6 W m⁻¹ °C⁻¹), has poor heat transfer capability so using ultrasound enhances the heat transfer in the medium. Another reason could be the axial dissipation of ultrasonic waves increasing the temperature rather than relying solely on radial heat conduction from the cartridge heater. The latter can not be the sole contributor to the temperature rise, as the highest temperature was not observed at higher ultrasonic-to-total power ratios.

4.3. Ultrasonic desorption efficiency enhancement

The ultrasonic desorption efficiency enhancement \( UDEE \) indicates the amount of energy saved when a portion of thermal power is replaced with ultrasonic power while the total power remains constant. Figure 5 shows the percent energy saved for both power levels (20 and 25 W) and at all three levels of frequency. The most efficient desorption process was achieved at an ultrasonic-to-total power ratio of 0.25. In addition, with an increase in this ratio, the efficiency drops drastically meaning that there is an optimal ratio of ultrasonic-to-total power resulting in the highest desorption efficiency enhancement. Regarding the ultrasonic frequency \( f_{US} \), there is a general downward trend in \( UDEE \) with an increase in \( f_{US} \).

![Figure 5 Ultrasonic desorption efficiency enhancement for zeolite / water at different frequencies and total power levels. The Uncertainty of the UDE is provided in Table 4.](image)

5. Conclusion

In this study, ultrasonic-assisted desorption of water from zeolite 13X was investigated. The extent to which application of ultrasound is effective was analyzed.
To do so, the effects of ultrasonic power and ultrasonic frequency on moisture removal and regeneration temperature were investigated. Comparing the moisture ratio at different ultrasonic-to-total power ratios shows that using ultrasound at lower power ratios, i.e. 0.20 and 0.25, significantly improves desorption relative to using only heat for regeneration. However, higher power ratios, i.e. 0.4 and 0.50, only slightly improve desorption relative to only heat. Using the newly defined metric ultrasonic desorption enhancement \( UDE \), the effects of ultrasonic frequency on moisture removal were analyzed and it was concluded that the effect of ultrasound on desorption is more significant at lower frequencies. Comparing the regeneration temperature of all experiments shows that ultrasonication increases the adsorbent temperature regardless of frequency, presumably due to the heat-transfer-enhancing nature of ultrasound. Not surprisingly, at all three frequencies the highest desorption was achieved at the highest regeneration temperature. Another defined indicator, the ultrasonic desorption efficiency enhancement \( UDEE \), was used to justify the use of ultrasound in moisture removal from zeolite 13X. Comparing the values of \( UDEE \) indicates that with an optimized ratio of ultrasonic-to-total power a ~24 % reduction in energy required for desorption of water from zeolite 13X can be achieved, relative to using only heat.

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NOMENCLATURE

\[
\begin{align*}
  f_{US} & : \text{ultrasonic frequency} & \text{Hz} \\
  I_{rms} & : \text{root mean square current} & \text{A} \\
  MR & : \text{moisture ratio} & \text{kg}_w/\text{kg}_z \\
  m_{dry} & : \text{mass of dry sample} & \text{g} \\
  m_{measured} & : \text{measured mass} & \text{g} \\
  P_{US} & : \text{ultrasonic power} & \text{W} \\
  P_{TH} & : \text{thermal power} & \text{W} \\
  T_{reg} & : \text{regeneration temperature} & \text{°C} \\
  TH & : \text{heat} & \text{dimensionless} \\
  UDE & : \text{ultrasonic desorption enhancement} & \text{dimensionless} \\
  UDEE & : \text{ultrasonic desorption efficiency enhancement} & \text{dimensionless} \\
  US & : \text{ultrasound} & \text{dimensionless} \\
  V_{rms} & : \text{root mean square voltage} & \text{V} \\
  \Delta m_{removed,US} & : \text{mass of adsorbate removed with ultrasound} & \text{g} \\
  \Delta m_{removed,non US} & : \text{mass of adsorbate removed without ultrasound} & \text{g} \\
  \Delta t & : \text{time period} & \text{s} \\
  \theta & : \text{phase angle} & \text{Rad}
\end{align*}
\]

REFERENCES


