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LOW-GRADE HEAT UTILIZATION THROUGH ULTRASOUND-ENHANCED DESORPTION OF ACTIVATED ALUMINA/WATER FOR THERMAL ENERGY STORAGE

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ABSTRACT

Sorption thermal energy storage (TES) seems to be an auspicious solution to overcome the issues of intermittent energy sources and utilization of low-grade heat. Ultrasound-assisted adsorption/desorption of water vapor on activated alumina is proposed as a means of low-grade heat utilization through TES. The effects of ultrasonic power on the storing stage (desorption of water vapor) were analyzed to optimize the desorption and overall efficiencies. To determine and justify the effectiveness of incorporating ultrasound from an energy-savings point of view, an approach of constant total (heat plus ultrasound) input power of 25 W was adopted. To measure the extent of the effectiveness of using ultrasound, ultrasonic-power-to-total power ratios of 0.2 and 0.4 were investigated and the results compared with those of no-ultrasound (heat only) at the same total power. The regeneration temperature and desorption rate were measured simultaneously to investigate the effects of ultrasonication on regeneration temperature and utilization of low-grade heat. The experimental results showed that using ultrasound facilitates the regeneration of activated alumina at both power ratios without increasing the total input power. With regard to regeneration temperature, incorporating ultrasound decreases the regeneration temperature hence justifying the utilization of low-grade heat for thermal energy purposes. In terms of overall energy recovery of the adsorption thermal storage process, a new metric is proposed to justify incorporating ultrasound and any other auxiliary energy along with low-grade heat.

Keywords: Ultrasound; Activated Alumina; Desorption; Regeneration; Thermal Storage; Low-Grade Heat.

NOMENCLATURE

ϵ	porosity (-)
η	thermal efficiency (-)
$\eta_{\Delta t}$	constant time thermal efficiency (-)
ρ_s	adsorbent density (kg m^{-3})
ΔH_{Ads}	enthalpy of desorption (kJ kg^{-1})
Δt	time period (s)
C_s	specific heat capacity (kJ kg^{-1}K^{-1})
C_f	heat capacity rate (W K^{-1})
h_w	enthalpy (kJ kg^{-1})
MR	moisture ratio (-)
m_{dry}	mass of dry sample (kg)
$m_{measured}$	measured mass (kg)
m_w	mass of removed moisture (kg)
m_s	mass of adsorbate (kg)
P_{TH}	thermal power (W)
P_{US}	ultrasonic power (W)
T	temperature (°C)
V	Volume (m^3)
TH	heat (-)
US	ultrasound (-)

1. INTRODUCTION

The inherent temporal and intermittent nature of solar radiation makes thermal energy storage (TES) a viable element in most solar thermal energy systems. In addition, increasing awareness of environmental issues related to thermal systems calls for higher thermal efficiency by utilizing/storing byproduct waste heat. Mainly, there are three types of thermal storage: sensible, latent and sorption. Sorption thermal storage has much higher energy storage density compared to the other types of thermal storage, a remarkable temperature rise, and the capability of long-term storage over seasonal variation in ambient temperature [1]–[6]. The stored thermal energy via sorption TES systems could be used as means of direct heating, sorption cooling and power generation after hours, days and seasons when it is needed. Modeling of adsorption TES systems has been previously performed using a variety of assumptions and models [7]–[14]. As invaluable and contributory these works are, they apparently lack a figure of merit that enables the comparison and justification of the TES systems based on the desorption dynamics of the adsorbent.

Activated alumina is porous Al_2O_3 with a maximum water adsorption capacity of 20% -38 % by mass [15].

As an adsorbate, activated alumina has many applications including dehumidification, thermal storage and removal of chemicals from water and air [16]–[20]. Srivastava et al. reported the adsorption enthalpy of the activated alumina-water pair to be about 2800 - 3000 kJ/kg and the regeneration temperature to be about 250 – 300 °C [18]. The relatively high values of adsorption enthalpy, high adsorption capacity and phenomenal porous volume of the activated alumina/water pair, compared to most other adsorbate/adsorbent pairs, makes it a promising candidate for dehumidification and TES applications. The downside, however, in general of using adsorbent materials is the prolonged and energy-consuming process of the desorption stage, necessitating more energy-efficient desorption processes beyond just conventional heating. The conventional drying method of heating adsorbents is the primary contributor to the long times required for regeneration and the energy-consuming nature of the desorption process. Recently, there have been many studies to resolve the problem of inefficiencies caused by sluggish heat and mass transfer in adsorbents by proposing auxiliary energy sources to enhance the regeneration process with utilization of low-grade heat [21]–[24]. One alternative energy source is *ultrasound*. The use of ultrasound on adsorbents has been recently studied as a means of overcoming insufficient heat and mass transfer during drying of the adsorbents [23], [25], [26]. Other than enhancing the regeneration of adsorbates in dehumidification and thermal storage, incorporating ultrasound has proven to be advantageous in other applications including but not limited to food, wood and fabric drying and water decontamination [16], [27]–[30]. The aim of this paper is to investigate the effects of ultrasonication on moisture removal from activated alumina from an energy-savings point of view since the total input power in all experiments is kept constant. In addition, the alteration in regeneration temperature under an acoustic field is also investigated in order to assess the feasibility of low-grade heat utilization along with ultrasonication. This study also aims to propose a novel metric to predict the energy recovery feature of a TES solely based on the storage (desorption) stage of the system.

2. MATERIAL AND EXPERIMENTAL SETUP

2.1 Activated alumina

The activated alumina beads used in this study were procured from Delta Adsorbents Div. of Delta Enterprises, Inc. The physical properties and specifications provided by the supplier are presented in Table 1.

Table 1: PHYSICAL PROPERTIES OF ACTIVATED ALUMINA

Bead diameter (mm)	3.175
Pore diameter (nm)	~ 4.8
Specific surface area (m^2/g)	350
Porous volume (ml/g)	0.5
Density (kg/m^3)	769

2.2 Experimental procedure

The constituent elements of the experimental setup used in this research are an aluminum 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 schematic diagram of the experimental setup is shown in Figure 1. The ultrasonic transducer used is a high efficiency piezoceramic (APC 90-4040) procured from APC INTERNATIONAL. The transducer is fixed to the desorption bed using resin epoxy.

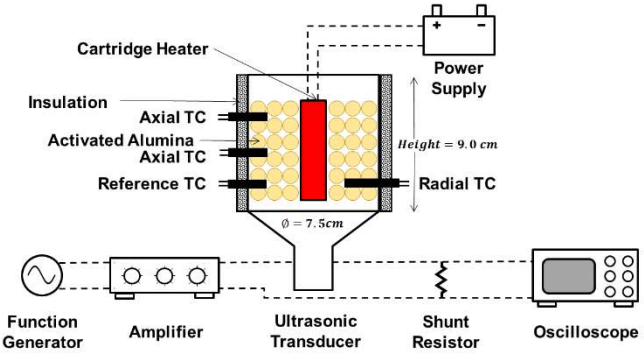

FIGURE 1: SCHEMATIC DIAGRAM OF EXPERIMENTAL SETUP

Drying of the activated alumina sample was accomplished by heating the sample in an oven at 280 °C and measuring the mass until no change in mass was detected. The drying process of the sample was confirmed using a vacuum oven. The mass of the dried sample was controlled to be 60.00 ± 0.01 g in all experiments. The dried sample was then saturated to 20% moisture ratio (*MR*) using an ultrasonic humidifier. During the saturation stage, the relative humidity and the temperature of the feed flow were controlled at 95%-100% and 20 °C respectively using a Honeywell HIH-6130 temperature and relative humidity sensor. The moisture ratio (*MR*), representing the mass of water adsorbed by the activated alumina, is used to describe the desorption process and is defined as:

$$MR = \frac{m_{measured} - m_{dry}}{m_{dry}} \quad (1)$$

where $m_{measured}$ is the measured mass of the sample and m_{dry} the measured mass of the dry sample. The resonant frequency of the unloaded transducer provided by the supplier, 28 kHz, was validated and the resonant frequency of the transducer-bed assembly was measured to be 24.1 kHz. The experimental ultrasonic (P_{US}) – thermal power (P_{TH}) combinations are presented in Table 2. Thermal power was regulated through a power supply connected to the cartridge heater shown in Figure 1. The ultrasonic power was regulated using a shunt resistor, an oscilloscope and voltage probes. For the detailed experimental procedure, please refer to our previous study [24]. Since activated alumina has low thermal conductivity, the

regeneration temperature was measured at four different locations using OMEGA T type thermocouples (wire diameter = 0.571 mm) and NATIONAL INSTRUMENTS data acquisition device NI 9212. The uncertainties of the measured and calculated parameters are determined following approach from[24].

TABLE 2: EXPERIMENTAL ULTRASONIC-THERMAL POWER COMBINATIONS

P_{Total} (W)	P_{TH} (W)	P_{US} (W)	P_{US}/P_{Total} (W)
25	25	0	0
25	20	5	0.20
25	15	10	0.40

The experimental period was limited to 50 minutes and the mass and temperatures were measured at 5-minute intervals. The mass of the bed was measured using an electronic scale (My Weigh SCMIM01) with a capacity of 1000 ±0.01 g.

3. RESULTS

3.1 Moisture ratio

Figure 2 shows the time dependence of the moisture ratio *MR* of the activated alumina for all three power combinations including no applied ultrasound (heat-only). It can be concluded from the figure that applying ultrasound with both ultrasonic-power-to-total power ratios (P_{US}/P_{Total}) enhances the desorption of water from activated alumina. At P_{US}/P_{Total} = 0.2 (20W TH + 5 W US) the effect of ultrasonication is significant and at P_{US}/P_{Total} = 0.4 (15W TH + 10 W US), the effect of ultrasonication becomes less significant. From a timesaving point, i.e. desorption speed[24], Figure 2 shows that at constant total input power, application of ultrasound leads to much faster desorption. This faster desorption would be especially favorable considering the intermittent nature of energy sources associated with TES.

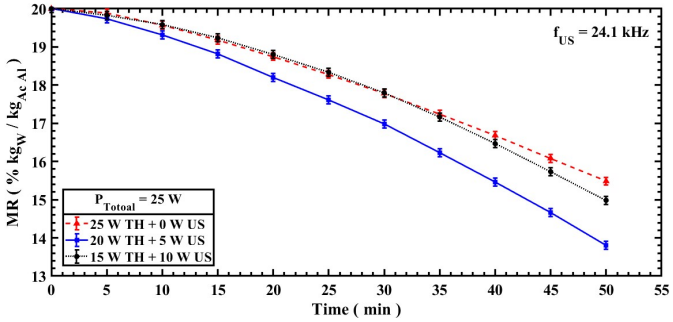

FIGURE 2: DESORPTION CURVES FOR ACTIVATED ALUMINA / WATER

3.2 Regeneration temperature

The average adsorbent temperature, evaluated as the average of the four thermocouples shown in Figure 1, for all experiments is shown in Figure 3. The lowest adsorbent temperature was observed at the lowest thermal input (15 W TH+ 10 W US) corresponding to P_{US}/P_{Total} = 0.4. At P_{US}/P_{Total} = 0.2 (20W TH + 5 W US), the adsorbate temperature is observed to be close to that with no ultrasound. This could be due to the fact that activated alumina as a porous medium has low thermal conductivity so ultrasonication inherently enhances the heat transfer in the adsorbent. In addition, the acoustic dissipation could be a contributor to the temperature rise to some extent.

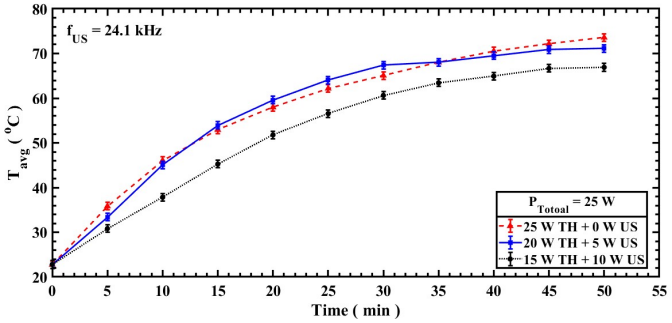

FIGURE 3: AVERAGE REGENERATION TEMPERATURE OF ACTIVATED ALUMINA / WATER

4. DISCUSSION

4.1 Model

Here we propose a simple theoretical model in order to estimate the impact of introducing ultrasound on the performance of an activated alumina-based TES system. The model is considered as an open system consisting of a single bed (Figure 4). During the storing stage (desorption), the heat transfer fluid enters the bed at a temperature higher than the bed temperature, thus supplying thermal energy to remove the adsorbate. In the harvesting stage (adsorption), the removed adsorbate is re-supplied to the adsorbate at the same temperature as the bed and the heat transfer fluid enters the bed at a temperature lower than the bed temperature, thus removing thermal energy from the bed. Several assumptions are considered in this approach to simplify the model without risking its universality. The bed is assumed to be a lumped system. That is to say, there is only temporal temperature variation and no spatial temperature gradient exists.

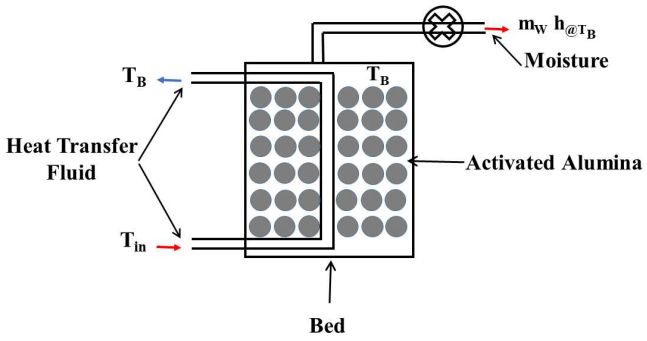

FIGURE 4: SCHEMATIC DIAGRAM OF THE MODEL

In addition, in the storing stage, the heat transfer fluid leaves the bed at the same temperature as the bed. Considering these assumptions, the energy balance for the storing stage is:

$$C_f(T_{in} - T_B)dt - dm_w\left(\Delta H_{Ads} + h_{w@T_B}\right) = \left[\rho_s V_B(1 - \epsilon)\, c_{s@T_B,dm_w}\right]dT_B \quad (2)$$

where C_f is the heat capacity rate of the working fluid, T_{in} the working fluid inlet temperature, T_B the adsorbent temperature, dm_w the mass of the removed adsorbate, ΔH_{Ads} the enthalpy of adsorption, h_w the enthalpy of the removed adsorbate (water vapor), ρ_s the adsorbate density, V_B the bed volume, ϵ the bed porosity and c_s the adsorbate specific heat capacity. It can be inferred from the energy balance that the input energy to the system is $C_f(T_{in} - T_B)dt$ and the stored energy (harvestable portion) is $dm_w\ \Delta H_{Ads}$. The efficiency of the TES is defined as

$$\eta = \frac{Q_{harve}}{Q_{input}} = \frac{\Delta m_w \Delta H_{Ads}}{C_f(T_{in} - T_B)\Delta t} \quad (3)$$

In this approach, the storing stage period (Δt) for different regeneration processes is considered constant. Since $\Delta H_{Ads}, C_f\ and\ \Delta t$ remain unchanged, equation (3) can be simplified to:

$$\eta_{\Delta t} = \frac{\Delta H_{Ads}}{C_f \Delta t} \times \frac{\Delta m_w}{T_{in} - T_B} = K\frac{\Delta m_w}{T_{in} - T_B} \quad (4)$$

where K is a product of constants and $\eta_{\Delta t}$ is the efficiency defined under a constant storage stage period Δt. For an infinitesimal increase in adsorbent temperature dT that causes the removal of dm adsorbate, equation (4) is reduced to:

$$\eta_{\Delta t} = K\frac{dm}{dT} \quad (5)$$

Since the mass of adsorbent (m_s) is constant, using the definition of MR in equation (1) we have:

$$dm = m_s\, d(MR) \quad (6)$$

Plugging equation (6) into equation (5), we can express the efficiency of a sorption-based TES system based on a figure of merit $[d(MR)/dT]$:

$$\eta_{\Delta t} = K'\frac{d(MR)}{dT} \quad (7)$$

where $\eta_{\Delta t}$ is the constant time thermal efficiency and K' is again a product of constants. The metric $[d(MR)/dT]$, representing the variation of adsorbate ratio with adsorbent temperature, is the slope of the moisture ratio-temperature curve and enables comparison of the energy recovery ratio of TES systems with different regeneration methods and at different regeneration temperatures. It should be emphasized that the newly defined constant time efficiency is not the actual efficiencies of the TES system, but rather are a reliable tool to compare different adsorption thermal energy methods.

4.2 Model application

The variation of the adsorbent moisture ratio with temperature is shown in Figure 5. It can be observed from the figure that applying ultrasound reduces the regeneration temperature and the higher $P_{US}\ /\ P_{Total}$ is, the lower the regeneration temperature becomes.

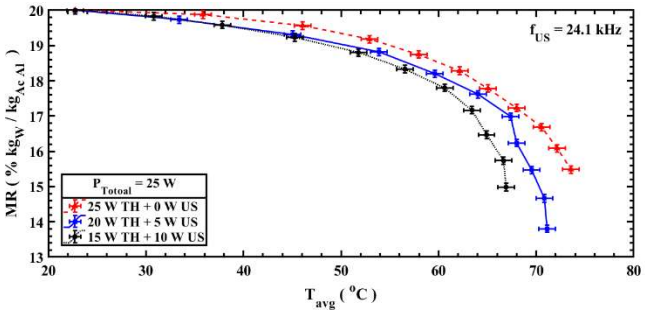

FIGURE 5: MOISTURE RATIO VARIATION VS. AVERAGE REGENERATION TEMPERATURE FOR ACTIVATED ALUMINA / WATER.

As informative as the moisture ratio-regeneration temperature curves are in Figure 6, they do not reveal which regeneration process would result in higher energy recovery. The average slope of the MR-T curve $[d(MR)/dT]$ for the three regeneration processes considered here are evaluated and presented in Figure 6. At P_{US}/P_{Total} = 0.2 (20W TH + 5 W US) and $P_{US}\ /\ P_{Total}$ = 0.4 (15W TH + 10 W US), the value of $[d(MR)/dT]$ is evaluated to be 43% and 28% higher compared to that of heat-only regeneration (25W TH + 0 W US). This suggests that integration of ultrasound leads to more efficient heat recovery in TES systems.

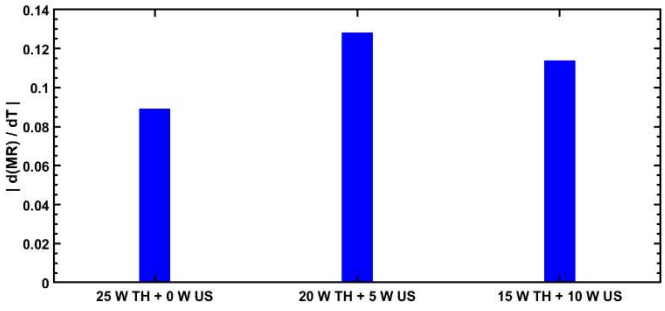

FIGURE 6: VARIATION IN CONSTANT TIME EFFICIENCY FOR THREE ULTRASONIC-POWER TO TOTAL-POWER RATIOS

5. CONCLUSION

Ultrasonic-assisted removal of water from activated alumina for application in low-grade heat utilization for thermal energy storage (TES) is proposed. The extent to which integration of ultrasound is effective for low-grade heat utilization was investigated and the effects of ultrasonic power on moisture removal and regeneration temperature were analyzed. Comparing the moisture removal and adsorbent temperature in ultrasound-integrated regeneration with those not using ultrasound at the same total power input suggests that application of ultrasound at both 0.2 and 0.4 ultrasonic-to-total power ratios (P_{US}/P_{Total}) enhances the desorption process and reduces the regeneration temperature. Regarding desorption enhancement, the effects of ultrasonication are observed to be more significant at $P_{US}/P_{Total} = 0.2$, and with respect to lowering the regeneration temperature the effects of ultrasonication are observed to be more significant at $P_{US}/P_{Total} = 0.4$ justifying utilization of low-grade heat. A simple model is presented to analyze the performance of TES systems. Using the newly defined metric *constant time efficiency* $\eta_{\Delta t}$, the thermal energy recovery of ultrasound-assisted thermal storage was shown to be greater than just using only heat.

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