PARTICLE SIZE DISTRIBUTION IMPACT ON HEAT AND MASS TRANSFER IN ADSORPTION REACTORS

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ABSTRACT

Adsorption refrigeration and desalination systems operate by exploiting the thermal effects accompanied by the alternating adsorption and desorption processes of the refrigerant in a porous material bed. Sorption systems are an important part of the transition to green energy, as they can be powered by renewable energy sources, including solar energy and industrial waste heat. Additional advantages are the absence of emissions, long operating time, and the possibility to use water as a refrigerant. The adsorption bed consisting of a heat exchanger covered with a granular adsorbent is the subject of analysis and experiments focused on improving the heat and mass transfer conditions, limited by the low adsorbent conductivity and adsorption bed porosity. Among the analyzed concepts, fluidization is a promising technology, but its effective implementation in adsorption chillers requires determining optimal operating conditions and sorbent parameters. Particle shape expressed by sphericity and size distribution are important factors that could influence the thermal and physical properties of the adsorption fluidized bed. The work aims to characterize the effect of adsorbent particle size changes on heat and mass transfer during adsorption/desorption cycles appropriate for adsorption cooling and desalination systems. Experimental tests of sorption cycles were carried out for adsorbent granulation in the range of 100 to 500 micrometers to determine the optimal grain distribution. Silica gel was used as the adsorbent because it provides an effective working pair with water as an ecological refrigerant. Experimental research was conducted utilizing a prototype test stand equipped with the Intensified Heat Transfer Adsorption Bed (IHTAB) reactor.

1 INTRODUCTION

Ecological sorption technologies are currently being developed in the areas of refrigeration, desalination systems, and dehumidification. The popularity of systems based on sorption phenomena is growing as adsorption technology meets the challenges of green transformation in the energy, cooling, and freshwater production industries (Riaz *et al.*, 2021; Choudhury *et al.*, 2013). Moreover, dynamically increasing demand for energy, unlimited exploitation of fossil fuels, and global climate change constitute crucial reasons to increase the share of low-grade heat and renewable energy resources in the global energy market. Introducing these changes to the energy production approaches is facilitated by the popularization of heat-operated adsorption cooling and desalination systems, which emerging as viable alternatives to conventional electricity-driven units (Grabowska *et al.*, 2024), which is also emphasized by the features of adsorption devices presented in Figure 1.

The typical adsorption chiller consists of an evaporator, an adsorption chamber, and a condenser, and many modifications are introduced to the described basic construction to increase the efficiency of these devices (Chen and Chua, 2020; Alsarayreh *et al.*, 2021). The cooling capacity of the adsorption refrigeration system is generated utilizing thermal effects occurring in adsorption and desorption processes on porous media surfaces, and improving the heat and mass transfer conditions in adsorption beds of the refrigerator are the most important research challenges undertaken to reduce the dimensions and increase the chillers' Coefficient of Performance.

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Figure 1: Advantages and disadvantages of adsorption devices (Grabowska *et al.*, 2018; Wang, Wang and Wu, 2014; Wang *et al.*, 2014)

There are many conventional and well-described methods for improving the adsorption unit efficiency, such as extending the heat exchanger surface(Alahmer, Ajib and Wang, 2019; Krzywanski *et al.*, 2018), increasing the adsorption bed number (Mitra *et al.*, 2016), and utilizing coated structures (Grabowska *et al.*, 2021). The greatest potential for significantly improving heat transfer conditions is the implementation of fluidized beds, which is one of the most recent developments in adsorption technology research and still requires many experimental analyses to define optimal fluidization parameters for adsorption chillers operation conditions (Krzywanski *et al.*, 2024).

The influence of geometrical parameters on improved circulating inclined fluidized beds (ICIFB) for HVAC duct systems has been experimentally analyzed in (Liang *et al.*, 2018). The parameters considered in the study included the inclined angle, base height of the regeneration bed, and particle channel height of the adsorbent bed. The analyses carried out confirmed that the optimal ICIFB system could increase adsorption/desorption performance by 32.4% and 23.5%, respectively, under the same operating conditions compared to the circulating erect fluidized bed system (CEFB) and the circulating inclined fluidized bed system (CIFB). In (Chen *et al.*, 2015) low-energy consumption silica gel circulating fluidized beds for the dehumidification of air conditioning systems has been investigated. The considered circulating fluidized bed system achieved the highest Energy Factor by 0.554 kg/kWh, and due to the lack of a motor improved the packed bed system by 124% and had the largest total adsorption rate. In addition, it was pointed out that increasing air velocities and regeneration temperatures caused adsorption/desorption performance to rise in circulating fluidized bed systems. An equally important factor as the conditions of the fluidization process are the porous material parameters that fill the adsorption bed (Krzywanski *et al.*, 2019). The effect of particle size changes from cycling of the thermochemical energy storage material on fluidizability and wall-to-bed heat transfer coefficients in the fluidized bed was investigated in (Talebi *et al.*, 2023). Particle size distributions with Sauter mean diameters significantly smaller than approximately 50 μm were found to be difficult to fluidize in a thermochemical energy storage system due to excessive channeling, resulting in low heat transfer coefficients.

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The analysis of fluidized beds in various technologies is well described, however, there is a lack of experimental studies in the literature concerned with the adsorbent particle size impact on the heat transfer conditions in fluidized beds implemented in adsorption cooling and desalination systems, therefore a detailed analysis of this issue was undertaken in this study.

Therefore, the main novelty of this work constitutes the assessment of the adsorbent grain distribution impact on the heat transfer in a fluidized bed under low-pressure operating conditions, typical for adsorption refrigeration devices, defined based on the original set of experimental tests.

2 MATERIALS AND METHODS

2.1 Materials

The most commonly used porous material as an adsorbent in adsorption cooling technology is a silica gel (Boruta, Bujok and Sztekler, 2021). Its popularity is dictated by ecology, as it is non-toxic, chemically stable, and, above all, it constitutes an effective working pair for water as a refrigerant. This choice is also related to economic considerations, as it is cheap, available from many suppliers, and in a wide range of granulations adsorbent. Accordingly, experimental studies were carried out using silica gel samples. The parameters of the analyzed adsorbent are presented in Table 1.

Table 1: The parameters of silica gel

Specific surface area m²/g	Porosity (ε) -	Total pore volume cm³/g	Thermal conductivity W/m·K	Bulk density kg/m³	Sphericity -	Particle size μm
800	0.44	0.404	0.176	750	0.70	100 – 160 200 – 250 300 – 350 400 – 500

Experimental fluidized adsorption/desorption cycles were carried out on four silica gel bed samples with different particle size distribution ranges according to the data in Table 1. Defined granulation ranges are dictated by previously conducted preliminary studies. Each sample had a mass of 20 grams, as determined by the parameters of the experimental test apparatus used.

2.2 Methods and equipment

Experimental research consisting of analyzing the impact of granulation on the heat transfer conditions in a fluidized bed was conducted utilizing a prototype test stand equipped with the Intensified Heat Transfer Adsorption Bed (IHTAB) reactor. The laboratory test stand constitutes a simplified model of an adsorption refrigerator and is composed of an adsorption chamber (4), evaporator (3), Welch LVS vacuum pump (2), and data acquisition and control system (1). The Welch LVS vacuum pump is utilized to maintain typical conditions of the adsorption chiller working cycle based on the water–silica gel system. The laboratory test stand is shown in Figure 1. Experimental research was conducted by the cycle defined as follows.

The tests began by reducing the pressure in the chambers to achieve the conditions prevailing in existing adsorption cooling and desalination systems. The fluidized state of the adsorption bed is achieved by creating an appropriate pressure difference between the two chambers of the experimental station. The fluidizing medium in this case is the water vapor produced in the evaporator. The pressure difference needed to achieve the fluidized state was determined experimentally. The pressure in the evaporator

reached a value of about 2600 Pa, which allowed water to boil at a temperature of 25°C. At this time, the pressure in the adsorption chamber was 1800 Pa. The pressure difference of 900 Pa between the chambers when the valve connecting them is opened allows the water vapor to flow and excitation of the fluidized state in the adsorbent bed located in the adsorption chamber.
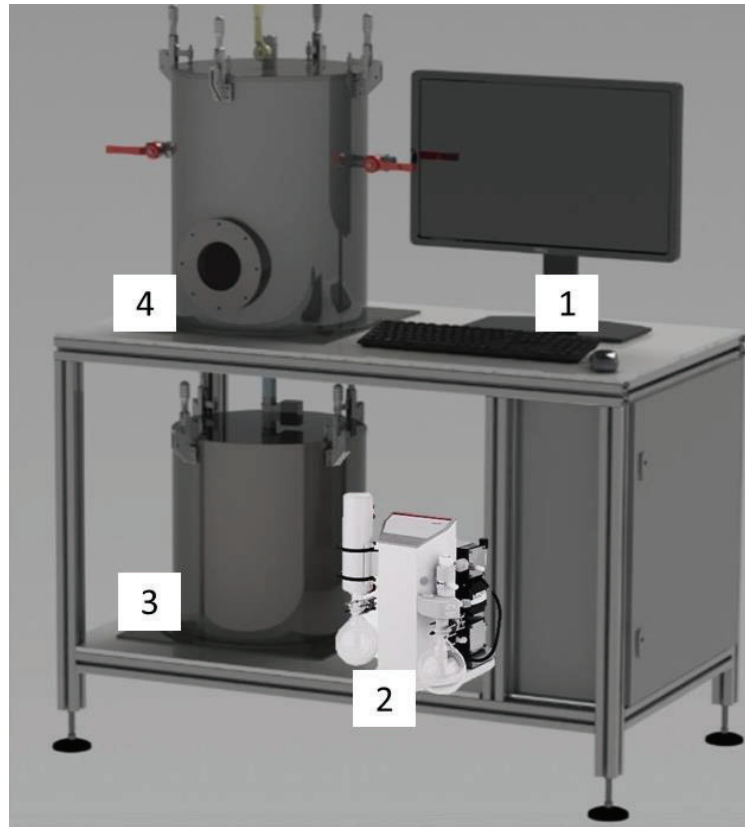

Figure 2: The scheme of the Intensified Heat Transfer Adsorption Bed (IHTAB) reactor

In the fluidized state, water vapor is adsorbed onto the silica gel surface, increasing the bed temperature. After 25 seconds of adsorption, a valve shuts off the steam supply from the evaporator, and the silica gel bed is heated to regenerate it. The pressure in the chambers during desorption is lowered to re-establish a differential pressure for the next adsorption cycle. Five adsorption/desorption cycles were carried out for each silica gel sample.

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3   RESULTS AND DISCUSSION

Figures 3-6 show the course of adsorption/desorption cycles for all tested silica gel granulations.
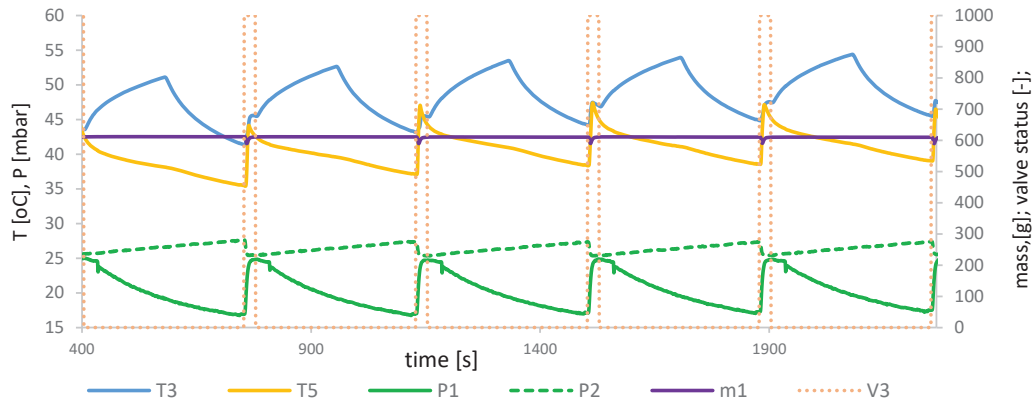

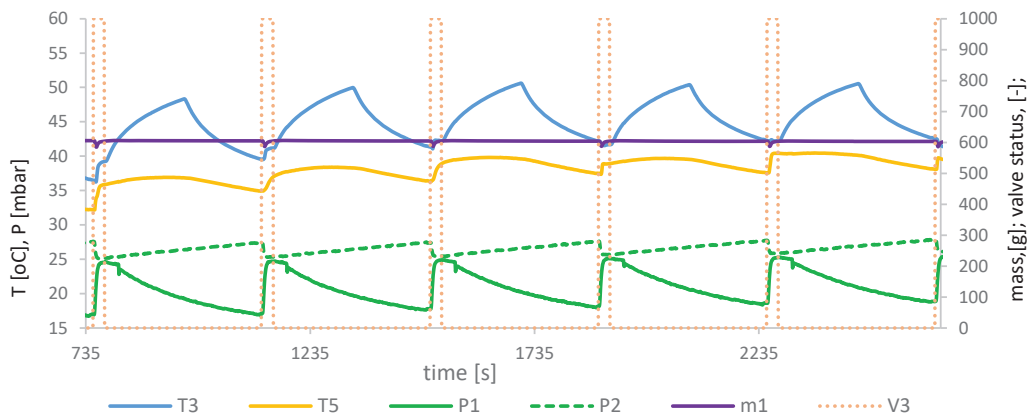**Figure 3:** The adsorption/desorption cycles for silica gel with particle size 100 – 160 μm

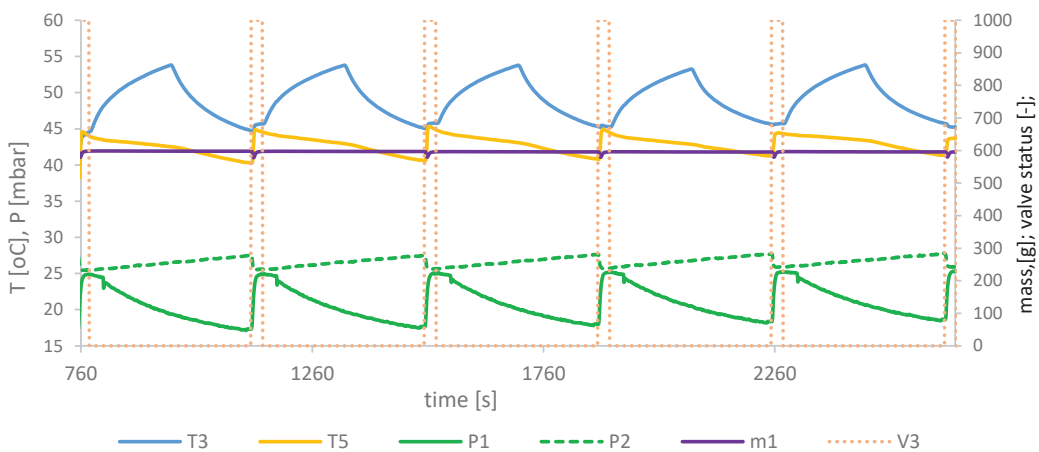**Figure 4:** The adsorption/desorption cycles for silica gel with particle size 200 – 250 μm

Figure 5: The adsorption/desorption cycles for silica gel with particle size 300 – 350 μm

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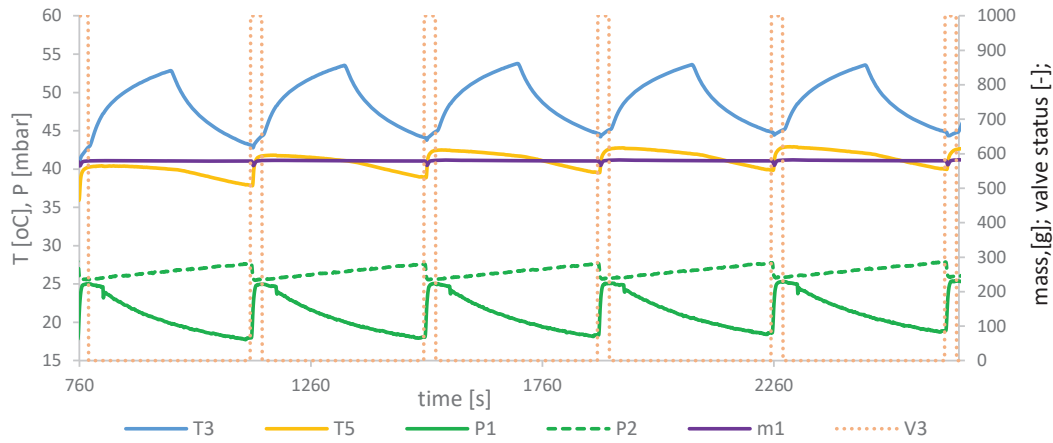https://doi.org/10.52202/077185-0197   2302

Figure 6: The adsorption/desorption cycles for silica gel with particle size 400 – 500 μm

The following data are presented on the connected charts (Figures 4-6): T3 - temperature of the adsorption bed at the central point on the surface of the heat transfer probe °C, T5 - temperature of the adsorption bed °C, P1 - pressure in the adsorption chamber mbar, P2 - pressure in the evaporator mbar, m1 - mass of the bed adsorption bed sample g, V3 - status of the valve between the adsorption chamber and the evaporator.

Figures 4-6 show the changes of the variables over time analyzed in five successive cycles of adsorption/desorption of water vapor in the sorbent bed under low-pressure conditions, mapping the working cycle of the adsorption chiller. The graphs show periodic pressure changes in the test stand chambers, which are related to the cyclical equilibrium between the evaporator and the adsorption chamber during the adsorption cycle. In addition, the effect of the adsorption process on temperature changes in the sorbent bed is visible. It is due to the adsorption of water vapor molecules in the silica gel pores, which is an exothermic phenomenon and occurs with the release of the adsorption heat which is confirmed in graphs 4-6 by cyclic increases in the adsorbent bed temperatures (measuring points: T3 and T5).

The crucial factor for analyzing heat transfer conditions in the fluidized adsorption bed is temperature changes over time because the following relationship was used to calculate the average values of the heat transfer coefficient h (Skrobek *et al.*, 2020; Krzywanski *et al.*, 2023):

$$h = \frac{Q}{A \cdot (T_3 - T_5)}, \qquad \left[\frac{W}{m^2 \cdot K}\right] \tag{1}$$

where: h – convective heat transfer coefficient W/m^2·K, Q – the power of the heat transfer probe located in the central point of the adsorption bed sample [W], A – the area of the heating surface of the heat transfer probe [m^2], T3 – temperature of the adsorption bed at the central point on the surface of the heat transfer probe °C, T5 – bed temperature at a defined distance from the bed central point.

Based on the experimental results, the average values of the convective heat transfer coefficient *h* for each of the analyzed particle size distributions of the silica gel samples were calculated and the results are summarized in table 2. The maximum measurement error considered the accuracy of the individual components, was calculated using the total differential. The maximum value of the measurement error, which ranged from 2.25% to 8.25 %, it should be considered that the results of experimental measurements are characterized by good accuracy.

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Table 2: the average values of the heat transfer coefficient

Particle size distribution μm	Heat transfer coefficient h W/m²·K
100 – 160	141
200 – 250	150
300 – 350	190
400 – 500	134

It can be seen from the data above that as the diameter of the silica gel particles increases, the heat transfer conditions improve, but only up to a certain point. The h coefficient reached its highest value of 190 W/m²·K for a particle size distribution of 300 – 355 μm, and then for a higher diameter it dropped sharply and reached the lowest value examined. This may be due to the better packing of the sorbent bed in the case of smaller diameters, which hinders diffusion and vapor adsorption throughout the adsorbent bed. Higher diameters are characterized by higher bed porosity, which favors vapor diffusion, but may worsen fluidization conditions. Therefore, a significant decrease in the value of the heat transfer coefficient h was recorded for the analyzed highest particle size distribution.

Achieving higher values of the heat transfer coefficient h in the adsorption bed is directly related to the improvement of heat and mass transfer conditions during sorption processes. Adsorption is an exothermic phenomena, therefore it requires effective collection of the adsorption heat produced, and desorption, due to its endothermic nature, requires heating of the adsorption bed. Reducing the demand for cooling and heating of adsorption beds during working cycle will increase the coefficient of performance COP, which, according to the following formula, describes the overall efficiency of the entire adsorption system:

$$COP = \frac{HP}{CC} = COP = \frac{\dot{m}_C \cdot Cp_C \cdot (\Delta T)}{\dot{m}_H \cdot Cp_H \cdot (\Delta T)} \qquad (2)$$

where: COP – coefficient of performance; HP – heating power [W]; CC – cooling capacity [W]; $\dot{m}_C, \dot{m}_H$ – a mass flow of chilled ($_C$) or hot ($_H$) water respectively [kg/s]; Cp_C, Cp_H – specific heat of chilled or hot water respectively [J/kgK]; ΔT – temperature difference at the inlet and outlet of the evaporator or of the heat exchanger built in the adsorption beds;

4 CONCLUSIONS

The study conducted in this paper aimed to analyze the influence of the particle size distribution of the adsorbent material on the heat transfer conditions in the fluidized bed under the operating cycle conditions of the adsorption cooling system. Experimental research was conducted utilizing a prototype test stand equipped with the Intensified Heat Transfer Adsorption Bed (IHTAB) reactor. The work analyzed the particle range from 100 to 500 micrometers, and already in this relatively narrow range the influence of particle size on the value of the heat transfer coefficient h has been already revealed. As the diameter of the silica gel increased, the h coefficient increased until it reached 190 W/m²K for particle size 300 – 350 μm, and then, for the range from 400 to 500 micrometers, the value dropped to its lowest level of 134 W/m²K. Considering a preliminary experimental study, this trend should be validated for a wider range of adsorbent particles used in adsorption chillers.

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