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Citation for published version (APA):

Document license:
TAVERNE

DOI:
10.1016/j.est.2020.101896

Document status and date:
Published: 01/12/2020

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
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Analysis and optimization of the closed-adsorption heat storage bed performance

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ARTICLE INFO
Keywords:
Thermal Energy Storage
Sorption Heat Storage
Modelling
Optimization
Energy efficiency

ABSTRACT
Sorption heat storage attracts considerable attention because its relatively high theoretical energy density compared to other heat storage methods offers various opportunities in the design of renewable and sustainable energy systems. However, limited heat transfer in the material bed remains one of the main limitations of a successful introduction to the market. In the present study, a mathematical model of the heat and mass transfer processes inside an adsorption bed of silica gel embedded with cylindrical and rectangular fins has been developed. A systematic analysis has been conducted to augment thermal transport in the adsorption bed with rectangular and pin fin configurations. A parametric study has been conducted for both fin configurations at different bed heights (δb), fin diameters/thicknesses (ϕfin/δfin) and fin spacings (δs). Further, a design-of-experiments study is conducted to relate the energy discharge (Edis) and peak power (Wpeak) to the various governing parameters, as such identifying which parameters maximize energy discharge (Edis) and peak power (Wpeak). The design-of-experiment study reveals that the rectangular fin configuration shows better performance compared to the cylindrical fin configuration.

1. Introduction

Energy usage in the built environment currently accounts for over 40% of total primary energy consumption in the U.S. and E.U. [1]. Space heating represents more than 50% in the E.U. Global energy-related CO₂ emissions grew by 1.4% in 2017, reaching a historic high of 32.5 Gt [2]. The increasing scarcity and cost of fossil fuels and incentives to reduce greenhouse gas emissions have led to a growing interest in solar energy. Solar energy is widely available and has the capability to meet the heat demand of the built environment over the year. Unfortunately, its intermittency and variability with weather conditions, time, location and seasons lead to a mismatch between heating demand and the available solar energy. To enhance the fraction of solar energy utilization and make solar energy products more practical and attractive, thermal storage systems are perceived as crucial components in solar energy applications. Methods of solar thermal energy storage are mainly divided into three types: sensible, latent and thermochemical [3]. Sensible and latent heat thermal storage are the most studied technologies in the recent past. Thermochemical storage can be divided into storage based on chemical reactions and storage based on physical sorption [4]. Large amounts of heat can be stored in reversible chemical reactions and sorption processes. In a sorption process, heat is stored by breaking the binding force between the sorbent and the sorbate in terms of chemical potential. The comparison between the energy storage density of sorption thermal storage with other thermal energy storage media is presented in Fig. 1. A smaller volume is needed for given storage capacity for sorption thermal storage, according to Hadorn [4], compared to for example a sensible heat storage system with water or a latent heat storage system.

Efforts on the development of novel commercial cooling/heating systems have extensively focused on thermally driven adsorption based cooling systems in the recent years since these systems are environmentally friendly and can be operated with a low-grade heat source such as solar energy or waste heat [5–7]. However, thermally driven adsorption heating/cooling systems cannot compete with traditional vapor compression cooling systems as far as their performances are concerned [8]. The performance of thermally driven adsorption heating/cooling systems is largely determined by the heat and mass transfer processes in the adsorbent bed. In recent years, many investigators studied heat and mass transfer enhancement techniques of adsorbent beds to improve the thermal performance of such systems [9–18]. These studies mainly focused on material characterization, on
reaction kinetics of TCMs and on thermal conductivity enhancement of sorption materials. Further, other studies are focusing on the optimization of the adsorber bed for sorption and thermochemical heat storage systems. In this regard, Golparvar et al. [19] investigated the optimum fin spacing for finned tube adsorber bed heat exchangers in an exhaust gas-driven adsorption cooling system. It was observed that the adsorber bed with a larger fin spacing experienced higher temperature gradients, which led to non-uniform adsorption and desorption processes throughout the adsorber bed heat exchanger, and consequently, a decrease in the adsorption cooling system performance was achieved. A similar kind of study was conducted by Mohammed et al. [20], who evaluated the performance of a newly designed modular packed bed for adsorption cooling systems. The adsorption kinetics of the materials were experimentally investigated and a transient local thermal non-equilibrium model was developed to study the heat and mass transfer processes inside the packed bed. Further, Mitra et al. [21] investigated the influence of the adsorbent particle size and the heat exchanger aspect ratio on the dynamic adsorption characteristics. Three heat exchanging domains with the same area but different aspect ratios (fin height to fin pitch ratio) along with two-particle sizes were evaluated. The dynamic uptake predicted by this CFD study shows a strong dependency on flow resistance of porous media for smaller particle size, whereas a weak dependency on thermal and intra-particle mass diffusion was observed for larger particles. Furthermore, a comparison of the adsorption dynamics predicted by the present CFD study and lumped kinetics model was performed to determine the validity of the lumped model concerning the absorber geometry and particle size. Verde et al. [22] developed an analytical model to determine the optimum geometrical and thermal parameters of a flat tube fin adsorber bed to reach the maximum system performance. The obtained results indicated that the thermal conductance of the bed and cooling capacity enhanced by reducing flat-tube thickness, and fin pitch. The specific thermal conductance increased by 2.5% when reducing the channel pitch from its design value to a minimum permissible (0.004 m). Çağlar [23] developed a 2D coupled heat and mass transfer model for the comparative analysis of finless and finned tube-type adsorbent bed for an adsorption cooling cycle. The working pair used in the simulations was silica gel–water. A significant enhancement in the heat transfer was obtained using a finned tube such that the temperature of the adsorbent in the finned tube adsorbent bed was at most 47.8 K higher than that in the unfinned tube adsorbent bed. The effect of fin design parameters on the thermal transport in the bed was also investigated using four different fin configurations. From the study, it was found that by increasing fin thickness to double the existing thickness, the temperature increases by 2–3 K only and has not a significant effect on the heat transfer. Increasing the fin radius decreases temperatures by 10–17 K while increasing the number of fins enhances the heat transfer significantly. Ilis et al. [24] conducted a study to investigate the effect of metal additives to the adsorbent bed on the performance of an adsorption chiller and optimized geometric parameters of a newly designed adsorbent bed. The temperature and water vapor concentration distributions of the star fin configuration were analyzed and various design parameters were optimized.

Most of the studies conducted so far are based on 1- or 2-dimensional numerical models to analyze the heat and mass transfer processes in the adsorbent beds. These types of numerical models can’t be used for the study of the heat and mass transfer processes in more complex geometries of the adsorbent bed. The present study focuses on the development of a 3-dimensional numerical model describing the combined heat and mass transfer processes in an adsorbent bed of silica gel to evaluate the effect of fin size and spacing for cylindrical and rectangular fin configurations on the performance. Besides, the effect of bed height on the heat and mass transfer in the adsorber bed is studied. Further, a new approach based on Taguchi’s design-of-experiments method (Taguchi and Wu [25]) is introduced to optimize the adsorbent bed configuration with respect to various design parameters. The Taguchi Standard Orthogonal Array design optimization technique drastically reduced the cost needed for the optimization. The Taguchi method is used to optimize the fin thickness, fin spacing and bed height for a selected range of parameters. As a result, the present study correlates the fin thickness or diameter ($\delta_{f}\text{or }\phi_{f}$), the fin spacing ($\delta_{s}$) and the bed thickness ($\delta_{b}$) to the energy extracted by heat transfer fluid (HTF) ($E_{\text{ed}}$) and to the peak power ($W_{\text{peak}}$) per unit heat exchanger surface area for both fin configurations. The optimum fin configuration, which produces maximum $E_{\text{ed}}$ and $W_{\text{peak}}$ is established based on the selected range of the parameters and discussed. Finally, various design conditions based on the correlations developed in the present work are suggested. The article is organized as follows: In the introduction section, the general background and the aim of this work are presented. After the introduction, the numerical model is discussed as used in the present study, including the mathematical formulation of the heat and mass transport equations employed in the silica gel bed, the computational procedure and the model validation. Further, the methodology of

![Fig. 1. Volume required to store 1850 kWh (with consideration of 25% heat losses, based on a 70°C temperature increase for water) [4]](image-url)
optimization using the Taguchi method is discussed, followed by the results of the numerical simulation and optimization study for the hydration of a silica gel bed. Finally, a summary of the key conclusions of the present work is presented.

2. Numerical Model

Fig. 2 (A) represents the front view of the proposed adsorber bed, where silica gel is placed on top of a metal frame and cooling water is supplied in a channel attached below the metal frame. The water vapor is transported from the top of the adsorber bed and heat generated due to the adsorption of water vapor in silica gel is transported to the HTF flowing in the water channel. The top view of the adsorber bed is presented in Fig. 2B where cylindrical and rectangular metallic fins are inserted into the adsorber bed to enhance thermal transport. Due to the symmetry in the fin distribution, a small control volume is considered in the present study and shown in Fig. 2C(a), and Fig. 2C(b), for the cylindrical and rectangular fin configuration respectively. The height of the bed and space between two consecutive cylindrical or rectangular fins are \( b \) and \( s \) respectively. The diameter and thickness of the cylindrical and rectangular fins are \( \phi_{\text{fin}} \) and \( \delta_{\text{fin}} \) respectively. The thickness of the metallic frame on which silica gel placed is 1 [mm] (\( \delta_p \)) and its properties are similar to the solid fin material. The considered control volume is divided into two domains, i.e. porous domain and solid fin domain. The thermophysical properties of silica gel, fin, water vapor and other operating parameters that have been used in this study are given in Table 1 (the data for these properties is taken from [20,23–28]).

The following assumptions have been made for the mathematical model for heat and mass transfer in both domains:

- The radiation heat transfer is neglected due to the relatively low working temperature in the system.
- The properties of the phases are isotropic and uniform. Unless specified otherwise the physical and chemical properties of the constituents are assumed to be constant.
- The gaseous adsorbate are in thermal equilibrium with the solid phase.
- The porous medium is not deformable.
- The gaseous adsorbate adheres to the ideal gas law.
- The effects of pressure work and viscous dissipation are negligible.
- Three-dimensional thermal equilibrium (i.e. the temperature of the solid Silica gel material and water vapor is in thermal equilibrium)

**Table 1** The thermophysical properties and operating parameters of the adsorption system used in the present study.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_p )</td>
<td>0.5 ( \times 10^{-3} ) m</td>
<td>particle diameter</td>
</tr>
<tr>
<td>( \varepsilon_b )</td>
<td>0.5</td>
<td>bed porosity</td>
</tr>
<tr>
<td>( \varepsilon_p )</td>
<td>0.3</td>
<td>silica gel pellet porosity</td>
</tr>
<tr>
<td>( D_v )</td>
<td>2.76 ( \times 10^{-3} ) m(^2)/s</td>
<td>vapour self-diffusion at 273 [K] and 0.1[MPa]</td>
</tr>
<tr>
<td>( C_{p,v} )</td>
<td>1864 J/kg.K</td>
<td>heat capacity of water vapor at 298 K</td>
</tr>
<tr>
<td>( C_{p,s} )</td>
<td>921 J/kg.K</td>
<td>heat capacity of solid silica gel</td>
</tr>
<tr>
<td>( C_{p,\text{fin}} )</td>
<td>475 J/kg.K</td>
<td>heat capacity of fin material</td>
</tr>
<tr>
<td>( \rho_{\text{fin}} )</td>
<td>7850 kg/m(^3)</td>
<td>density of fin</td>
</tr>
<tr>
<td>( k )</td>
<td>1.4 W/mK</td>
<td>thermal conductivity of Silica gel</td>
</tr>
<tr>
<td>( k_{\text{fin}} )</td>
<td>44.5 W/mK</td>
<td>thermal conductivity of fin</td>
</tr>
<tr>
<td>( E_a )</td>
<td>4.2 ( \times 10^{4} ) J/mol</td>
<td>activation energy surface diffusion - silica gel</td>
</tr>
<tr>
<td>( M_w )</td>
<td>0.01802 kg/mol</td>
<td>molar mass of water vapor</td>
</tr>
<tr>
<td>( \Delta M )</td>
<td>2800 kJ/kg</td>
<td>iso-steric heat of adsorption</td>
</tr>
<tr>
<td>( D_s,0 )</td>
<td>2.54 ( \times 10^{-4} ) m(^2)/s</td>
<td>surface diffusivity - silica gel</td>
</tr>
<tr>
<td>( R )</td>
<td>8.314 J/mol.K</td>
<td>ideal gas constant</td>
</tr>
<tr>
<td>( n )</td>
<td>0.9012</td>
<td>Dubinin-Astakhov fit coefficient (1) - Silica gel 127 B</td>
</tr>
<tr>
<td>( \beta_{E,0} )</td>
<td>2745 J/mol</td>
<td>Dubinin-Astakhov fit coefficient (2) - Silica gel 127 B</td>
</tr>
<tr>
<td>( T_i )</td>
<td>20 °C</td>
<td>initial temperature</td>
</tr>
<tr>
<td>( T_{eva} )</td>
<td>10 °C</td>
<td>evaporator temperature</td>
</tr>
<tr>
<td>( T_{HTF} )</td>
<td>20 °C</td>
<td>cooling temperature of HTF</td>
</tr>
<tr>
<td>( T_{con} )</td>
<td>30 °C</td>
<td>condenser temperature</td>
</tr>
<tr>
<td>( T_{reg} )</td>
<td>80 °C</td>
<td>regenerator temperature</td>
</tr>
<tr>
<td>( p_i )</td>
<td>100 Pa</td>
<td>initial pressure</td>
</tr>
<tr>
<td>( C_i )</td>
<td>0.05 mol/m(^3)</td>
<td>initial concentration</td>
</tr>
</tbody>
</table>

Fig. 2. (A) Schematic of the proposed adsorber bed frontal view, (B) Top view of the adsorber bed, (C) equivalent computational domain for cylindrical and rectangular fin configurations
is considered for the modeling of the porous medium.

With these considerations, the mathematical formulation of the heat and mass transport model in each of the different domains is discussed below.

2.1. Vapor Transport In Porous Medium

To simulate the adsorption process in the porous domain, the mass conservation equation for the adsorbate gas is written as:

\[ \varepsilon_{\text{eff}} \frac{\partial C}{\partial t} - \nabla \cdot (D_{\text{eff}} \nabla C) + \nabla (u \cdot C) = R_t \]  

(1)

where \( C \) is the concentration of the water vapor and \( \varepsilon_{\text{eff}} \) is the effective porosity which can be presented as:

\[ \varepsilon_{\text{eff}} = \varepsilon_b + (1 - \varepsilon_b) \varepsilon_p \]  

(2)

where \( \varepsilon_b \) and \( \varepsilon_p \) are the bed porosity and pellet porosity of silica gel respectively. In eq. (1), \( D_{\text{eff}} \) is an effective diffusion coefficient, which can be molecular self-diffusion of water molecules in the vacuum space and physical gas diffusivity in the porous medium. \( R_t \) is the reaction term which will be discussed in the reaction kinetics section. The physical gas diffusivity in a porous medium can be estimated by:

\[ D_{\text{eff}} = \frac{D_m}{\tau} \]  

(3)

where \( \tau \) is the tortuosity which is approximated by the Millington and Quirk model [29] for a packed bed of spherical pellets (\( \tau = \varepsilon_b^{-1/3} \)). \( D_m \) is the molecular diffusion of water vapor and the value of \( D_m \) can be given by [30]:

\[ D_m = D_p \frac{p_T}{p_{\text{ref}}} \left( \frac{T}{T_{\text{ref}}} \right)^2 \]  

(4)

where \( D_p \) characterizes the vapor self-diffusion, \( p_{\text{ref}} \) and \( T_{\text{ref}} \) are the reference pressure and temperature respectively. The \( p \) is the gas pressure and given by gas law (\( p = CRT \), where \( C \) is the concentration, \( R \) is the universal gas constant and \( T \) is the temperature). The vapor transport in the porous medium results not only from diffusion but also from advection, where a difference in pressure causes bulk motion of the gas. This leads to a viscous flow and, therefore, the vapor transport in the porous medium is governed by Darcy’s law considering also the acceleration due to gravity. The Darcy velocity (\( u \)) in the porous medium is given by:

\[ u = -\frac{k}{\mu} (\nabla p - \rho g) \]  

(5)

where \( \rho \) is water vapor density and \( g \) is universal gravitational constant. The \( k \) is the permeability of the porous medium, and it can be obtained from the semi-empirical Blake–Kozeny equation as:

\[ k = \frac{d_p^2 \varepsilon_b^2}{150(1 - \varepsilon_b)^2} \]  

(6)

where \( d_p \) is the particle diameter. The Sutherland law or the viscosity-temperature relation is used to determine the viscosity of gas (\( \mu \)) in the range of \(-156 \, {\text{[C]}} \) to \(1787 \, {\text{[C]}} \), where the ratio \( S/T \) is empirically taken as 0.505.

\[ \mu = \mu_{\text{ref}} \left( \frac{T}{T_{\text{ref}}} \right)^{1/2} \left( \frac{1 + S/T}{1 + S_{\text{ref}}/T_{\text{ref}}} \right) \]  

(7)

with \( T_{\text{ref}} \) and \( \mu_{\text{ref}} \) as reference temperature and viscosity respectively.

2.2. Heat Transfer in Porous Medium

The heat transfer in the porous silica gel bed is governed by the heat transfer diffusion equation, which can be written as:

\[ (\rho C_p)_{\text{eff}} \frac{\partial T}{\partial t} + \rho C_p u \nabla T - k_{\text{eff}} \nabla^2 T = Q \]  

(8)

where \( (\rho C_p)_{\text{eff}} \) is the effective volumetric heat capacity, \( k_{\text{eff}} \) is the effective thermal conductivity. The \( Q \) is the heat generated due to the adsorption of water vapor in silica gel and its value depends on the reaction term \( R_t \) and will be discussed in the reaction kinetics section. The effective volumetric heat capacity \( (\rho C_p)_{\text{eff}} \) is calculated by the following equation:

\[ (\rho C_p)_{\text{eff}} = \rho C_p \varepsilon_{\text{eff}} + \rho C_{\text{ads}} (1 - \varepsilon_{\text{eff}}) \]  

(9)

The effective thermal conductivity \( k_{\text{eff}} \) of the TCM layer or packed bed is a rather complex property as it has many dependencies. The thermal conductivity depends, among others, on geometrical features, the thermal conductivity of the solid adsorbent and the gaseous adsorbate. In turn, these properties are a function of the temperature. A common theoretical model for the effective thermal conductivity is given by Zehner and Schlunder [31], which is satisfactory over a broad range of solid-to-fluid thermal conductivities and solid fractions, as follows:

\[ \frac{k_{\text{eff}}}{k_b} = 1 - \sqrt{1 - \varepsilon_b} + \frac{2(1 - \varepsilon_b)}{\lambda B} \left( \frac{1 - \lambda B}{1 - \lambda B} \right)^{1/2} \ln \left( \frac{1 - \lambda B}{2} - \frac{B - 1}{1 - \lambda B} \right) \]  

(10)

where \( \lambda \) is the thermal conductivity ratio (\( \lambda = k_b/k_c \)) and \( B \) the shape factor. The value of the shape factor \( B \) is given by:

\[ B = 1.25 \left( \frac{1 - \varepsilon_b}{\varepsilon_b} \right)^{10/9} \]  

(11)

2.3. Heat Transfer in Solid Fin and Bottom Plate

The heat transfer in the fin can be calculated with heat transfer diffusion equation [32]:

\[ \rho_b C_p \varepsilon_{\text{fin}} \frac{\partial T}{\partial t} - k_{\text{fin}} \nabla^2 T = 0 \]  

(12)

where \( \rho_b \), \( C_p \), \( \varepsilon_{\text{fin}} \) and \( k_{\text{fin}} \) are density heat capacity and thermal conductivity of the metallic fin respectively.

2.4. Reaction Kinetics for Silica Gel

Solving the intra-particle mass balance equations is often time-consuming. To avoid this problem, in practice often a lumped approach is followed as an approximation, which has proven to be physically consistent [21,33]. The last term in eq. (1) is the reaction term, which is calculated, using the rate of change for the water uptake:

\[ R_t = (\varepsilon / M_w)(1 - \varepsilon_{\text{eq}}) \frac{\partial q}{\partial t} \]  

(13)

where \( \varepsilon \) is the density of the solid phase, \( M_w \) is the molecular weight of water. The \( q \) is the average adsorbate adsorbed in the particle. This is also referred to as the water uptake of the material (the mass of adsorbed adsorbate per unit mass of the dry adsorbent). In this work the Linear Driving Force (LDF) model, with a lumped mass transfer coefficient \( K_{\text{LDF}} \) is applied to describe the reaction rate [34,35]:

\[ \frac{\partial q}{\partial t} = K_{\text{LDF}} (q_{\text{eq}} - q) \]  

(14)

where \( q_{\text{eq}} \) is the amount of adsorbate that is adsorbed in the equilibrium situation (explained later). For diffusion-controlled kinetics the mass transfer coefficient \( K_{\text{LDF}} \) can be calculated as [28]:

\[ K_{\text{LDF}} = \frac{4F_0 D_{\text{D}}}{d_p^2} \]  

(15)
where \( F_0 \) is a geometric parameter that depends on the adsorbent particle shape and its value is 15 for spherical adsorbent particles [36]. The \( D_{seff} \) is an effective surface diffusion parameter that lumps the relevant diffusion mechanism. In porous materials, the path for the diffusion of the water vapor is ‘tortuous’ as the pores of various diameters are twisted and interconnected. Accounting for this effect leads to the following expression for the effective surface diffusion coefficient:

\[
D_{seff} = \frac{D_{s}}{\tau}
\]  

(16)

In the case of microporous silica gel, it is reported that surface diffusion is the dominant intra-particle diffusion process. For mesoporous silica gel, with pore sizes larger than 2 [nm], Knudsen diffusion should also be considered. For this reason, it is assumed that the contribution of Knudsen diffusion is negligible. It might also be interesting to note that in contrast the previous studies that focus on open systems, molecular diffusion, and the external film resistance, do not play a role in closed systems since the gaseous phase consists merely of one constituent, water vapor. The effective diffusion parameter is thus a function of the surface diffusivity which is usually described using an Arrhenius equation:

\[
D_{s} = D_{s0}\exp\left(-\frac{E_{a}}{RT}\right)
\]  

(17)

where \( D_{s0} \) is the pre-exponential constant of the surface diffusion, \( E_{a} \) the activation energy of surface diffusion and \( R \) is the universal gas constant (values are given in Table 1).

Silica gel has the property of adsorbing relatively large quantities of water at low as well as at moderate partial pressures. The adsorption of the water vapor in silica gel is a physical phenomenon and the adsorption equilibrium model of the silica gel bed describes the relationship between the equilibrium water uptake and the local conditions, typically the temperature and vapor pressure. The adsorption isotherm models are often derived based on the governing physical phenomena. These phenomena vary between working pairs and pore sizes (distributions) of the adsorbent. The silica gel type considered in this work is micro-porous according to the IUPAC (International Union of Pure And Applied Chemistry) classification [37]. However, no consistent classification can be made as other researchers classify it as mesoporous. Nevertheless, it is assumed that the adsorption equilibrium of the stored material is best described by the Type I isotherms. The model adopted in this work is that of Dubinin-Astakhov (D-A) as the fit coefficients for the material under consideration, silica gel 127 B, are available [38]. According to this model, the equilibrium water uptake can be expressed as:

\[
q_{n} = q_{0} \exp\left(-\left(\frac{A}{\beta E_{0}}\right)^{n}\right)
\]  

(18)

In this equation \( q_{0} \) is the maximum water uptake capacity, \( \beta E_{0} \) and \( n \) are fit coefficients. Besides, \( A \) is the adsorption potential [39] and can be expressed as:

\[
A = RT \ln\left(\frac{p_{sat}}{P}\right)
\]  

(19)

where \( p_{sat} \) is the saturation pressure of the absorptive in equilibrium with the liquid bulk phase of the studied temperature \( T \).

The source term \( Q \) in the eq. (8) is the heat generated or consumed in adsorber bed which is given by:

\[
Q = R_{c}\Delta H
\]  

(20)

where \( R_{c} \) is the reaction rate as introduced previously and \( \Delta H \) is the enthalpy of the reaction (given in Table 1).
and implicit schemes depending on the problem. The time stepping technique may vary in order and the time step itself may vary in size depending on the evolution of the solution with time. The maximum time step is defined as 0.5 min, however, at the initial stage of convergence, the time step is automatically set to a very small value by the solver, in the order of $10^{-3}$ seconds.

The simulation model as presented above has been validated with the experimental work of Wu et al. (2014) [6] (Fig. 4 (a)). Wu et al. (2014) [6] considered a cylindrical silica gel bed of 0.11 m and 0.01 m outer and inner radius respectively. A water jacket was installed at the outer surface of the silica gel bed which acts as a heat source. The hot water enters the water jacket and heat is transferred to the silica gel bed. On the inner surface of silica gel, a condenser having pressure 2337 Pa is connected which condenses the water vapor. The initial pressure and temperature are 1000 Pa and 20 °C respectively. The heating and cooling water temperature were 80 °C and 20 °C respectively. The heat transported in the bed causes the dehydration of silica gel and stores thermal energy. The temperature variation at the radius 100 [mm] had been measured by the thermocouple. The measured experimental temperature variation is compared with the results obtained by the developed thermal model and shown in Fig. 4 (a). Further, our developed thermal model is also validated with another numerical study Mitra et al. [21] in terms of uptake and shown in Fig. 4 (b). Mitra et al. [21] conducted a numerical study to see the effect of the adsorber bed aspect ratio on ethanol vapor uptake in activated carbon. The study was conducted for three different aspect ratios, where the ethanol vapor

![Fig. 4. Model validation: (a) in terms of bed temperature with an experimental study of Wu et al. [6], (b) in terms of uptake with Mitra et al. [21]](image-url)
is transported to the activated carbon from the top. The obtained results are presented in Fig. 4(b) and compared with the present developed model. The obtained results from both experimental and numerical studies are in good agreement with the present developed numerical model. It is therefore concluded that the developed numerical model can be used for further numerical calculations.

3. Taguchi Method for Parametric Optimization

The design optimization using the Taguchi method is widely used in research and industry to reduce the number of experiments and still to realize enough adequate data to understand the effects of many relevant parameters on the targeted output [24,40]. The Taguchi method is based on a carefully chosen orthogonal array and analyzing the resulting (from calculations) signal-to-noise ratios considering many process variables with the aim to drastically reduce the number of numerical simulations needed to come to the most optimal design [41].

To employ the Taguchi method for optimization, the following steps are taken:

- **The optimization goals for the considered problem are specified:** The present study aims to maximize the amount of energy transported ($E_{dis}$) to the HTF and to maximize the peak power ($W_{peak}$) per unit surface area of heat exchanger fluid in a certain time frame for cylindrical and rectangular fin configurations.

- **The parameters that influence the optimization goals $E_{dis}$ and $W_{peak}$ are specified:** In this study, as presented in Table 2, three different parameters have been selected considering four levels of each: bed height ($\delta_b$), half of the fin thickness/diameter ($\delta_{fin}/2$ or $\phi_{fin}/2$) and half of the fin spacing ($\delta_s/2$). The values of $\delta_b$, $\delta_{fin}/2$ or $\phi_{fin}/2$ and $\delta_s/2$ are ranging from 0.01 m to 0.025 m, 0.0005 m to 0.002 m and 0.0025 m to 0.01 m, respectively.

- **The orthogonal array is carefully chosen:** Since there are three dependent parameters and each dependent parameter has four levels, the L16 orthogonal array is chosen based on the Taguchi method. This means that for the considered parameters with four levels each, the 64 possibilities for independent runs are reduced to 16 using the Taguchi method.

- **A Signal to Noise analysis is performed:** Taguchi strongly endorsed for multiple runs, is to use Signal to noise (S/N) ratio. This approach is to be used to measure the performance characteristics deviating from the desired values. The S/N ratio determines the most vigorous set of operating settings from variation within the results. The objective function in this work is the maximization of $E_{dis}$ and $W_{peak}$, and, hence, the ratio of S/N ($\eta$) is defined according to the Taguchi method as:

$$\text{Larger is better: } S/N(\eta) = -10 \log_{10}\left(\frac{1}{y^2}\right)$$  \hspace{1cm} (21)

A. Temperature [°C] profile and (B) water uptake ($q$) at different time intervals (5, 15, 30 min) for the cylindrical (Top, $\phi_{fin} = 0.0025$ m) and rectangular fin (Bottom, $\phi_{fin} = 0.001$ m) configurations.

---

Table 2: L16 orthogonal array for cylindrical and rectangular fin configurations

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Parameters</th>
<th>$\delta_b$ [m]</th>
<th>$\delta_{fin}/2$ or $\phi_{fin}/2$ [m]</th>
<th>$\delta_s/2$ [m]</th>
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<tbody>
<tr>
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<td>0.0005</td>
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<td>L2</td>
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<tr>
<td>L3</td>
<td></td>
<td>0.010</td>
<td>0.0015</td>
<td>0.00975</td>
</tr>
<tr>
<td>L4</td>
<td></td>
<td>0.010</td>
<td>0.0020</td>
<td>0.0100</td>
</tr>
<tr>
<td>L5</td>
<td></td>
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<td>0.0005</td>
<td>0.0050</td>
</tr>
<tr>
<td>L6</td>
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<td>0.015</td>
<td>0.0010</td>
<td>0.0025</td>
</tr>
<tr>
<td>L7</td>
<td></td>
<td>0.015</td>
<td>0.0015</td>
<td>0.0100</td>
</tr>
<tr>
<td>L8</td>
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<td>0.0075</td>
</tr>
<tr>
<td>L9</td>
<td></td>
<td>0.020</td>
<td>0.0005</td>
<td>0.0075</td>
</tr>
<tr>
<td>L10</td>
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<td>0.020</td>
<td>0.0010</td>
<td>0.0100</td>
</tr>
<tr>
<td>L11</td>
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<td>0.020</td>
<td>0.0015</td>
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</tr>
<tr>
<td>L12</td>
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<td>0.00950</td>
</tr>
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<td>L13</td>
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<td>0.025</td>
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<td>0.0100</td>
</tr>
<tr>
<td>L14</td>
<td></td>
<td>0.025</td>
<td>0.0010</td>
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<td>0.0050</td>
</tr>
<tr>
<td>L16</td>
<td></td>
<td>0.025</td>
<td>0.0020</td>
<td>0.0025</td>
</tr>
</tbody>
</table>
Fig. 6. Variation of power output with time at bottom plate surface and average water uptake of the bed for different fin configurations

Fig. 7. Effect of fin diameter and fin thickness on temperature variation of the bed
where y is the output of each experiment defined in the orthogonal array. In this study, the η values are determined by using Minitab 17.0 software [42]. The larger is better characteristic is used in our problem since the maximum values for $E_{\text{dis}}$ and $W_{\text{peak}}$ are required. The results obtained from the L16 cases for both fin configurations were used to construct response surfaces by considering the factors as bed height, half of the fin thickness or fin radius, and half of the fin spacing for both fin configuration and the response as the different objective functions $E_{\text{dis}}$ and $W_{\text{peak}}$. The 16 cases of the orthogonal array (L16) considered for the present study are presented in Table 2 for both fin configurations.

4. Results and Discussion

Numerical simulations have been conducted for cylindrical and rectangular fin configurations to investigate the effect of bed height, fin diameter or thickness, fin spacing and evaporator pressure. The obtained results are discussed in terms of temperature variation and water uptake. Next, the energy discharge and peak power are correlated with bed height, fin diameter or thickness, fin spacing using the results obtained from the L16 design-of-experiment study. An optimum design is suggested for the selected range of parameters.

4.1. Effect of Different Fin Configuration

Fig. 5 shows the influence of the fin configuration on the temperature and water uptake within the computational domains having $\delta = 0.01\ m$, $\eta = 0.0025$, $\delta = 0.001\ m$ and $\delta = 0.01\ m$ at different time intervals. Four horizontal (x-y) equidistant planes are shown, starting from 2 [mm] distance from the bottom of the silica gel bed and at a mutual distance of 2 [mm]. The initial temperature and pressure are considered to be 20 °C and 100 Pa, respectively. The evaporator temperature is taken to be 10 °C, and the corresponding concentration and pressure are 0.52 mol/m$^3$ and 1230 Pa, respectively. Fig. 5A and 5B represent the temperature distribution and water uptake in the computational domain after 5 min, 15 min and 30 min for both the cylindrical and rectangular fin configurations. From Fig. 5A and 5B, it is observed that the temperature near the fin surfaces is lower and increases with an increase in the distance to the fin surface. However, at the same instance, the water uptake is higher near the fin surface and decreases with an increase in the distance to the fin. The reason for this finding can be explained with the help of the modified Dubinin-Astakhov (D–A) equation [38]. The adsorption capacity of the adsorbent material increases with decreasing adsorbent's temperature. The temperatures for the cylindrical fin configuration are higher as compared to the ones for the rectangular fin configuration due to the lower contact surface area of silica gel with the solid fin, which reduces heat transport from the silica gel to the fin.

Fig. 6 presents the power output ($P_{\text{out}}$) at the bottom of the plate and average water uptake in the bed with time for the selected operating parameters. The power output is defined here as the energy transported to the HTF per unit of time and per unit surface area of the bottom plate. The left y-axis presents power output and the right y-axis presents the water uptake. The power output sharply increases at the initial stage of the adsorption process up to maximum value. This can be explained by the linear driving force model (eq. (14)) in the reaction...
At the initial stage of adsorption, there is a high difference in equilibrium water uptake and actual water uptake, which is initially set to zero, which advances water vapor adsorption in the silica gel. Further, the power output starts decreasing with time as the adsorption rate of water vapor decreases due to the reduction in the difference between equilibrium water uptake and actual water uptake in the silica gel bed. The peak power is higher for the rectangular fin configuration because the silica gel bed has a higher contact surface area with the metallic fin structure that causes higher heat transport to the HTF.

### 4.2. Effect of Fin Diameter and Fin Thickness

Fig. 7 shows the influence of fin diameter and fin thickness on the temperature variation in the cylindrical and rectangular fin configurations at 5 min. The temperature distribution is shown for three different fin diameters and fin thicknesses at four different planes starting at a height of 0.002 m from the bottom surface of the bed and spaced 0.002 m each. The bed height, fin spacing and other parameters are the same as discussed in section 4.1. The larger diameter of the fin increases the contact surface area to the silica gel bed and reduces the volume of the active silica gel material, which leads to a reduced heat storage capacity per unit reactor volume. The increase in the contact surface area causes a higher heat transfer to the bottom surface of the fin. A similar pattern in the temperature variation can also be seen for the rectangular fin configuration. However, in this case, the contact surface area is not

---

### Table 3

<table>
<thead>
<tr>
<th>Cylindrical Fin configuration</th>
<th>Rectangular fin configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_b$ [m]</td>
<td>$d_{fin}/2$ [m]</td>
</tr>
<tr>
<td>L1 0.010</td>
<td>0.0005</td>
</tr>
<tr>
<td>L2 0.010</td>
<td>0.0010</td>
</tr>
<tr>
<td>L3 0.010</td>
<td>0.0015</td>
</tr>
<tr>
<td>L4 0.010</td>
<td>0.0020</td>
</tr>
<tr>
<td>L5 0.015</td>
<td>0.0005</td>
</tr>
<tr>
<td>L6 0.015</td>
<td>0.0010</td>
</tr>
<tr>
<td>L7 0.015</td>
<td>0.0015</td>
</tr>
<tr>
<td>L8 0.015</td>
<td>0.0020</td>
</tr>
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<tr>
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</tr>
<tr>
<td>L13 0.025</td>
<td>0.0005</td>
</tr>
<tr>
<td>L14 0.025</td>
<td>0.0010</td>
</tr>
<tr>
<td>L15 0.025</td>
<td>0.0015</td>
</tr>
<tr>
<td>L16 0.025</td>
<td>0.0020</td>
</tr>
</tbody>
</table>
increasing with increasing fin thickness. Therefore, increasing the fin thickness for this configuration has a low impact on peak power produced. Besides, it also reduces the effective heat storage capacity of the reactor. The temperature of the bed is typically the highest at the top and decreases towards the bottom due to the presence of the metallic bottom surface of the bed.

Fig. 8 represents the variation of average water uptake for both configurations at different values for the fin diameter ($\phi_{\text{fin}} = 0.002 \text{ m}, 0.004 \text{ m and } 0.005 \text{ m}$) and fin thickness ($\delta_{\text{fin}} = 0.001 \text{ m}, 0.002 \text{ m and } 0.003 \text{ m}$). An increase in fin diameter advances the adsorption rate in the bed as the higher fin diameter causes a higher heat transfer from the bed to the HTF. An increase in the fin thickness does not show a large increase in the water uptake as the contact area of the silica gel bed is similar for all fin thicknesses. There are small changes in the water uptake noticeable which are due to a reduction in the volume of silica gel. For the cylindrical fin configuration, an increase in diameter shows significant differences in the water uptake due to a larger contact surface area of the fin with silica gel bed as well as a reduction in the volume of the bed.

4.3. Effect of Bed Height

Numerical simulations have been conducted for three different bed heights i.e. 0.01 m, 0.02 m and 0.03 m. The influence of the bed height on the temperature variation in the bed is shown in Fig. 9 for the cylindrical fin configuration at 5 min. The other initial and boundary conditions are the same as considered in the previous section. Near the bottom plate, the temperature of the bed is higher for the lower bed height because of the higher adsorption rate which results in higher heat generation. However, for the higher bed height, it is vice versa. The higher bed height reduces the adsorption rate and has a negative effect on the water uptake, as shown in Fig. 10. From Fig. 10 it is observed that if the height of the adsorber bed is doubled, the water uptake time is approximately also doubled and if the bed height becomes 3 times as large then the water uptake time also becomes three times as large. Hence the typical time scale to reach a certain level for the water uptake is linearly increasing with the height of the adsorber bed.

4.4. Effect of Evaporator Pressure

The evaporator pressure is an important parameter in the adsorption system. Therefore the study has also been conducted at different evaporator pressures and the influence of evaporator pressure on the temperature variation is shown in Fig. 11 at 5 min. The numerical simulation has been conducted for three different evaporator pressures i.e. 1230 Pa, 1709 Pa and 2344 Pa. From the obtained results it is clear that an increase in evaporator pressure causes an increase in the temperature of the bed, which can be understood on the basis of reaction kinetics. A higher evaporator pressure results in a greater adsorption potential that on its turn augments the adsorption rate of water vapor.

Table 4

<table>
<thead>
<tr>
<th>Fin configuration</th>
<th>Cylindrical Fin</th>
<th>Rectangular fin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2_{\text{dis}}$</td>
<td>$\delta_{\text{fin}}/2$</td>
<td>$\delta_{\text{v}}/2$</td>
</tr>
<tr>
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<td>2582.00</td>
</tr>
<tr>
<td>$b$</td>
<td>9.59</td>
<td>338.00</td>
</tr>
<tr>
<td>$c$</td>
<td>-149.3</td>
<td>5547.00</td>
</tr>
<tr>
<td>$d$</td>
<td>-22.8</td>
<td>-2151.00</td>
</tr>
<tr>
<td>$e$</td>
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<td>115.2</td>
</tr>
<tr>
<td>$f$</td>
<td>10.21</td>
<td>30.87</td>
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<td>91.60</td>
</tr>
<tr>
<td>$i$</td>
<td>75.09</td>
<td>516.00</td>
</tr>
<tr>
<td>$j$</td>
<td>5.16</td>
<td>237.00</td>
</tr>
<tr>
<td>$S$</td>
<td>99.95 %</td>
<td>90.11 %</td>
</tr>
<tr>
<td>$R^2$</td>
<td>99.87 %</td>
<td>90.11 %</td>
</tr>
<tr>
<td>$R^2_{(adj)}$</td>
<td>99.87 %</td>
<td>90.11 %</td>
</tr>
</tbody>
</table>

Increasing with increasing fin thickness. Therefore, increasing the fin thickness for this configuration has a low impact on peak power produced. Besides, it also reduces the effective heat storage capacity of the reactor. The temperature of the bed is typically the highest at the top and decreases towards the bottom due to the presence of the metallic bottom surface of the bed. Fig. 8 represents the variation of average water uptake for both configurations at different values for the fin diameter ($\phi_{\text{fin}} = 0.002 \text{ m}, 0.004 \text{ m and } 0.005 \text{ m}$) and fin thickness ($\delta_{\text{fin}} = 0.001 \text{ m}, 0.002 \text{ m and } 0.003 \text{ m}$). An increase in fin diameter advances the adsorption rate in the bed as the higher fin diameter causes a higher heat transfer from the bed to the HTF. An increase in the fin thickness does not show a large increase in the water uptake as the contact area of the silica gel bed is similar for all fin thicknesses. There are small changes in the water uptake noticeable which are due to a reduction in the volume of silica gel. For the cylindrical fin configuration, an increase in diameter shows significant differences in the water uptake due to a larger contact surface area of the fin with silica gel bed as well as a reduction in the volume of the bed.
and causes an elevated temperature of the bed as shown in Fig. 11. Further, the influence of evaporator pressure on the variation of the average amount of water vapor adsorbed inside the adsorbent bed with time is shown in Fig. 12. An increase in the evaporator pressure causes an increase in the average amount of water vapor adsorbed which can be understood with the help of the Dubinin-Astakhov (D–A) equation [38]. The adsorption capacity of the adsorbent material increases with decreasing of adsorbent’s temperature and increasing of adsorbate’s pressure. The adsorption process takes longer to reach the equilibrium conditions when the evaporator pressure is higher. The equilibrium water uptake for the 1230 Pa, 1709 Pa and 2344 Pa evaporator pressure is 0.21, 0.27 and 0.37 respectively.

4.5. Optimization of Heat Exchanger Design Parameters

One of the objectives of this study is to optimize the adsorbent bed of a closed adsorption heat storage system investigating the optimum fin thickness, fin spacing and bed height. This has been achieved by considering the elementary 3D cuboid designs with two types of fin configurations filled with silica gel between the spaces as introduced in Fig. 3. The study plan as described earlier has been conducted by considering an L16 orthogonal array as presented in Table 3 for both fin configurations. The $E_{\text{dis}}$ and $W_{\text{peak}}$ values are calculated for different cases as presented in Table 3 by applying the developed numerical model. Below the effect of bed height ($\delta_b$), fin diameter or fin thickness ($\delta_{\text{fin}}$ or $\delta_{\text{fin}}$), and fin spacing ($\delta_s$) on the energy extracted ($E_{\text{dis}}$) and the peak power ($W_{\text{peak}}$) are discussed.

Fig. 13 shows the mean values of the Signal-to-Noise (SN) ratios (computed using eq. (21)) to investigate the effect of different design parameters on $E_{\text{dis}}$ and $W_{\text{peak}}$ for the cylindrical and rectangular fin configurations. Fig. 13(a) presents the mean values of SN ratios for the cylindrical fin configuration at a different levels of $\delta_b/2$, $\delta_{\text{fin}}/2$ and $\delta_s/2$ for $E_{\text{dis}}$. The maximum values are obtained at the level 0.025 m, 0.0015 m and 0.01 m for $\delta_b/2$, $\phi_{\text{fin}}/2$ and $\delta_s/2$ respectively. Similarly, Fig. 13(c) presents the mean values of SN ratios for the rectangular fin configuration at different levels of $\delta_b/2$, $\phi_{\text{fin}}/2$ and $\delta_s/2$ for $E_{\text{dis}}$. Now the maximum values are obtained at the level 0.025 m, 0.0005 m and 0.01 m for $\delta_b/2$, $\phi_{\text{fin}}/2$ and $\delta_s/2$ respectively. At these levels, the value of $E_{\text{dis}}$ is maximum. For both fin configurations, the maximum value of $E_{\text{dis}}$ is obtained at $\delta_s/2 = 0.025$ m which is the highest level for the selected parameter. This effect is observed because a higher bed height results in a higher volume of the bed, which consequently results in more heat generation and as such a higher value of $E_{\text{dis}}$ while the other parameters remain the same. The maximum value of $E_{\text{dis}}$ is obtained at $\phi_{\text{fin}}/2 = 0.0015$ m for the cylindrical fin configuration and at $\phi_{\text{fin}}/2 = 0.0015$ for the rectangular fin configuration. This can be understood by the fact that a smaller diameter of the fin results in a smaller contact area with the adsorber bed, which causes lower heat transport to the HTF. For larger values of the diameter the dissipated energy $E_{\text{dis}}$ decreases as the actual volume of the silica gel bed also reduce. For the rectangular fin configuration, the $E_{\text{dis}}$ is highest at the lowest level of $\delta_{\text{fin}}/2 (0.0005 \text{ m})$ as the increase in the fin thickness only reduces the actual volume of the silica gel bed. Further the highest value of $E_{\text{dis}}$ is obtained at the maximum level of $\delta_b/2 = 0.01 \text{ m}$ for both fin configurations as the volume of the silica gel bed is the largest.

Fig. 13 (b) and (d) present the variation of the mean values of the SN ratios at different levels of $\delta_b/2$, $\phi_{\text{fin}}/2$ or $\delta_{\text{fin}}/2$ and $\delta_s/2$ for $W_{\text{peak}}$ for the cylindrical and rectangular fin configurations respectively. In Fig. 13(b), the maximum SN ratio for $W_{\text{peak}}$ for the cylindrical fin configuration is obtained at the levels 0.015 m, 0.0015 m and 0.0025 m for $\delta_b/2$, $\phi_{\text{fin}}/2$ and $\delta_s/2$ respectively. Therefore the maximum value for $W_{\text{peak}}$ will also be obtained at these levels. The value of $W_{\text{peak}}$ is highest at $\delta_b/2 = 0.015 \text{ m}$ because a further increase of the bed height causes reduced heat transfer to the bottom surface of the fin and a decrease of the bed height results in a smaller volume of the bed also leading to a reduction in peak power. A similar trend is obtained with the rectangular fin configuration for $\delta_b/2$ as shown in Fig. 13 (d). The maximum $W_{\text{peak}}$ value is obtained at $\phi_{\text{fin}}/2 = 0.0015 \text{ m}$ and $\delta_b/2 = 0.0005 \text{ m}$ for the cylindrical and rectangular fin configuration respectively. This can be understood as the higher fin thickness and diameter levels lead to reduced volumes of the silica gel bed and, consequently, result in lower heat generation. This is not true for the lower values of the fin diameter ($\phi_{\text{fin}}/2 = 0.0005 \text{ m}$ and $\phi_{\text{fin}}/2 = 0.001 \text{ m}$) because low values of the fin diameter result in poor heat transport from bed to fin and hence low peak powers. Maximum values for $W_{\text{peak}}$ are obtained at $\delta_b/2 = 0.0025 \text{ m}$ for the cylindrical fin configuration (Fig. 13(b)) and $\delta_b/2 = 0.005 \text{ m}$ (Fig. 13(d)) for the rectangular fin configuration. The lower fin spacing leads to a fast discharging rate and results in a higher peak power. However, this is different for the level $\delta_b/2 = 0.0025 \text{ m}$ (Fig. 13(d)) as the lowest level of $\delta_b/2$ results in small volume of bed which not able to produce much power than $\delta_b/2 = 0.0025 \text{ m}$

Based on the results obtained from the simulations, correlations were developed for each of the different objective functions in terms of non-dimensional bed height ($\frac{\delta_b}{\delta_b^{\text{min}}}$), half of fin thickness or diameter ($\frac{\delta_{\text{fin}}}{\delta_{\text{fin}}^{\text{min}}}$) and half of fin spacing ($\frac{\delta_s}{\delta_s^{\text{min}}}$). Here $\delta_{\text{fin}}^{\text{min}}$ is the minimum value of half of the fin spacing considered in the orthogonal array and its value is given by 0.0025 m. The correlations are expressed in the form:
where \(a, b, c, d, e, f, g, h, i\) and \(j\) are the coefficients obtained from regression analysis and summarized in Table 4 for the different objective functions. The values for the standard error (S) and the determination coefficients \(R^2\) and \(R^2(adj)\) are also presented in Table 4. All the quadratic regression models show a value of the determination coefficient \(R^2\) higher than 93%, which implies that 93% of the variation can be explained by the fitted model. The closer the value of \(R^2\) to 100%, the better the empirical models fit the actual data. On the other hand, the smaller the value of \(R^2\), the less relevant the dependent variables are in the model in explaining the behavior of variations [43]. So, for a good statistical model, \(R^2(adj)\) should be close to \(R^2\). The obtained \(R^2\) values as presented in Table 4 indicate that there is a high degree of relationship between the observed and predicted values. Fig. 14 shows the comparison between the simulated results with the correlation results to assess the accuracy of the correlations. It is seen that the developed correlations are in good agreement with the simulation results for all objective functions. The maximum error obtained in the predicted and calculated values are ±5% for \(E_{dis}\) and ±15% for \(W_{peak}\). All results from the correlations have 95% and 85% confidence levels for \(E_{dis}\) and \(W_{peak}\) respectively as presented in Fig. 14.

Based on the developed correlation various design conditions are suggested for \(E_{dis}\) and \(W_{peak}\). The contour design conditions for \(E_{dis}\) and \(W_{peak}\) for cylindrical and rectangular fin configurations are presented in Fig. 15 and Fig. 16 respectively. The contours of \(E_{dis}\) holding the value of \(\delta_b/2 = 0.00625\) m are shown in Fig. 15(a), where the x-axis presents bed height and the y-axis represents the fin radius. For the selected range of \(\delta_b/2\) and \(\phi_{fin}/2\) at \(\delta_b/2 = 0.00625\) m, the design range of \(E_{dis}\) is 117.72 J to 247.43 J. From Fig. 15 (a), it is also observed that for \(\delta_b/2 = 0.00625\) m, the effect of fin radius is quite less on the \(E_{dis}\) for lower bed height. Fig 15 (b) represents the design range of \(E_{dis}\) for the selected range of \(\delta_b/2\) and \(\phi_{fin}/2\) at \(\delta_b/2 = 0.00125\) m. The design range of \(E_{dis}\) is obtained between 40 J to 490 J and it’s also observed that for a certain \(E_{dis}\), the \(\delta_b/2\) value decreases with an increase in \(\delta_s\). Similarly, Fig. 15 (c) and Fig. 15 (d) present the contour of \(W_{peak}\) holding \(\delta_b/2\) and \(\phi_{fin}/2\) at \(\delta_b/2 = 0.00625\) m and \(\delta_b/2 = 0.00125\) m respectively. The design range of \(W_{peak}\) at \(\delta_b/2 = 0.00625\) m for the selected range of \(\delta_b/2\) and \(\phi_{fin}/2\) is in the range of 1000 W/m² - 2500 W/m². For a specific peak power and constant fin spacing \(\delta_b/2 = 0.00625\) m, the fin radius decreases with an increase in the bed height up to a level and afterward, the fin radius starts increasing. Fig 15 (d) presents the contour plots of \(W_{peak}\) where \(\phi_{fin}/2\) holds at 0.00125. The design range for \(W_{peak}\) holding the \(\phi_{fin}/2 = 0.00125\) m and selected values of \(\delta_b/2\) and \(\delta_b/2\) varies from 900
$W/m^2$ to 3400 $W/m^2$. The maximum peak power is obtained with the minimum value of $\delta_b/2$ and $\delta_s/2$ and for a particular value of peak power, the effect of bed height is minimal at lower $\delta_s/2$ and major for high $\delta_s/2$.

Fig. 16 (a) and (b) present the contours of $E_{dis}$ for the rectangular fin configuration holding the value of $\delta_s/2$ and $\delta_{fin}/2$ at 0.00625 m and 0.00125 m respectively. The value of $E_{dis}$ is obtained in the range of $\sim85 J – 255 J$ for the selected range of $\delta_b/2$ and $\delta_{fin}/2$ at constant $\delta_s/2 = 0.0025 m$. It is also observed that for a specific value of $E_{dis}$ the effect of fin thickness is small when the bed height is lower as shown in Fig. 16 (a). Further the design range of $E_{dis}$ for constant $\delta_{fin}/2 = 0.00125 m$ and selected range of $\delta_b/2$ and $\delta_s/2$ is in the range of $\sim20 J – 255 J$ as shown in Fig 16 (b). Fig 16 (c) and (d) present the contours of $W_{peak}$ for the rectangular fin configuration keeping the value of $\delta_s/2$ and $\delta_{fin}/2$ at 0.00625 m and 0.00125 m respectively. From Fig. 16 (c) the design range of $W_{peak}$ for the selected range of $\delta_b/2$ and $\delta_{fin}/2$ at $\delta_s/2 = 0.00625 m$ is $\sim 2300 W/m^2 – 3300 W/m^2$. It is also observed that at lower values of $\delta_b/2$, $\delta_{fin}/2$ has a minor influence on $W_{peak}$ and the effect is greater at higher $\delta_b/2$. Fig. 16 (d) presents the design range of $W_{peak}$ for the selected range of $\delta_b/2$ and $\delta_s/2$ at $\delta_{fin}/2 = 0.00125 m$ and the obtained design range is $\sim 2000W/m^2 – 3300W/m^2$. From Fig. 16 (d), it can also be observed that for a certain value of $W_{peak}$ and constant $\delta_{fin}/2$, if $\delta_s/2$ increases the $\delta_b/2$ decreases up to certain $\delta_b/2$ and then decreases.

5. Conclusions

In the present study, a mathematical model of the heat and mass transfer processes inside an adsorption bed of silica gel embedded with cylindrical and rectangular fins has been developed. A systematic analysis has been conducted to augment thermal transport in the adsorption bed with rectangular and pin fin configurations. A parametric study has been conducted for both fin configurations at different bed heights ($\delta_b$), fin diameters/thicknesses ($\phi_{fin}/\delta_{fin}$) and fin spacings ($\delta_s$). Further, a design-of-experiments study is conducted to relate the energy discharge ($E_{dis}$) and peak power ($W_{peak}$) to the various governing parameters, as such identifying which parameters maximize energy discharge ($E_{dis}$) and peak power ($W_{peak}$).

Detailed numerical simulations have been conducted for the heat and mass transfer processes to investigate the effect of bed height ($\delta_b$), fin thickness or diameter ($\delta_{fin}$ or $\phi_{fin}$) and fin spacing ($\delta_s$) on the energy discharge ($E_{dis}$) and peak power ($W_{peak}$). The numerical simulations were performed for 16 cases for both fin configurations. Based on these results, correlations were developed for $E_{dis}$ and $W_{peak}$ for both fin configurations which are found to be 95% confidence level for $E_{dis}$ and 85% for $W_{peak}$. Further, the contour for $E_{dis}$ and $W_{peak}$ has been plotted considering the fin thickness and fin spacing as a constraint. For the cylindrical fin configuration, the optimum value of $\delta_b$, $\phi_{fin}$ and $\delta_s$ that can produce maximum $E_{dis}$ and $W_{peak}$ is 0.025 m, 0.003 m 0.02m and 0.015 m, 0.003 m 0.005 m respectively. However, for rectangular fin configuration, the optimum value of $\delta_b$, $\delta_{fin}$, $\delta_s$ for $E_{dis}$ and $W_{peak}$ is 0.025 m, 0.001 m 0.02m and 0.015 m, 0.001 m 0.01 m respectively.
The design-of-experiment study reveals that the rectangular fin configuration shows better performance compared to the cylindrical fin configuration. This study demonstrates the need for parametric optimization for the efficient design of a finned adsorber bed for a closed sorption heat storage system. Such studies could further be extended by conducting a techno-economic study of these types of systems integrated with the built environment to reduce the heating and cooling cost of the building.

Author Credit

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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.

Acknowledgments

This research has been made possible by the Energy Pads program, funded by TKIenergo and work is done in cooperation with ArEnergy and De Beijer RTB.

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