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Comparative Study on Performances of Waste Heat Driven Adsorption Cooling System Using Silica Gel/Methanol and Silica Gel/Water Working Pair

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ABSTRACT

The present investigation juxtaposes the functioning of two distinct pairings: silica gel-water and silica gel-methanol, within dual-bed adsorption cooling configurations. The selection of these working pairs hinges upon their alignment with specific cooling requisites. Notably, silica gel-water configurations find employment in air conditioning scenarios, whereas silica gel-methanol setups cater to refrigeration demands. By employing cooling water set at 30°C, the proposed refrigeration setup integrating silica gel-water and silica gel-methanol pairs exhibits commendable potential for harnessing low-grade heat sources within the temperature range of 60°C to 90°C, thus functioning as the driving heat reservoir. Intriguingly, the ongoing investigation posits that the silica gel-water adsorption system outperforms the silica gel-methanol adsorption system across various parameter configurations, as evidenced by superior cooling efficiency and Coefficient of Performance (COP). Noteworthy simulation outcomes underscore that the temperature while operation, hot and cold-water streams, exert significant influence on the COP and cooling effect of the adsorption chiller system.

1. INTRODUCTION

In remote locales, the demand for cooling stands prominent as a necessity for preserving the integrity of edibles, pharmaceuticals, and immunizations. Additionally, cooling plays a pivotal role in maintaining fish quality on fishing vessels, where the dissipation of waste heat from diesel engines assumes significant relevance [1].

Urban centres rely on conventional vapor compression refrigeration systems to address the cooling requisites for sustaining food and vaccine quality. As noted by the (IIR) i.e., International Institute of Refrigeration, approximately that 15% of the world's generated power finds application in refrigeration and air conditioning endeavours [2]. Projections suggest that air conditioning systems alone might account for in excess of 45% of the overall consumption of energy in residential and commercial structures [3]. In tandem with the ascending trajectory of global economic expansion, there has been a corresponding surge in energy usage, aimed at fulfilling the cooling prerequisites of conventional refrigeration method and air conditioning equipment in both industrial and structural contexts. It is noteworthy that these devices hinge on conventional synthetic refrigerants and fossil fuels, such as hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and chlorofluorocarbons (CFCs) [4]. However, these choices entail grave environmental ramifications by reason of their ozone depletion potential (ODP) and substantial global warming potential (GWP) [5].

Moreover, the emphasis on low-grade thermal heat (comprising solar, industrial/automobile waste heat, and geothermal) propelled adsorption refrigeration systems has garnered significant interest [6, 7]. This attention stems from their potential to cater to cooling requirements in rural regions and on fishing vessels, while concurrently addressing concerns about ozone depletion, global warming, and the diminishing reserves of fossil fuels that arise from conventional vapor compression technologies [8]. A distinguishing facet of these systems lies in their environmentally conscious approach, leveraging natural or alternative refrigerants. This deliberate choice negates the employment of substances like HFCs, CFCs, or HCFCs, renowned for their GWP, and zero-ODP [9].

Numerous researchers have extensively explored adsorption systems concerning cooling and air conditioning. The impression of operational parameters on cooling output and COP was meticulously analysed by Saha et al. [10] who engineered and devised a dedicated silica gel–water adsorption chiller tailored for air conditioning scenarios. In the realm of dual-bed adsorption cooling, Xia et al. [11] uncovered a pinnacle COP of 0.43 at a triad temperature of 84.4/30.5/16.5°C. An exploration by Lu et al. [12] encompassed two distinct adsorption cooling configurations: macro-porous silica gel/LiCl-methanol and micro-porous silica gel-water. The studies executed by them unveiled a noteworthy 59.5% augmentation in specific cooling power (SCP) within the silica gel/LiCl-methanol cooling setup compared to its silica gel–water counterpart. Furthermore, the viability of the silica gel/LiCl-methanol design extends to cold storage applications. Through meticulous investigation, Pan et al. [13] scrutinized silica gel-water adsorption chiller running by low grade heat energy, attaining an SCP of 125.0 W/kg and a COP of 0.51 under specific operational temperatures (86/30/11℃ for hot water inlet/cooling water inlet/chilled water outlet respectively).

A trusted system for refrigeration is single-stage two-bed adsorption was used in this investigation because it delivers a quasi-continuous cooling effect. Compared to a single bed adsorption system, this dual bed adsorption system performs better. The adsorbent in this system is silica gel, while the adsorbates are water and methanol. The silica gel-water adsorption system can produce temperatures beyond sub-zero [14, 15], while the silica gel-methanol adsorption system can have temperatures below sub-zero [16, 17].

The above literature review shows that adsorption refrigeration systems using silica gel as the adsorbent involve addressing specific technical challenges and understanding areas that require further exploration. While silica gel is a commonly used adsorbent, understanding its performance with different refrigerants under various operational conditions remains a challenge. Key knowledge gaps include optimizing adsorbent-refrigerant pairs for better performance, improving heat and mass transfer efficiency, and ensuring cyclic stability. Reducing the adsorption-desorption cycle time is crucial for enhancing system efficiency. However, there is still a gap in understanding the best methods to optimize these cycle times while maintaining energy efficiency. To address these research gaps, the primary focus of the current study is to evaluate the performance of a single-stage adsorption cooling system using silica gel/methanol and silica gel/water as adsorbent-adsorbate combinations.

2. ADSORPTION COOLING SYSTEM PRINCIPLE

In this current research the simplest two-bed adsorption cooling system is shown schematically in the Figure 1.

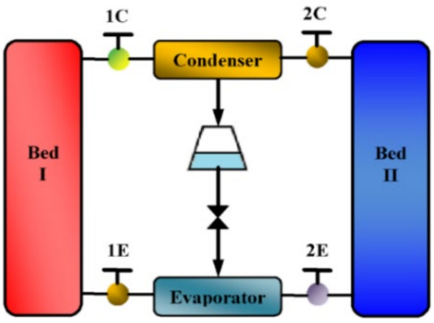

Figure 1. Schematic diagram of the two beds adsorption cooling system

The adsorbent bed I is heated during the first half of the cooling cycle to begin the process of regeneration desorption. Figure 2 represents details design of adsorber/desorber bed. Connected to the condenser but segregated from the evaporator, valve 1C opens and valve 1E closes, causing liquid refrigerant to vaporize for cooling production. Following evaporation, the refrigerant vapor progresses towards adsorber bed II, and valve 2E is activated. Sequentially, upon valve 2C closure, this reactor is detached from the condenser and cooled to initiate the adsorption of refrigerant vapor. Next step orchestrates a reversal, swapping the heating and cooling sequences.

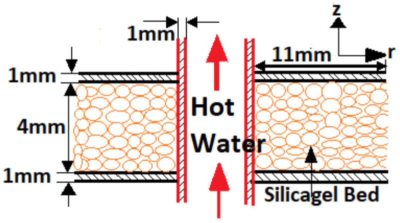

Figure 2. Silica gel between fins

3. MATHEMATICAL MODEL

A lumped parameter model was built to investigate how operational parameters affect the performance of the proposed adsorption chiller. In this comparison, both systems maintained uniform physical dimensions for all four heat exchangers (evaporator, condenser, and adsorber/desorber beds). The equilibrium adsorption capacity of the silica gel-water system was calculated using the adjusted Freundlich model [18], whereas the equilibrium adsorption capacity of the silica gel-methanol system was calculated using a correlation based on the Langmuir type [19].

3.1 Model description

The simulated configuration is shown in Figure 3. Silica gel spherical beads form a slender layer within the heat exchanger tubes' fins within the adsorber/desorber.

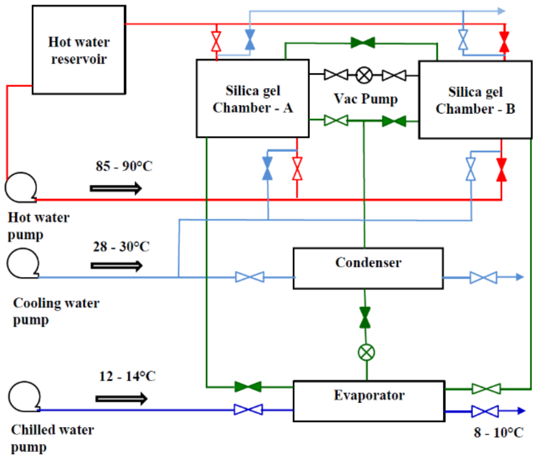

Figure 3. Schematic representation of an adsorption chiller

3.2 Simulation procedure

The thermal distribution within the silica gel bed is solved by finite difference substitution of the partial derivatives in the steady 2–D (radial symmetry) heat conduction Eq. (1) and solving the resulting algebraic equations numerically through MATLAB code.

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{T}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial z} \tag{1}$$

The temperature profile of the silica gel bed between fins has been developed under heating with burning water inlet temperature of 85°C and is shown in Figure 4.

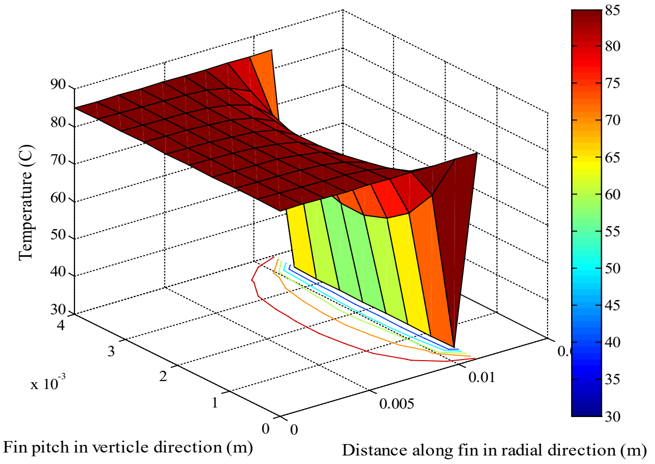

Figure 4. Silica gel bed temperature profile while undergoing desorption with the hot water inlet temperature of 85°C

3.3 Model description

Adsorption-based cooling systems capitalize on the temperature-responsive sorption nature of adsorbents to facilitate cooling processes. Within sub-atmospheric pressure refrigeration arrangements, microporous silica gel is favored for its elevated water adsorption capacity in environments with low humidity levels. The operation of solar heat-driven adsorption chillers involves the utilization of solar thermal energy to induce desorption, leading to the release of refrigerant water vapor from heated adsorbent beds. Condensation in the condenser follows, after which the vapor proceeds to the evaporator, where low-pressure evaporation induces cooling. In dual-bed chillers, the second adsorber concurrently captures water vapor from the evaporator. The second bed's silica gel, being relatively dry and cool, functions as an initiator for evaporation. Hence, cyclic operations dictate the system's functioning. During any given operation, one adsorber undergoes desorption (heating phase), while another engages in adsorption (cooling phase). Sequential heating and cooling of adsorbers demarcate these phases, facilitating a near-continuous cooling effect within the system.

Figure 4 illustrates the schematic representation of a dual-bed adsorption chiller's flow diagram.

3.4 Assumptions

The assumptions mentioned below are the mathematical model made to simplify to understand.

- Pressure and temperature are considered to be constant throughout the adsorber bed.
- The system of water and silica gel particles functions like a continuous media.
- The consideration of mass transfer resistance within micropores and interstitial regions is omitted.
- The adsorbed and desorbed water's specific heat is the same as the bulk liquid water's.

3.5 Governing equations

3.5.1 Adsorption kinetics

The effectiveness of mass and heat transfer within the bed of adsorbent significantly impacts adsorption kinetics. Enhanced adsorption rates using the same adsorbent material correspond to improved heat transfer capabilities. In the simulated adsorption chiller, silica gel is intricately positioned among the fins of the adsorbent bed, forming a delicate layer around the outer surface of the heat exchanger. This arrangement facilitates even access of water vapor to all regions of the silica gel simultaneously. Consequently, employing the linear driving force kinetic (LDF) model, the simulation of adsorption/desorption rates is conducted, focusing on surface diffusion and excluding inter-particle mass transfer. In other words, the linear driving force kinetic (LDF) model is utilized to simulate adsorption/desorption rates, with emphasis on surface diffusion while disregarding inter-particle mass transfer.

$$\frac{dx}{dt} = k_s\,(x^*(P,T) - x) \tag{2}$$

where, k_s denotes the total mass transfer coefficient

$$k_s = \frac{15\,D_s}{R_p^2} \tag{3}$$

R_p signifies the mean radius of adsorbent particles. The rate of adsorption/desorption relies on surface diffusion occurring within an adsorbent particle, with the surface diffusivity (Ds) intricately linked to temperature fluctuations.

$$D_s = D_{so}\,exp^{\left[\frac{-E_a}{RT}\right]} \tag{4}$$

where, D_{so} represents the pre-exponential constant, while E_a signifies the activation energy for surface diffusion.

From the mentioned Eqs. (2)-(4), we get

$$\frac{dx}{dt} = 15\,\frac{D_{so}Exp^{\left[\left(\frac{-E_a}{RT}\right)\right]}}{R_p^2}(x^*(P,T) - x) \tag{5}$$

To enhance precision, Saha et al. [6] opted for a customized adaptation of the Freundlich model to match experimental outcomes concerning the silica gel-water amalgamation. By incorporating the influence of partial pressure interactions between the adsorbent bed and its corresponding heat exchanger, this particular modification enhances the applicability of the modified Freundlich model in predicting adsorption isotherms unique to the Silica gel-water system.

$$x^*(P,T) = A(T_{sg})\left[\frac{P_{sat(T_W)}}{P_{sat}(T_{sg})}\right]^{-B(T_{st})} \tag{6}$$

$$A(T_{sg}) = A_0 + A_1T_{sg} + A_2T_{sg}^2 + A_3T_{sg}^3$$
$$B(T_{sg}) = B_0 + B_1T_{sg} + B_2T_{sg}^2 + B_3T_{sg}^3$$

The parameters A_0–A_3 and B_0–B_3 were determined through the application of least square fits to the experimental data [6].

3.5.2 Methanol properties

The vapor pressure of methanol in its saturated state, as described by Antoine's equation, is expressed as follows.

$$P_s = 133.3 \times 10^{\left(A_1 - \left(\frac{B}{(T+C)}\right)\right)} \quad (7)$$

where, T is in °C, A_1= 8.072, B = 1574.99 and C = 238.86

3.5.3 Mass equation

The mass balance equation for water is written as follows, ignoring the gaseous phase.

$$\frac{dm_w}{dt} + m_{sg}\left(\frac{dx_{des}}{dt} + \frac{dx_{ads}}{dt}\right) = 0 \quad (8)$$

In this context, msg corresponds to the mass of silica gel contained within each bed, and mw denotes the mass of water in the evaporator. The subscripts "ads" and "des" distinctly indicate the processes of adsorption and desorption, respectively.

Parameter and property values adopted for simulation

The physical parameters of the heat exchangers and the property values of the chiller system have been listed in Table 1 and Table 2.

Table 1. Property values and physical parameters used in the simulation model

Parameters	Values	Units
$C_{p,hex}$	950	J kg^{-1} K^{-1}
$C_{p,sg}$	924	J kg^{-1} K^{-1}
D_{so}	2.54×10^{-4}	m^{2}s^{-1}
E_a	4.2×10^4	J mol^{-1}
$h_{fg,meth}$	1.165×10^6	J kg^{-1}
$h_{fg,w}$	2.5×10^6	J kg^{-1}
m_{con}	24.28	Kg
m_{eva}	12.45	Kg
m_{sg}	47	Kg
Q_{st}	2.8×10^6	J kg^{-1}
R_p	7.1×10^{-4}	m
UA_{bed}	3500	W K^{-1}
UA_{con}	15330	W K^{-1}
UA_{eva}	4870	W K^{-1}

Table 2. Heat transfer fluids' flow rates

Parameter	Value (kg s^{-1})
Hot water	1.3
Cooling water flow to adsorber	1.6
Cooling water flow to condenser	1.3
Chilled water flow	0.7

3.5.4 Equations for energy balance

Through the utilization of a lumped simulation model and the omission of heat losses, the modeling encompassed the sorption bed (comprising adsorber and desorber), evaporator, and condenser [14].

Parameters for Chiller Performance

Cooling capacity and COP are the primary indicators of adsorption chiller performance.

The mathematical expression for the chiller's cooling capacity (Q_{chill}) is expressed as:

$$Q_{Chill} = m_{f,chill} c_{pf} \int_0^{t_{cycle}} \left(T_{Chill,in} - T_{Chill,out}\right) dt \quad (9)$$

The expression for the COP of the chiller can be represented as:

$$COP = \frac{Q_{Chill}}{Q_{Heat}} \quad (10)$$

where, heat input,

$$Q_{heat} = m_{f,hot} c_{p,f} \int_o^{t_{cycle}} \left(T_{hot,in} - T_{hot,out}\right) dt \quad (11)$$

4. RESULTS AND DISCUSSION

The purpose of this study was to evaluate the performance of a low-grade heat-driven adsorption chiller. The experiment used silica gel-water and silica gel-methanol as the adsorption working pairs to test differences in driving source, cooling water, and chilled water input temperatures. The study also looked into how cycle time affected system effectiveness. Cooling capacity and COP were included as the main evaluation criteria as crucial performance metrics.

4.1 Hot water inlet temperature's upshot

Detailed analysis of Figures 5 and 6 reveals the intricate impact of raising the hot water inlet temperature on the adsorption chiller's operational outcomes.

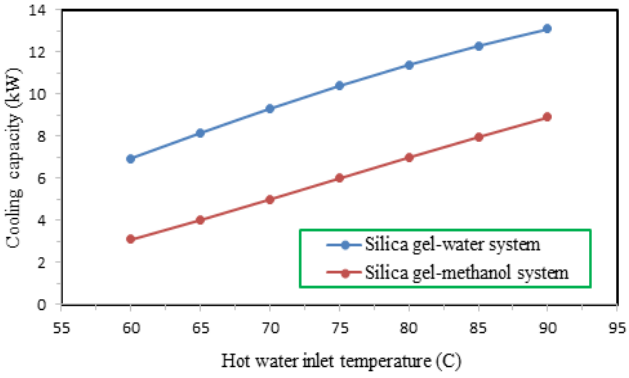

Figure 5. Influence of hot water inlet temperature on cooling capacity

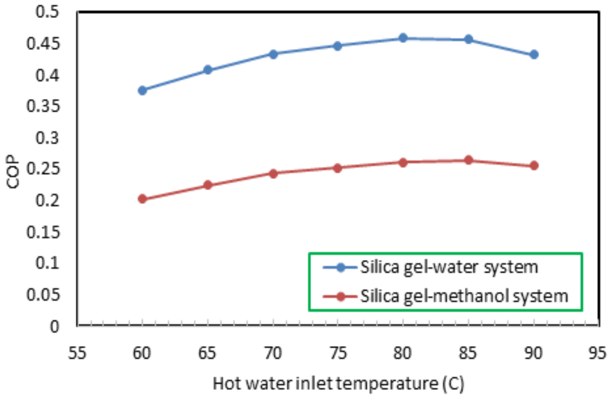

Figure 6. Consequences of hot water inlet temperature variation on COP

The graphical representations provide a comprehensive view of the dynamics between cooling capacity, COP, and chilled water outlet temperature, taking into account two distinct adsorbent-adsorbate pairings. Of particular significance is the synchronous enhancement in the chiller's cooling capacity as the hot water inlet temperature advances from 60°C to 90°C, while keeping the cooling water temperature constant at 30°C, as depicted in Figure 5. Meanwhile, the chiller's COP exhibits an initial increase followed by a subsequent decline, with the optimal value pinpointed at 85°C, as shown in Figure 6.

4.2 Impact of cooling water inlet temperature

Figures 7 and 8, in contrast, offer a comprehensive investigation into how alterations in the cooling water inlet temperature manifest in terms of the chiller's cooling capacity, COP, and the resultant temperature of chilled water output. These analyses encompass both the silica gel-water and silica gel-methanol adsorption configurations. The chiller's cooling capacity increases (Figure 8), along with a concurrent rise in COP (Figure 9), and a corresponding decrease in chilled water output temperature. This study also carefully examines a decrease in the cooling water inlet temperature from 40 to 20°C.

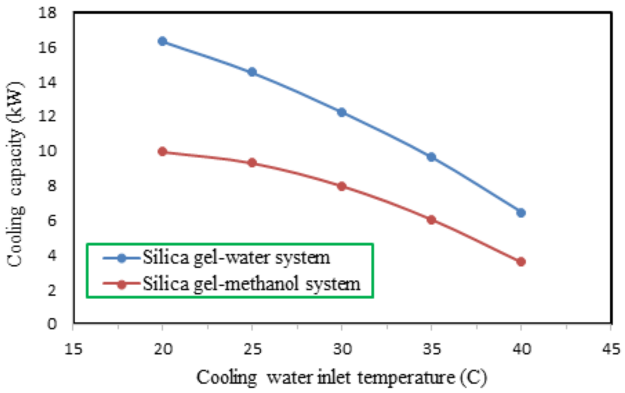

Figure 7. Impact of cooling water inlet temperature on cooling capacity

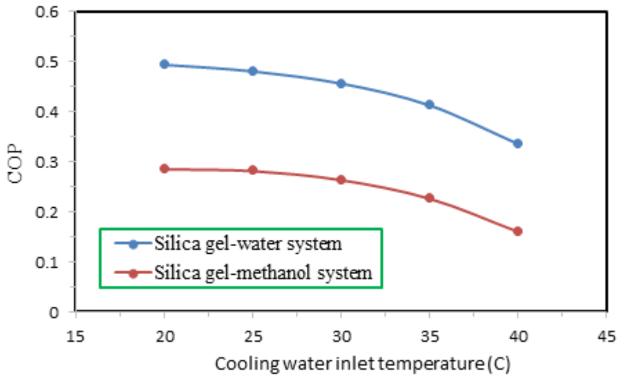

Figure 8. Impact of cooling water inlet temperature on COP

4.3 Impact of chilled water inlet temperature

Figures 9 and 10 visually depict the significant effect of variations in cooling water inlet temperature on the chiller's operational characteristics. Notably, as the chilled water input temperature is heightened from 10°C to 20°C (Figure 9), the chiller's cooling effect registers a notable enhancement. This change is mirrored in the COP of the chiller, which follows a similar increasing trend (Figure 10).

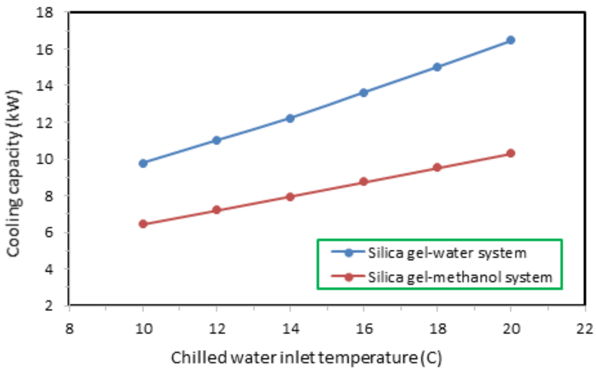

Figure 9. Impact of chilled water inlet temperature on cooling capacity

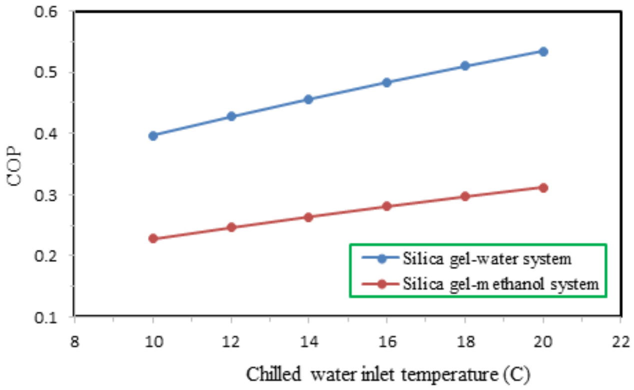

Figure 10. Impact of chilled water inlet temperature on COP

4.4 Effect of hot water flow rate

Depicted in Figures 11 and 12, the alterations in chiller operation due to changes in hot water flow rates are evident. The variations in cooling capacity and COP for two distinct adsorbent-adsorbate pairings are clearly demonstrated, offering valuable information regarding their response to different conditions. The capacity of cooling the chiller improves as flow rate of the hot water is noticeably amplified and noted as from 1.0 to 4.0 kg/s (Figure 11), while the chiller's COP declines (Figure 12).

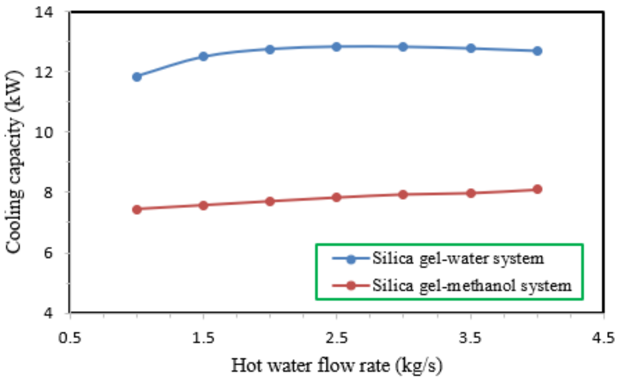

Figure 11. Impact of hot water flow rate on cooling capacity

4.5 Chilled water flow rate's impact

As presented within Figures 13 and 14, provide a visual representation of the consequential effects of adjusting chilled water flow rates on chiller attributes – cooling capacity and COP. This dual analysis, conducted for two specific adsorbent-adsorbate combinations, reveals a clear initial enhancement in both cooling effect (Figure 13) and COP (Figure 14) with an escalating chilled water flow rate from 0.2 to 1.0 kg/s. Remarkably, at higher chilled water flow rates, these performance metrics exhibit a near-flat trend, showcasing an intriguing behavior.

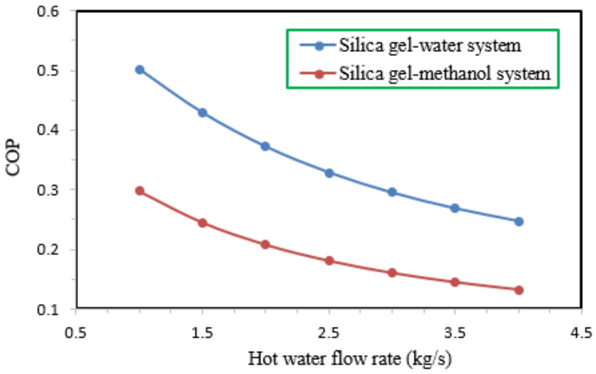

Figure 12. Impact of hot water flow rate on COP

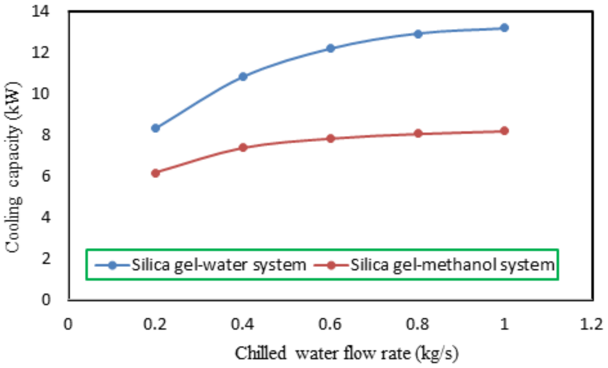

Figure 13. Impact of chilled water flow rate on capacity of cooling

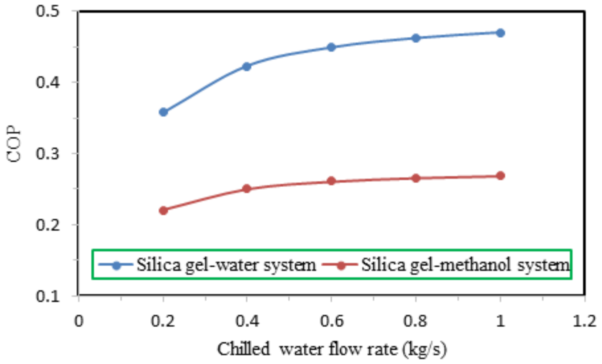

Figure 14. Impact of chilled water flow rate on COP

4.6 Adsorption/desorption time's impact

In an intermittent cycle operation, the significant sensible heat load stemming from the silica gel adsorbent, heat exchanger metal, and adsorbed water masses, due to rapid alternation between heating and cooling, engenders notable heat losses. By extending the cycle time, the instances of sensible heating and cooling for each bed within a specific duration are obviously reduced. Consequently, this lengthened cycle time of operation corresponds to decreased driving heat consumption. Hence, ultimately enhancing the COP. Conversely, extending the cycle time has the opposite effect and result on the cooling capacity.

Below shown Figures 15 and 16 are able to present the impact on the chiller's cooling capacity through its cycle time and COP under rated operating conditions. Furthermore, it's evident that the chiller employing the pair of silica gel-water surpasses its silica gel-methanol counterpart in both cooling capacity and COP. However, it is important and noteworthy to take into consideration that at the cycle time is abbreviated and shorten then the capacity of cooling is restricted and controlled due to insufficient duration for effective adsorption or desorption processes.

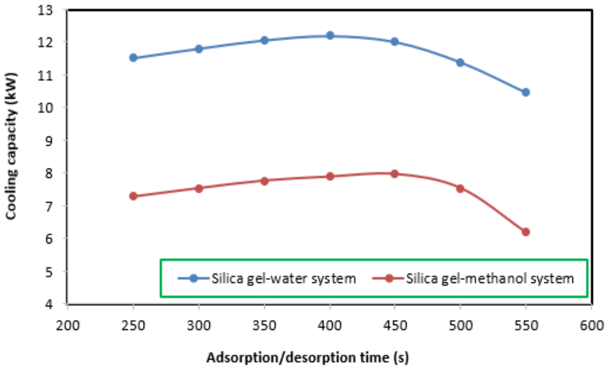

Figure 15. Impact of adsorption/desorption time on cooling capacity

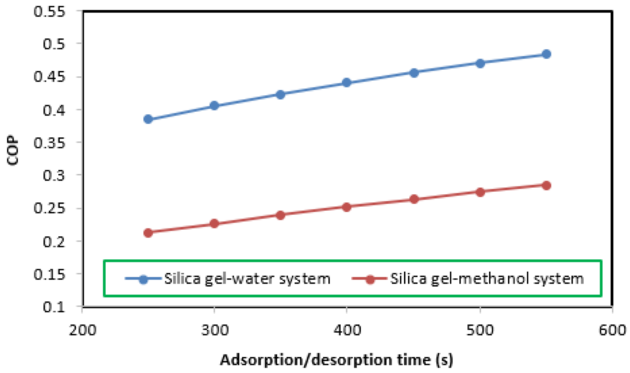

Figure 16. Impact of adsorption/desorption time on COP

5. CONCLUSION

The current study specifically indicating few outcomes and conclusions. Through the application of a lumped parameter model, an in-depth exploration was carried out to assess the feasibility of propelling adsorption refrigeration systems using silica gel-water and silica gel-methanol as working pairs. This investigation encompassed a comprehensive heat source spectrum, ranging from 50°C to 90°C. Furthermore, the research examined the multifaceted effects of varying operational parameters—encompassing heat transfer fluids' temperatures, flow rates, and cycle duration—on the overall performance of the chiller. Within this comprehensive study, a comparative analysis was conducted, unravelling the distinct impacts of operational conditions on adsorption refrigeration systems that utilize silica gel-water and silica gel-methanol. Furthermore, a juxtaposition between simulated outcomes and experimental findings under identical operating conditions was executed, yielding the subsequent primary deductions:

(i) With the cooling water with the degree of 30°C, the suggested refrigeration orderline with silica gel-water and silica gel-methanol pairs may effectively use low-grade heat sources amid from 60°C to the extent of 90°C as the noteworthy driving heat source. The chiller water may work with a temperature difference of as little as 30 degrees Celsius between the heat sink and the heat source.

(ii) Anticipatedly, the system of the silica gel-water consistently outperforms the silica gel-methanol counterpart in cooling capacity and COP across various conditions. This is attributed to silica gel's superior water adsorption capacity compared to methanol, coupled with water's significantly higher latent heat of vaporization. It can be considered most remarkable conclusion of the current study.

(iii) The simulation outcomes clearly uncover a substantial influence of operating temperatures, specifically with the levels of hot and cooling water, on the chiller's COP and capacity of cooling. Remarkably, in relation to the quantity of heat transfer fluids employed, the oscillations in operating temperatures wield a more profound impact on the system's overall implementation and performance.

(iv) The chiller's capacity of cooling and COP are influenced by the cycle time of adsorption/desorption while operation. The observations of the current study reveal that as cycle duration lengthens, the chiller's COP shows noticeable improvement. Notably, an optimal adsorption/desorption cycle time of 450 seconds emerges, coinciding with the peak cooling capability. The study also observes the limitation which arises when the cycle time is brief, and it hampering satisfactory adsorption or desorption processes. A decline in cooling capacity, measured in kJ/s, follows the extension of the cycle time during longer cycles. To attain optimal efficiency during the operation, adhering to the ideal cycle time is imperative for the chiller's operation.

Moreover, the study's observations unveil distinct insights, as elucidated above. The elevation of hot water inlet temperatures yields an upswing in the cooling capacity of both systems—silica gel-water and silica gel-methanol. Notably, the COP achieves its peak at a driving temperature of 85°C. The drop in cooling water temperatures improves the efficiency of adsorption refrigeration systems. Lowering the cooling water inlet temperature increases the chiller's cooling capacity and COP while concurrently lowering the temperature of the chilled water leaving the evaporator. The chiller's chilling capacity and COP are strengthened by raising the chilled water inlet temperature, but the chilled water's temperature decrease in the evaporator is also amplified. The chilling capacity is also strengthened by an increase in the hot water flow rate, albeit this is accompanied by a simultaneous decrease in the chiller's COP.

This analysis can be useful for the following real-world applications. These systems can be combined with solar panels, making them ideal for cooling in remote, off-grid areas without access to conventional electricity. In urban areas, solar-powered adsorption refrigeration can reduce electricity demand for air conditioning, contributing to energy-efficient buildings. Silica gel adsorption systems are suitable for cooling large spaces, such as commercial buildings or factories, especially where conventional air conditioning is energy-intensive. Additionally, these systems can operate using waste heat from industrial processes or engines, making them highly efficient for industries that produce large amounts of excess heat.

As highlighted in this analysis, the COP is quite low. Therefore, research into new or modified adsorbent materials with higher adsorption capacity and thermal conductivity could greatly enhance system performance. Hybrid adsorbents or composite materials may provide better efficiency than pure silica gel. Future research should focus on optimizing system components, such as heat exchangers and the design of the adsorption bed, to improve efficiency and reduce the overall system size.

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NOMENCLATURE

ads	processes of adsorption
cp	specific heat of fluid
COP	coefficient of performance
des	processes of desorption
D_S	the surface diffusivity (m^2/s)
D_{SO}	pre-exponential constant
E_a	activation energy for surface diffusion (J/mol)
ks	total mass transfer coefficient
m_{sg}	mass of silica gel contained within each bed
m_w	mass of water in the evaporator
$m_{f\,chill}$	mass of water in chiller
$m_{f\,hot}$	mass of water circulates in heat exchanger for desorption
P	adsorbate pressure (N/m^2)
t	cycle time
r	radius of silicgel bed (m)
R	gas characteristic constants
Rp	mean radius of adsorbent particles (m)
T	Temperature of adsorbent (°C)
Tw	Temperature of water (Refrigerant)
Tsg	Temperature of refrigerant at saturated vapour pressure
Tst	Temperature of refrigerant at saturated liquid pressure