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Performance Dynamics of Activated Carbon-Methanol Pair in Adsorption Refrigeration Systems

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ABSTRACT

Adsorption refrigeration systems have shown potential for addressing the adverse effects of traditional compressor-based refrigeration systems. Adsorption refrigeration systems that utilise activated carbon and methanol demonstrate good performance, especially at temperatures below 0 °C. This combination significantly improves the cooling performance of the system, making it a dependable option for freezing applications. Despite having the potential to meet cooling demand and be eco-friendly, the adsorption refrigeration system has several drawbacks that hinder its commercialisation. This paper discusses the properties of the activated carbon methanol pair in the adsorption refrigeration system. The focus is on the desorption temperature, thermal stress, repeatability and reliability of the experimental process. The experimental method was used to evaluate the performance of the activated carbon-methanol system in the solar-powered adsorption refrigeration prototype. The experiments involved monitoring the temperatures in the adsorber bed, condenser and evaporator. Experiment results show that activated carbon methanol does not depict good properties when the adsorber bed temperature is more than 120 °C. Also, findings show that the pair does not provide reliable results after thermal stress and lacks repeatability. Desorption of the activated carbon methanol pair was observed to start at a temperature of 45 °C. This shows that adsorption refrigeration systems could solve the cooling demand when subjected to the required operating conditions. Also, low-grade heat can be utilised to produce cooling for domestic and industrial processes.

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INTRODUCTION

The absorption refrigeration system is among the two sorption technologies that use low-grade heat energy to produce cooling. Adsorption refrigeration system (ARS) shows a promising potential to solve the cooling demand. Recently, the cooling demand has increased due to increased industrial development, urbanisation, increase in income, improved access to electricity and the need for food preservation (Khosla et al., 2021; Peters & Sayin, 2022). The working principle of the adsorption refrigeration system depends on components namely adsorber bed, condenser and evaporator. The adsorption refrigeration system operates through four main processes which are isosteric heating ($Q_{1\text{-}2}$), isobaric heating and desorption ($Q_{2\text{-}3}$), isosteric cooling and condensation ($Q_{3\text{-}4}$) and isobaric adsorption or evaporation ($Q_{4\text{-}1}$). Such processes are represented by the actual and ideal thermodynamic processes as shown in Figure 1. The adsorber bed reaches maximum saturation of adsorbates during isosteric heating ($Q_{1\text{-}2}$), while the minimum saturation occurs at the end of isobaric desorption ($Q_{2\text{-}3}$). T_{evap}, T_{cond}, P_{evap} and P_{cond} represent the evaporator temperature, condenser temperature, evaporator pressure and condenser pressure, respectively.

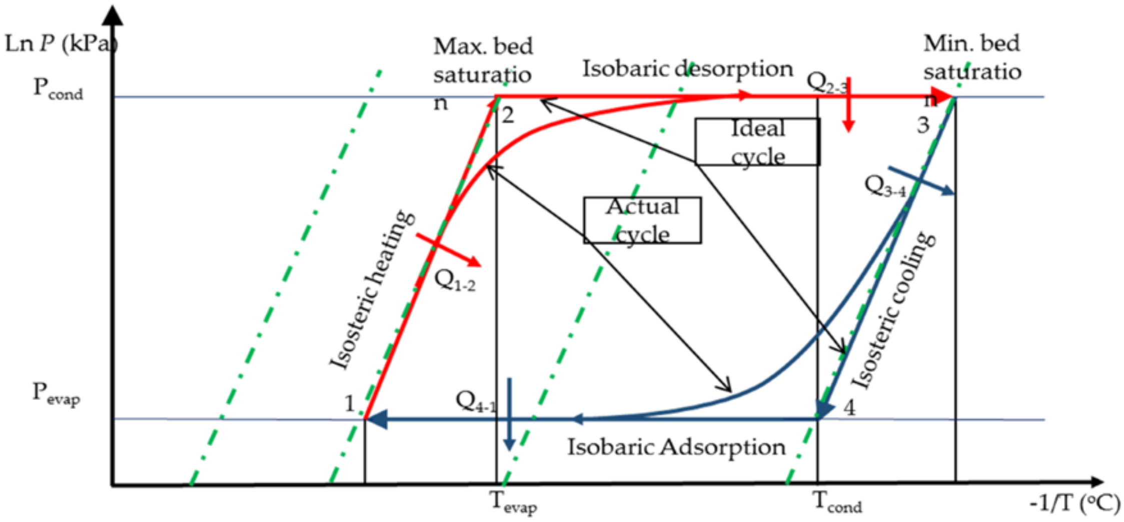

Figure 1: Ideal and actual thermodynamic processes of adsorption refrigeration system Source: Calautit (2020)

Activated carbon methanol pair is used in the developed adsorption refrigeration system. The selection of methanol was based on its ability to utilise low-temperature heat sources. The ability of methanol to provide cooling at temperatures below 0 °C positions it as a suitable option for freezing and other refrigeration applications (Wang et al., 2010). The thermophysical property of methanol including its high latent heat of vaporisation makes it a best choice as an adsorbate in ARS (Aalderik et al., 2021; Goyal et al., 2016; Sha and Baiju, 2021). Activated carbon has a high surface area and adsorption capacity, making it a suitable adsorbent for ARS (Zeng et al., 2017).

The potential of adsorption refrigeration systems to utilise low-grade heat from waste heat of industrial processes, engine exhausts, solar energy and others is limited by the low specific cooling power (SCP) and Coefficient of performance (COP). These properties attract researchers in the adsorption refrigeration system. Adsorption refrigeration can achieve efficient cooling with a relatively simple design, easy to maintain and environmentally friendly (Wang & Oliveira, 2006). ARS attracts the use of various adsorbates such as water, glycol, methanol, ethanol, ammonia and others. This has led to a focus on the development of various adsorbents like activated carbon, calcium chloride, silica gel, zeolite and other chemical and other composite adsorbents (Baiju et al., 2022; Grekova et al., 2019; Jin et al., 2013; Sha & Baiju, 2021; Wolak, 2017). Selecting the right adsorbent-adsorbate pair is critical during the initial design phase of an adsorption refrigeration system. The choice of a suitable heat source is also crucial as it significantly influences the system's performance.

This study examines the temperature challenges of using activated carbon and methanol in adsorption refrigeration systems. Exploring the dynamics and changes of ARS is crucial for improving the operational performance of adsorption refrigeration systems. The study used granular activated carbon methanol pair. The prototype was developed based on theoretical calculations and experimental data from the literature. The findings from this research contribute to ongoing efforts to enhance the effectiveness, efficiency, and commercial viability of adsorption refrigeration systems.

METHODS AND MATERIALS

The ARS was developed in the laboratory to test the performance and temperature behaviour of the ARS. The adsorber bed uses simulated solar thermal energy as a driving power of the system. The flat plate adsorber bed made of copper tubes filled with activated carbon and methanol was used in the experimental process and is shown in Figure 2. The system consists of three units: adsorber bed, condenser and evaporator. High response to temperature change and the ability to measure temperature in millisecond intervals led to the selection of type k thermocouple sensors. Type K thermocouple sensors were installed in all units of ARS to monitor the system's temperature behaviour. The developed ARS was tested for leakage by pressurising the system up to 5 bar for 24 hours and vacuuming the system and was carried out and the system was left for 24 hours to ensure that there was no chance for leakages. The temperature was measured at an interval of one second and recorded on the computer using a Pico-08 data logger. Before the heating cycles started, two litres of methanol were filled into the adsorption refrigeration system. The heating to initiate the cooling process was carried out from an average ambient temperature of 21 ℃ which was recorded in the conditioned room. 90 ℃ was selected as desorption temperature to depict the ability of activated carbon methanol to desorb at lower temperatures (Sha & Baiju, 2021). Later, the adsorber bed was heated to 120 ℃ to ensure all methanol was desorbed. The adsorbate was cooled in the condenser and then to the evaporator for cooling purposes. After cooling in the evaporator, the adsorbates flow to the adsorber bed for adsorption to take place. The performance and cooling behaviour of the system was monitored and analysed. MATLAB 2024a and Microsoft Excel 2016 were used to analyse the recorded data to determine the cooling behaviour of ARS. To supplement the findings, a comparison with relevant literature detailing the use of activated carbon-methanol pairs was done.

Figure 2: Adsorber bed for ARS integrated with glass louvers

RESULTS AND DISCUSSIONS

The adsorption process experienced while filling methanol was observed to be an exothermic process after the liberation of heat to the adsorber bed. Similar results about the exothermic nature of activated carbon methanol ARS were reported by Wu et al. (2015) and Sidhareddy et al. (2023) also, the exothermic nature of activated carbon on Volatile Organic compounds was reported by (Cloirec et al., 2012). Filling methanol in the system caused the immediate rise in temperature from the ambient temperature of 21 ℃ to 43.5 ℃. This necessitated to allow the adsorber bed to cool back to the ambient temperature before starting the experimental process. The temperature profile of the liberated energy in the adsorber bed is shown in Figure 3. The AD 1 to 4 represent the adsorber bed sensor, while the inner temperature is the air temperature in the adsorber bed, and the other values represent the condenser and evaporator temperatures. The thermocouple sensors for the adsorber bed, as shown in Figure 3, indicate that sensor 3 (AD 3) measured the highest temperature rise due to the non-uniform distribution of methanol within the adsorber bed tubes. Conversely, the evaporator thermocouple sensors demonstrated an immediate drop in temperature, which resulted from the methanol flow into the evaporator after the system was filled with methanol. The average ambient temperature remained constant, as the adsorber bed or the heating system did not affect it.

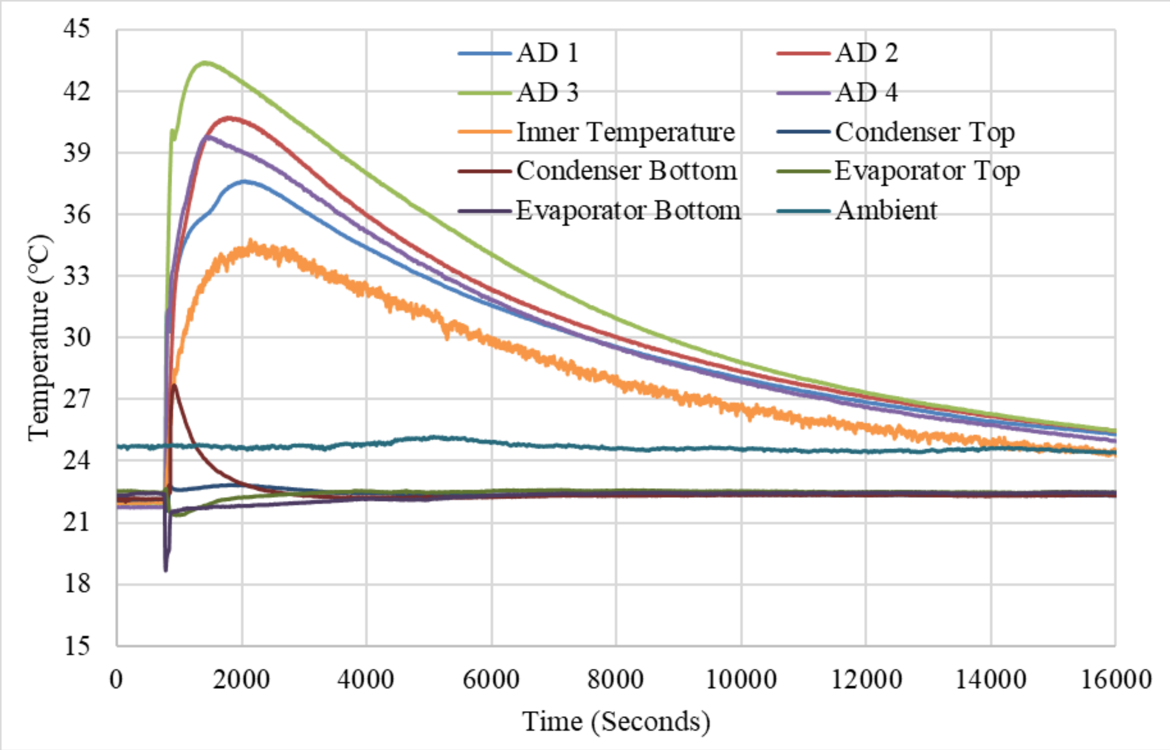

Figure 3: Temperature profiles in the adsorber bed of ARS

The desorption and adsorption characteristics of the activated carbon-methanol pair affected the temperature distribution in the adsorber bed. The desorption process began when the temperature of the adsorber bed rose from the ambient temperature of 21 °C to 45 °C. Additionally, an increase in the condenser temperature was observed immediately after the adsorbate began to flow from the adsorber bed to the condenser. The adsorber bed was heated up to 120 °C as a maximum desorption temperature of the activated carbon methanol pair. These experimental results indicate that activated carbon methanol pair can use low-grade heat from different sources.

During the experiment, it was observed that the activated carbon methanol pair cannot tolerate thermal stresses and fatigue as its chemical and physical properties get degraded. The methanol was observed to degrade after being heated at a temperature greater than 120 ℃. The system could not repeat the cooling cycle at the evaporator temperature below 9 ℃. The change in properties of methanol was reported by Wang et al. (2010) that when activated carbon methanol is heated at a temperature greater than 120 °C, methanol tends to decompose. Also, Wang described that methanol is accompanied by the dissociation problem above 120 °C in the presence of copper material. This brings experimental limitations that the activated carbon methanol system should not be operated at a temperature greater than 120 ℃ as a maximum temperature that can change its chemical and physical properties. The increase in temperature beyond 150 ℃ in the adsorber bed favours the formation of non-condensable gas, commonly dimethyl ether which hinders the adsorption and desorption process. Figure 4 shows the temperature profile in the system after the adsorber is subjected to a temperature above 120 ℃.

The temperature profile in the adsorber bed was subjected to two heating cycles followed by cooling to observe the evaporator behaviour. The condenser temperatures exhibited a similar trend in the two heating and cooling cycles. It was noted that the evaporator temperature decreased in cooling capacity after the first cycle, indicating that methanol could not reach a lower temperature than the first cycle. The air temperature in the adsorber bed, as indicated by "Inner Temperature" sensor, showed a rapid increase during heating and a faster cooling rate than the adsorber bed sensors during the cooling process. Overall, the temperature profile indicates that the system failed to maintain the cooling temperature. Additionally, the system's repeatability in providing reliable results was poor.

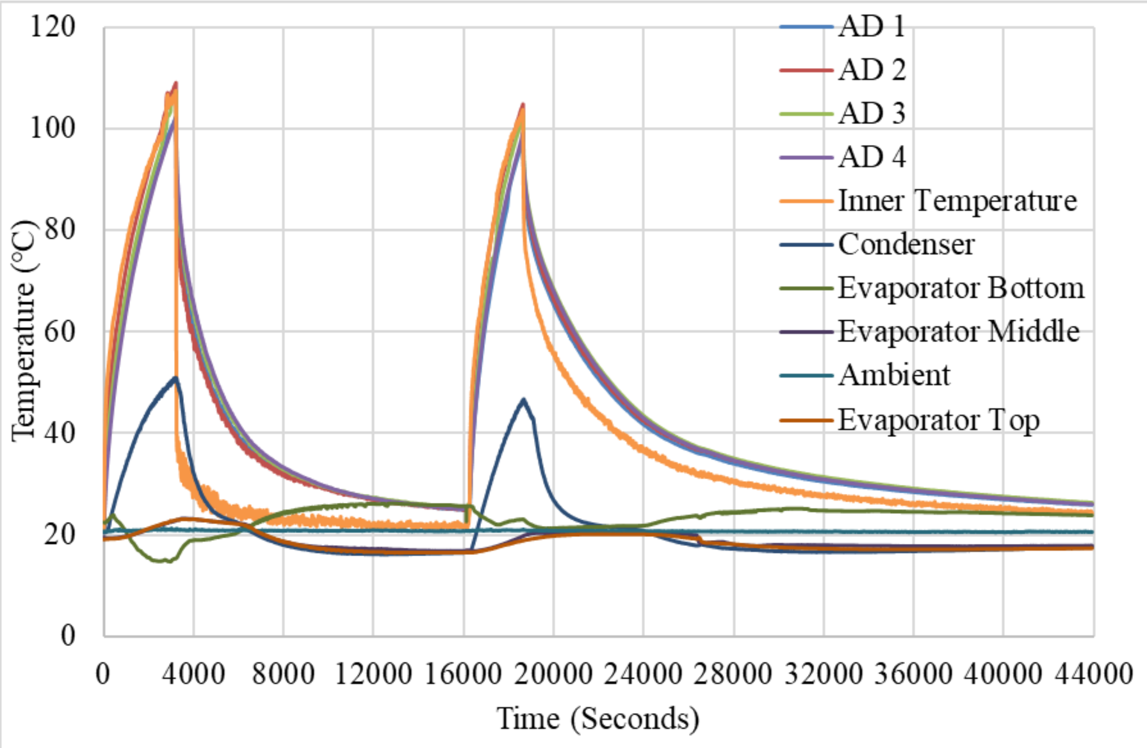

Figure 4: Temperature profiles of the system after being heated beyond 120 °C

The ability of the activated carbon methanol pair to desorb at lower temperatures and the ability to utilise low-grade heat sources make it the best pair for solid adsorption refrigeration, as asserted by various researchers. However, the methanol can decompose by different mechanisms such as dehydration or dehydrogenation to form formaldehyde (HCHO) or dimethyl ether (CH_3OCH_3) with the help of a catalyst or when the adsorber bed is subjected to high temperature (Hu, 1998; Omojola et al., 2018; Svelle et al., 2005). The change of properties of methanol to dimethyl ether occurs when the adsorber bed temperature exceeds 120 °C (Mohamad and Bennacer 2011). Yet, literatures claim that the methanol decomposition is slow in the adsorption refrigeration system. The change in properties and chemical reactions of methanol is shown in the chemical reactions (1) to (4).

$$2CH_3OH \rightarrow CH_3OCH_3(\text{dimethyl-ether}) + H_2O \quad (1)$$

$$3CH_3OH \rightarrow CH_3OCH_2OCH_3(\text{methoxymethyl methyl ether}) + H_2O + H_2 \quad (2)$$

And

$$2CH_3OH \rightarrow CH_3CH_2OH\ (\text{ethanol}) + H_2O \quad (3)$$

Formation of formaldehyde

$$CH_3OH \rightarrow HCHO\ (\text{formaldehehyde}) + H_2 \quad (4)$$

The preparation of the adsorption refrigeration prototype has a significant impact on the performance of the system. The ARS needs to be tested under both vacuum and high-pressure conditions to identify potential leakages. The activated carbon methanol system must be maintained in a vacuum condition before filling the adsorbate. It is essential for the system to operate in a closed cycle and prevent leakage or infiltration of ambient air into the system. Leakages decrease the adsorption capacity, resulting in poor cooling in the evaporator. Additionally, leaking can cause the system to lose methanol to the environment, decreasing the mass of adsorbate available for other cooling cycles. Ashes or small particles from activated carbon lead to methanol contamination. The contaminated methanol deposits particles and other debris in the condenser and evaporator.

CONCLUSIONS

The experimental results indicate that the activated carbon methanol refrigeration system exhibits varying behaviours influenced by temperature. The introduction of methanol into the Adsorption Refrigeration System (ARS) demonstrates an exothermic reaction by releasing heat to the surrounding. During the experiments, the air temperature in the adsorber bed reached 43.5 °C. The desorption was observed to start when the condenser temperature increased and the adsorber bed temperature rose to 45 °C. The low desorption temperature indicates that the activated carbon methanol system can effectively utilise low-temperature sources for cooling. The operation of the adsorption refrigeration system was limited to a maximum desorption temperature of 120°C. When the adsorber bed temperature exceeded 120 °C, the properties of methanol changed, resulting in a loss of cooling capability. The decomposition of methanol at temperatures surpassing the maximum desorption threshold contributed to a decline in cooling efficiency. It is crucial to monitor the internal temperature of the adsorber bed, as inadequate management can compromise the chemical properties of methanol. Specifically, methanol can transform into dimethyl ether, which negatively impacts the system's cooling performance in the evaporator. The ARS demonstrated the potential to address cooling demands by using low-grade heat sources due to its desorption temperature characteristics. However, implementing the activated carbon and methanol combination in adsorption refrigeration systems poses several challenges, ranging from the prototype development phase to the operational stage.

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