15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

Experimental Investigation of Cycle Time Effects on the Performance of a Three-Bed Adsorption Chiller

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Abstract

Adsorption chillers are environmentally friendly refrigeration systems that utilize waste heat from industrial processes or residential sources as a thermal energy input. These systems have gained attention as a potential alternative to conventional vapor compression chillers in response to global environmental challenges. To overcome the relatively low cooling performance of adsorption chillers, various studies have focused on employing multi-bed configurations. In this study, we experimentally investigated the effect of cycle time on the performance of a three-bed adsorption chiller. The experimental setup consisted of three adsorption beds, each incorporating a MOF-based adsorbent. Cycle time was varied from 300 to 420 seconds in 30-second intervals, resulting in a total of five experimental conditions. The results showed that increasing the cycle time from 300 to 330 seconds led to a notable improvement, with the coefficient of performance (COP) increasing by approximately 16.2% and the cooling capacity by 6.3%. However, when the cycle time exceeded 330 seconds, the average variations in COP and cooling capacity were limited to 4.5% and 0.2%, respectively.

Keywords: Adsorption chiller;Cycle time; Multi-bed; Performance evaluation;

1. Introduction

An adsorption chiller is a thermal-driven cooling system that utilizes microporous materials as adsorbents. Because it can operate using low-grade waste heat below 90 °C as the driving thermal source, it is considered a promising alternative to conventional electrically driven vapor-compression refrigeration systems. However, its practical application is still limited due to relatively low efficiency and restricted cooling capacity [1].

To overcome these limitations, various studies have been conducted. Rogala et al. [2] experimentally and numerically investigated a plate-tube type adsorption chiller employing a silica gel–water pair. They reported that, with optimized fin spacing and fin height, the system achieved a maximum COP of 0.6 and SCP of 750 W/kg, confirming that the plate-tube configuration exhibited superior heat transfer performance compared to conventional fin-tube designs. Since the performance of an adsorption chiller depends strongly on the type of adsorbent, research has also focused on applying alternative materials beyond conventional silica gel. Tso et al. [3] experimentally studied an adsorption refrigeration system using a composite adsorbent of zeolite 13X/$CaCl_2$ with water, and analyzed the effects of incorporating heat and mass recovery processes. Their results showed that the COP and SCP increased by approximately 125% and 103%, respectively, compared to a basic cycle without recovery, demonstrating the performance enhancement potential of zeolite-based systems.

More recently, studies have been extended to adsorption chillers employing multiple adsorption beds. Chorowski and Pyrka et al. [4] experimentally investigated a 3-bed adsorption chiller driven by low-temperature waste heat, focusing on the effects of cycle time and bed-switching sequences. The system exhibited stable cyclic operation, achieving a maximum COP of 0.52, and demonstrated effective cooling performance even under low-temperature heat source conditions through appropriate bed-switching control.

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15th IEA Heat Pump Conference 2026 - ACY5.3 - https://doi.org/10.23697/t3yq-a529

To further address the limitations of adsorption chillers, it is essential to conduct additional experimental studies that clarify the performance characteristics of multi-bed adsorption systems.

Accordingly, this study experimentally investigates the effects of cycle time variation on the performance and efficiency of a 3-bed adsorption chiller.

2. Experimental methodology

The 3-bed adsorption chiller consists of an evaporator, a condenser, and three adsorption beds. Fig. 1 shows a schematic diagram and photograph of the 3-bed adsorption chiller. When the refrigerant water evaporates on the outer surface of the tubes in the evaporator, the generated vapor is adsorbed by two adsorption beds connected to the evaporator through valves. During this adsorption process, adsorption heat is generated on the fin surfaces of the heat exchangers inside each adsorption bed, where the adsorbents are fixed. To remove this adsorption heat, cooling water is supplied through the inner tubes of the heat exchangers.

Meanwhile, in the bed where desorption occurs, hot water is supplied through the inner tubes of the heat exchanger as a heat source to promote water vapor desorption. The desorbed vapor moves to the condenser, where it is condensed, and then returns to the evaporator through a connecting tube, forming a closed-cycle operation.

As the adsorption beds gradually reach a saturated state and the desorbing bed becomes dry, the roles of the beds must be periodically switched to maintain continuous cycle operation. Therefore, in this study, an experimental apparatus was designed to periodically switch the adsorption and desorption modes of the beds by controlling the valves with an automatic valve control system according to a preset time schedule.

To investigate the effect of cycle time on the chiller's performance during these mode transitions, the cycle time for adsorption and desorption was varied from 300 s to 420 s at 30 s intervals, resulting in five experimental conditions.

CAU-10H, a metal–organic framework (MOF)-based material, was selected as the adsorbent. Five constant-temperature water baths were used to supply chilled water, cooling water, and hot water to the test section. The flow rates of the supplied fluids were measured using volumetric flowmeters, and the inlet and outlet temperatures were measured using RTD sensors.

The experimental results were analyzed based on the temperature and flow rate data collected from the data acquisition unit (DAQ), and performance indices were calculated using Eqs. (1-2). The cooling capacity in Eq. (1) represents the cooling performance, while the COP in Eq. (2) indicates the efficiency of the adsorption chiller. Additionally, Eq. (3) defines the heat input from the heat source side used for the COP calculation.

$$Q_c = \frac{\int_0^{cyt} \dot{m}_{chw} c_{p,w} (T_{chw,in} - T_{chw,out}) dt}{cyt} \quad (1)$$

$$COP = \frac{Q_c}{Q_h} \quad (2)$$

$$Q_h = \frac{\int_0^{cyt} \dot{m}_{hw} c_{p,w} (T_{hw,in} - T_{hw,out}) dt}{cyt} \quad (3)$$

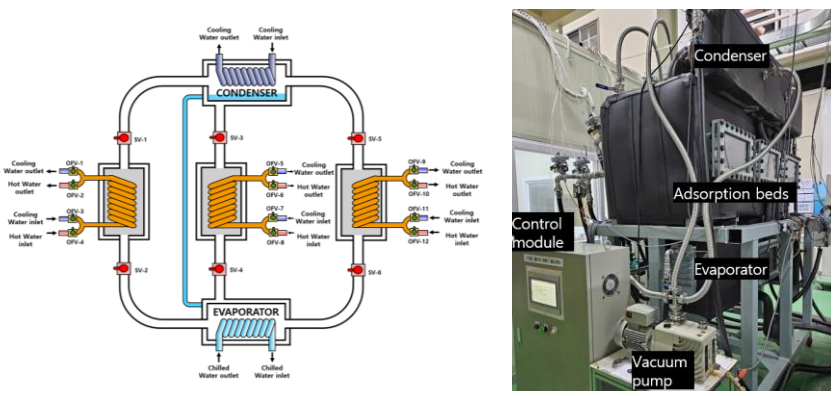

Figure 1. Schematic diagram and photograph of the 3-bed adsorption chiller.

3. Result and discussion

Fig. 2 shows the variation in COP and cooling capacity of the 3-bed adsorption chiller with respect to cycle time. As for the COP, it increases sharply from 0.199 to 0.231 (approximately 16.2%) as the cycle time extends from 300 s to 330 s. Beyond 330 s, the rate of increase becomes moderate, with an average rise of about 4.5%, reaching a maximum of 0.264 at a cycle time of 420 s.

The cooling capacity also improves from 5.30 kW to 5.64 kW (about 6.3%) as the cycle time increases from 300 s to 330 s. However, when the cycle time increases from 330 s to 360 s, the cooling capacity slightly decreases by about 0.4%, and further increases in cycle time leads to less than 0.1% variation.

This trend indicates that, due to the adsorption capacity limit of the adsorption beds, extending the cycle time beyond a certain point does not result in further performance improvement of the chiller. Since the COP also increases sharply between 300 s and 330 s and changes gradually thereafter, the optimal operating cycle time for the 3-bed adsorption chiller investigated in this study is estimated to be around 330 s.

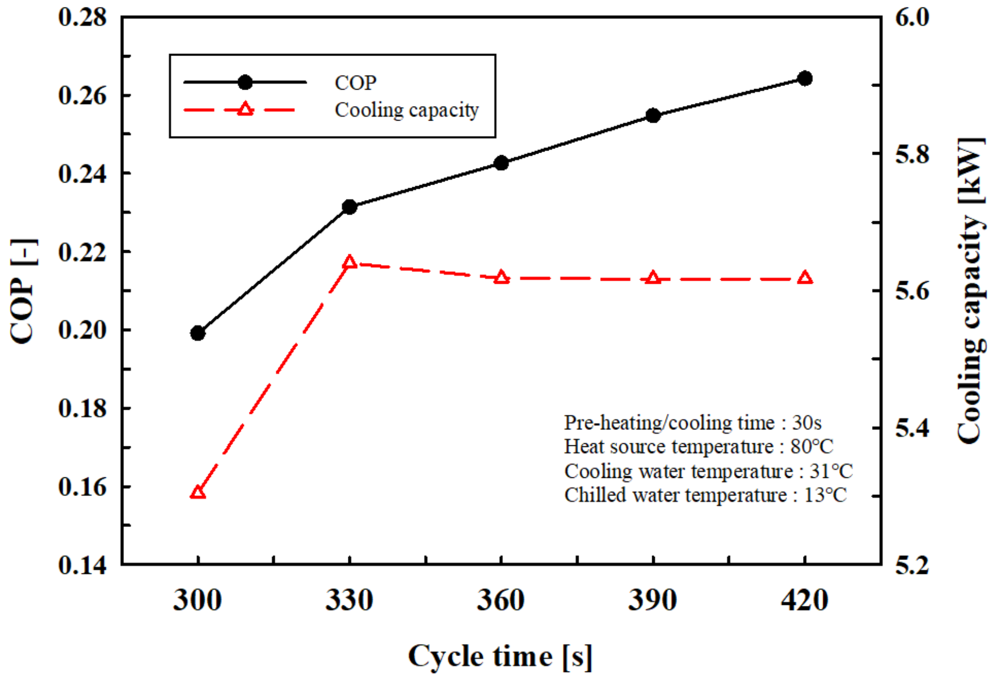

Figure 2. Experimental results of the 3-bed adsorption chiller according to cycle time: COP and cooling capacity..

4. Conclusion

In this study, the influence of cycle time on the COP and cooling capacity of a 3-bed adsorption chiller was experimentally investigated.

The COP increased significantly by approximately 16.2% as the cycle time extended from 300 s to 330 s, but exhibited only a gradual improvement thereafter, reaching a maximum value of 0.264 at 420 s. Similarly, the cooling capacity increased by 6.3% up to 330 s and showed negligible variations (<0.1%) beyond this point.

These results suggest that, due to the limited adsorption capacity of the system, the optimal operating cycle time for the 3-bed adsorption chiller is approximately 330 s.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea (No. RS-2025-02315209).

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