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Development of an Adsorption Heat Pump System Driven by Low-Temperature Waste Heat Using MOF Adsorbents

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Abstract

This study aimed to investigate thermal performance of an adsorption heat pump system regenerated at the low temperature of 55 °C using MOF (Metal-Organic Framework) adsorbents. MOFs can exhibit a higher Specific Cooling Power (SCP) compared to conventional adsorbents such as silica gel, making them a promising option for reducing the volume of adsorption heat pump systems. In this study, an aluminum-based MOF adsorbent was synthesized, and its adsorption–desorption isotherms were measured. The SCP was maximized using a technique of coating adsorbents on the reactor surface, and a falling film evaporator was employed to improve the heat transfer coefficient through thin-film evaporation. A cooling cycle was confirmed to form under desorption at 55 °C and cooling water at 30 °C, producing cooling at 20 °C. It is expected that adsorption heat pump systems operating with such low-temperature desorption heat sources can enable the utilization of low-grade waste heat—such as that from data centers—for cooling purposes.

Keywords: Adsorption heat pump; Metal-organic framework; Specific cooling power, Low-temperature waste heat

1. Introduction

With the rise of AI, the amount of energy consumed by data centers is increasing exponentially. According to projections by the International Energy Agency (IEA), global data center energy consumption is expected to approach 1,000 TWh by 2030 [1]. This massive amount of energy is used to operate IT equipment and maintain appropriate temperatures in server rooms, but most of it is ultimately discarded as heat after being consumed by the chips. In traditional air-cooled data centers, the exhaust heat temperature generally does not exceed 40 °C, resulting in low exergy and making it difficult to reuse. However, as the heat flux of major chips such as GPUs increases, the adoption of liquid cooling is expanding. Liquid cooling enables much higher cooling performance, allowing the coolant temperature to be maintained at higher levels, and consequently increasing the exhaust heat temperature to around 50 °C. As a result, technologies for reusing the enormous amount of waste heat generated in data centers are becoming increasingly important [2,3].

Adsorption heat pumps are gaining attention as a method for utilizing data center waste heat for cooling, because—like absorption heat pumps—they are driven by thermal energy, yet can operate with comparatively lower heat-source temperatures. Pan et al. [4] developed an adsorption heat pump using silica gel as the adsorbent and considering solar energy as the heat source; their system operated with a 70 °C heat source and achieved a COP (Coefficient of Performance) of 0.485 and an SCP (Specific Cooling Power) of 140.3 W/kg. Cui et al. [5] also developed an adsorption heat pump using silica gel, demonstrating that the system could produce chilled water at 23 °C under outdoor conditions of 30 °C using a low-grade heat source of 50 °C. Cherpakova et al. [6] showed analytically that using mesoporous silica gels, it is possible to achieve high SCP

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values in the range of 0.7–3.1 kW/kg under outdoor conditions of 30 °C with heat-source temperatures of 50–60 °C.

While previous studies have demonstrated that cooling is feasible using the low-temperature waste heat discharged from data centers, most of these studies are limited by their reliance on silica gel as the adsorbent. Metal–organic frameworks (MOFs) are porous materials whose properties can be tailored through various structural combinations, and Al-MOF in particular exhibits a large change in water uptake near the operating conditions of adsorption heat pumps. To leverage the excellent adsorption–desorption characteristics of MOFs, this study fabricated an adsorption heat-pump system using Al-MOF as the adsorbent and evaluated its thermal performance using a low-grade heat source of 55 °C.

2. Experimental Setup

2.1. Preparation of Al-MOF Adsorbers

Water was used as the working fluid in the adsorption heat pump system, and a metal organic framework (MOF) with a high water uptake per unit mass was employed as the adsorbent. To utilize low-temperature waste heat below 55 °C for cooling, an aluminum-based MOF (Al-MOF) with a low regeneration temperature was applied. The desorption temperature, cooling-water temperature, and chilled-water temperature of the adsorption heat pump system were set to 55 °C, 30 °C, and 20 °C, respectively. Accordingly, during the desorption process, the relative pressure (P/P_o) of the adsorber is calculated to be approximately 0.27 using Eq. (1). Similarly, during the adsorption process, the relative pressure (P/P_o) of the adsorber is obtained as 0.55 from Eq. (2).

$$P/P_o = \frac{P_{sat}(T_{condenser})}{P_{sat}(T_{adsorber})} = \frac{P_{sat}(T=30\ ℃)}{P_{sat}(T=55\ ℃)} = 0.27 \quad (1)$$

$$P/P_o = \frac{P_{sat}(T_{evaporator})}{P_{sat}(T_{adsorber})} = \frac{P_{sat}(T=20\ ℃)}{P_{sat}(T=30\ ℃)} = 0.55 \quad (2)$$

Figure 1 shows the adsorption–desorption isotherms of the applied Al-MOF. For the adsorbent without a binder, the water content changes significantly at a relative pressure (P/P_o) of approximately 0.4–0.5. In other words, under the desorption operating condition ($P/P_o \approx 0.27$), the water uptake remains below 0.1, indicating effective desorption. Under the adsorption operating condition ($P/P_o \approx 0.55$), the water uptake exceeds 0.3, indicating favorable adsorption behavior. Therefore, it is expected that the adsorption heat pump cycle will be well established under these operating conditions.

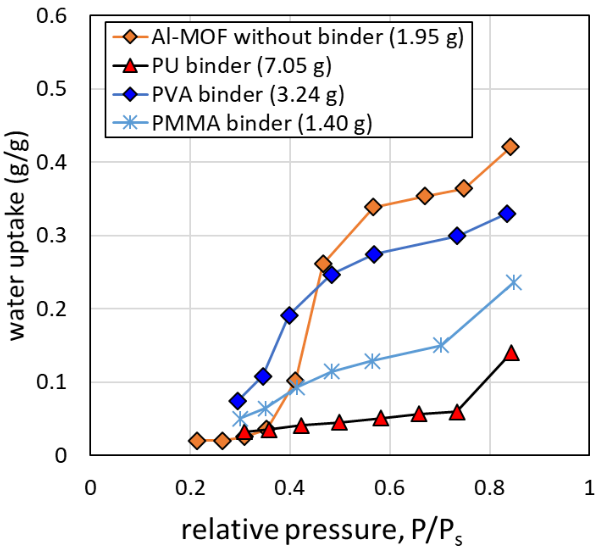


Fig. 1. Adsorption isotherm of Al-MOF coating layers using different binders.

The Al-MOF adsorbent is in powder form and therefore must be mixed with an appropriate binder to be coated onto the copper fin-tube heat exchanger. During the mixing process, changes in porosity and hydrophilicity can alter the adsorption–desorption characteristics. Figure 1 presents the adsorption–desorption isotherms of the Al-MOF when mixed with three binders: polyurethane (PU), polyvinyl alcohol (PVA), and polymethyl methacrylate (PMMA). For all three binders, the water uptake decreases compared to that of the pure adsorbent, while the sample mixed with PVA retains the best adsorption performance. Consequently, PVA was selected as the binder for coating the adsorbent in this study.

Figure 2 shows the results of coating the Al-MOF adsorbent onto the copper fin-tube heat exchanger using a PVA binder. When the dip-coating layer is made too thick, cracks form on the surface and the coating peels off; therefore, a thin coating and drying process is repeated. After 12 repeated coatings, the amount of adsorbent coating was measured, and the adsorbent mass was found to be 611 g.

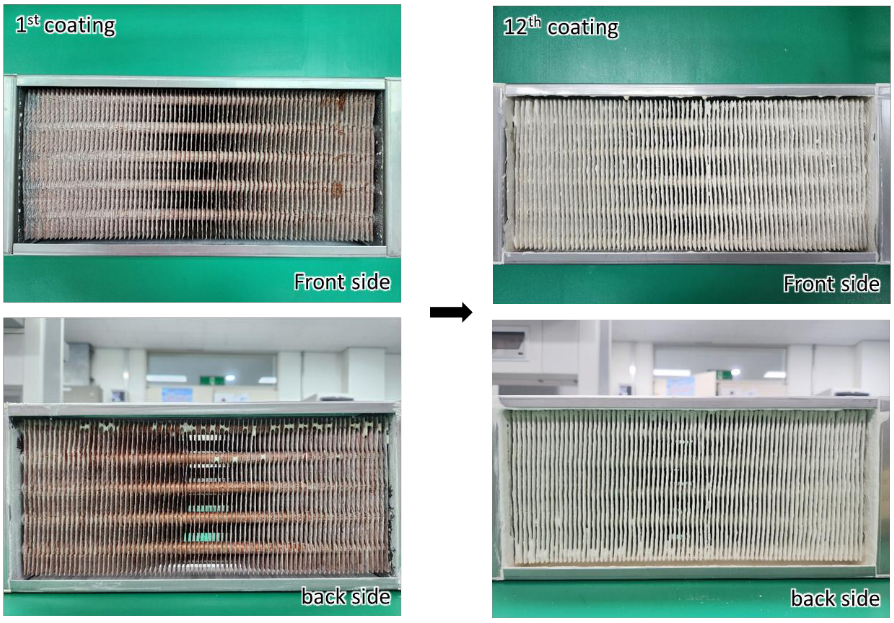


Fig. 2. Coating of Al-MOF adsorbents on the copper fin-tube heat exchanger.

2.2. Test section and experimental procedure

Figure 3 presents the schematic and actual photographs of the adsorption heat pump system, which consists of a single adsorber, an evaporator, and a condenser. All three components employ copper fin-tube heat exchangers with the same outer dimensions of 300 × 127 × 44 mm³, but the fin configurations were differentiated to optimize heat and mass transfer. The adsorber was equipped with square fins spaced 4 mm apart to allow uniform coating of the adsorbent. The evaporator used densely arranged square fins with a 2.1 mm spacing to maximize the heat-transfer area. For the condenser, fins were omitted because the presence of fins caused condensate to accumulate improperly, hindering heat transfer.

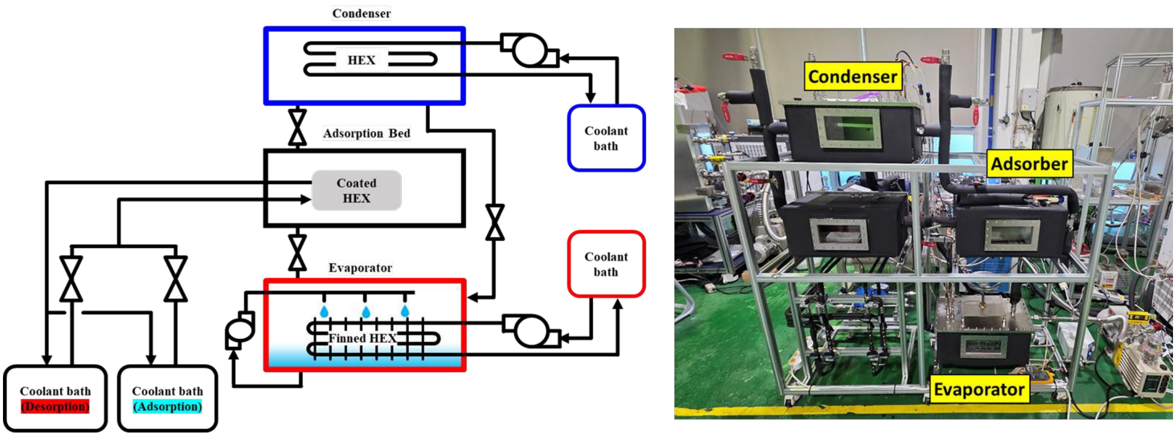


Fig. 3. A schematic drawing (Left) and an actual picture (Right) of the adsorption heat pump system with a single adsorber.

Table 1 presents the detailed operating conditions of the adsorption heat pump system. The adsorber undergoes repeated heating and cooling cycles; during the heating step, the inlet hot-water temperatures of 55 °C and 60 °C were examined, while during the cooling step the cooling-water temperature was fixed at 30 °C. The cooling-water temperature supplied to the condenser was also set to 30 °C, and the inlet temperature of the chilled water entering the evaporator was set to 20 °C. Distilled water was used for all hot, cooling, and chilled-water loops, and the flow rates were maintained at 10 L/min for all streams.

The adsorption–condensation and desorption–evaporation times were both set to 300 s (5 min), and the switching time required to transition the adsorber temperature between adsorption and desorption was set to 60 s (1 min). The temperatures and pressures inside the adsorber, evaporator, and condenser chambers were measured using RTD sensors and pressure gauges, while the inlet and outlet temperatures of the hot water, cooling water, and chilled water were measured using T-type thermocouples. The flow rates were measured using a turbine flow meter.

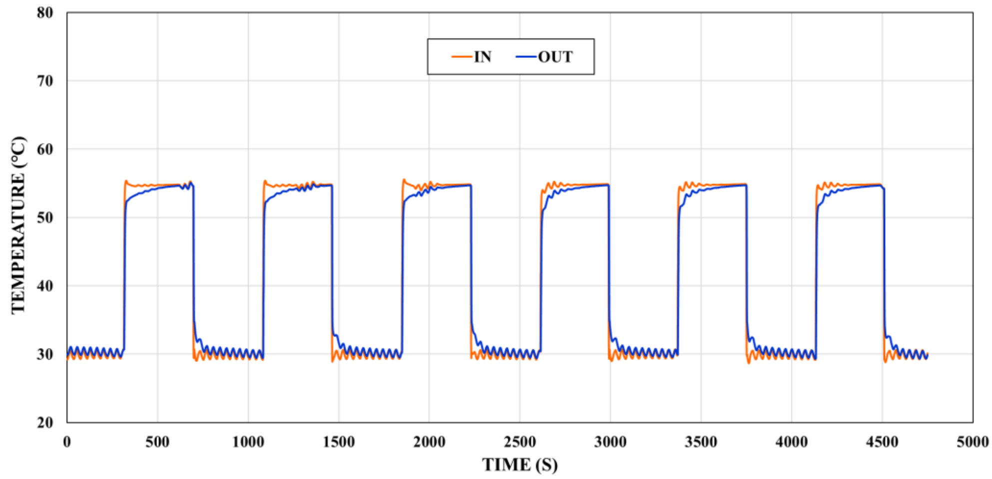
Table 1. Test condition of adsorption heat pump system

Components	Item	Value
Adsorber	Adsorbent mass (kg)	0.611
	Cooling water inlet T (°C)	30
	Cooling water flow rate (L/min)	10
	Heating water inlet T (°C)	55, 60
	Heating water flow rate (L/min)	10
Condenser	Cooling water inlet T (°C)	30
	Cooling water flow rate (L/min)	10
Evaporator	Chilled water inlet T (°C)	20
	Chiller water flow rate (L/min)	10
Cycle operation	Adsorber heating time (s)	60
	Adsorption/condensing time (s)	300
	Adsorber cooling time (s)	60
	Desorption/evaporation time (s)	300

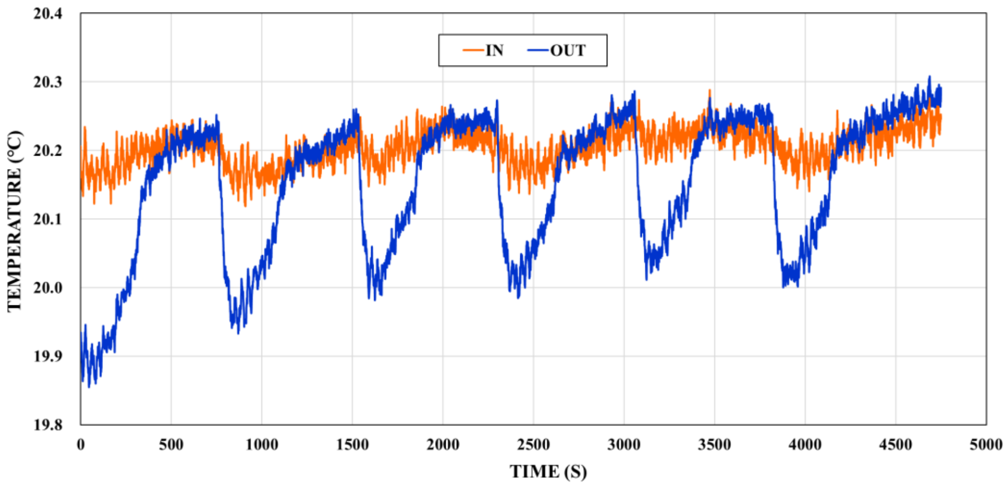
3. Results and Discussion

3.1. Heat transfer rates of the adsorption heat pump system

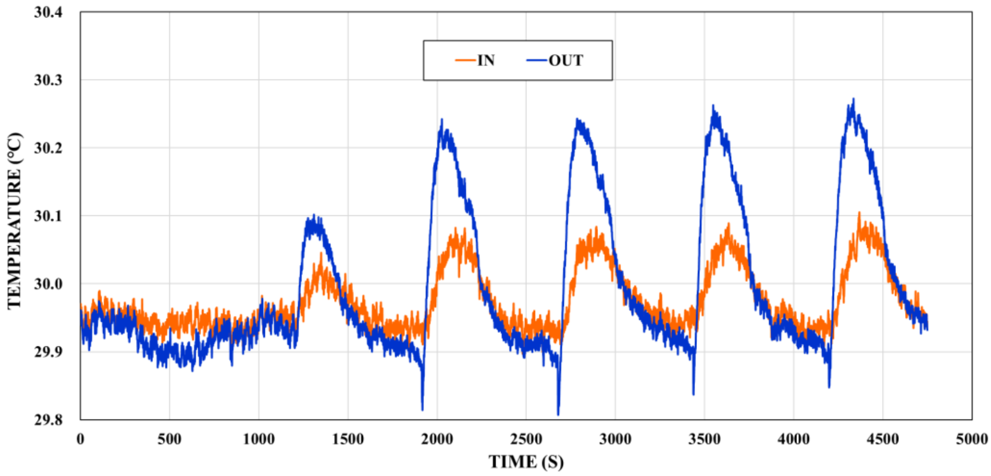
Figure 4 shows the variations in the inlet and outlet temperatures of the heat-transfer media (water) flowing through the adsorber, evaporator, and condenser under the desorption temperature of 55 °C. In the adsorber, 30 °C cooling water flows for 300 s, after which it is switched to 55 °C hot water (switching time: 60 s); hot water then flows for another 300 s, and this cycle is continuously repeated. During the adsorption process, when 30 °C cooling water flows, the adsorber is connected to the evaporator, and evaporation occurs in the evaporator, which causes the chilled-water outlet temperature to decrease. Conversely, during the desorption process, when hot water flows through the adsorber, the adsorber is connected to the condenser, and the water vapor desorbed from the adsorber moves to the condenser and condenses, resulting in an increase in the cooling-water outlet temperature.



(a) Inlet and Outlet temperatures of the adsorber



(b) Inlet and Outlet temperatures of the evaporator



(c) Inlet and Outlet temperatures of the condenser

Fig. 4. Inlet and Outlet temperatures flow through the adsorber, evaporator, and condenser.

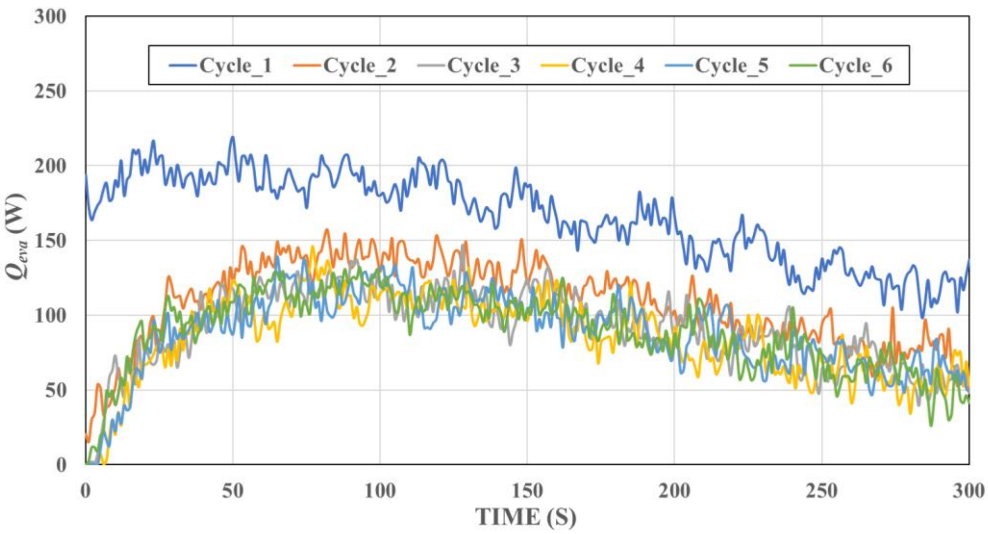
The heat-transfer amounts calculated for each of the six repeated cycles are presented in Fig. 5. The heat-transfer amount was determined from the inlet and outlet temperatures of the heat-transfer media flowing through each chamber, as calculated using the following equation.

$$Q_{eva} = \dot{m}_{cw} c_{p,cw} \left(T_{i,cw} - T_{o,cw}\right) \quad (1)$$

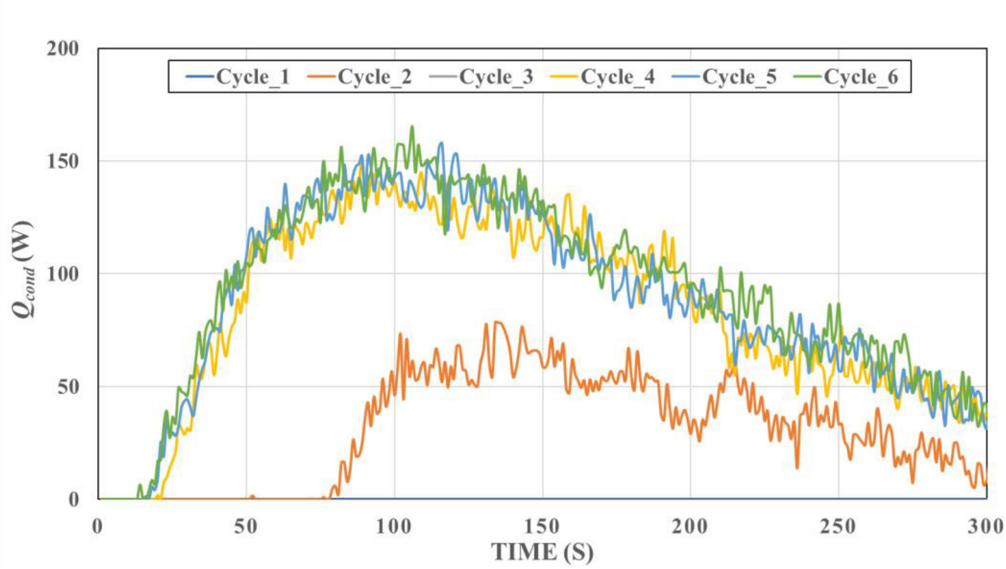
$$Q_{cond} = \dot{m}_{w} c_{p,w} \left(T_{i,w} - T_{o,w}\right) \quad (2)$$

$$Q_{des} = \dot{m}_{hw} c_{p,hw} \left(T_{i,hw} - T_{o,hw}\right) \quad (3)$$

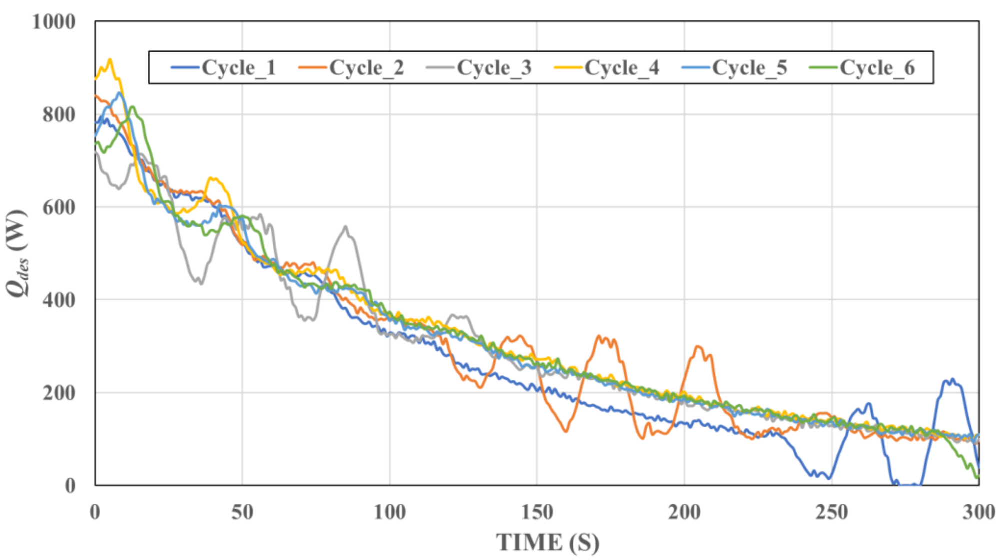
In Eqs. (1), (2), and (3), Q_{eva}, Q_{cond}, and Q_{des}represent the cooling capacity delivered to the chilled water in the evaporator, the condensation heat transferred to the cooling water in the condenser, and the desorption heat supplied to the adsorber during the desorption process, respectively. $\dot{m}$, c_p, T_i, and $T_o$denote the mass flow rate, specific heat at constant pressure, and the inlet and outlet temperatures of the heat-transfer media in each chamber. The subscripts *cw*, *w*, and *hw* refer to chilled water, cooling water, and hot water, respectively.



(a) Heat transfer rates of the evaporator



(b) Heat transfer rates of the condenser



(c) Heat transfer rates of the adsorber

Fig. 5. Heat transfer rates of the adsorber, evaporator, and condenser at each cycle.

In Fig. 5, the cooling capacity of the evaporator appears significantly higher only during the first cycle. This is because, at the initial stage, the adsorbent is in a dry state, allowing strong adsorption to occur, which in turn promotes a large amount of evaporation. However, starting from the second cycle, the cooling capacity decreases, and from the third to the sixth cycles it becomes nearly constant. The average cooling capacity over the stabilized third to sixth cycles is approximately 88.4 W.

In contrast, the condensation heat shows an opposite trend. In the first cycle, almost no desorption occurs, so the heat-transfer amount is close to zero. As desorption begins from the second cycle onward, the condensation heat increases. Similarly, averaging the condensation heat over the third to sixth cycles yields approximately 86.3 W, which is similar to the evaporative cooling capacity.

The adsorber shows relatively consistent desorption heat across all six cycles with no significant variation. The average desorption heat for cycles three through six is about 318 W. Table 2 summarizes the heat-transfer amounts obtained from the evaporator, condenser, and adsorber (during the desorption process) for each cycle.

Table 2. Heat transfer rates at each cycle for evaporator, condenser, and adsorber

Cycle #	Qeva (W)	Qcond (W)	Qdes (W)
1	166.0	0	287
2	108.0	31.0	313
3	91.0	78.5	309
4	84.9	85.1	327
5	88.3	88.7	317
6	89.3	93.0	319
average	**88.4**	**86.3**	**318**

3.2. SCP and COP

The SCP (Specific Cooling Power), which represents the cooling capacity per unit mass of adsorbent, can be calculated by dividing the cooling capacity of the evaporator by the mass of the adsorbent, as shown in Eq. (4). In addition, the system COP (Coefficient of Performance) can be calculated by dividing the cooling capacity generated in the evaporator by the desorption heat supplied during the desorption process, as expressed in Eq. (5).

$$SCP = \frac{Q_{eva}}{m_{ad}} \tag{4}$$

$$COP = \frac{Q_{eva}}{Q_{des}} \tag{5}$$

In Eq. (4), m_{ad}denotes the mass of the adsorbent. Using the experimental results in Table 2, the calculated SCP is 144.7 W/kg, and the COP is 0.278. This SCP value is higher than the value of 113.1 W/kg reported by Xu et al. [7], who used silica gel under a 60 °C hot-water condition, demonstrating that the MOF adsorbent provides superior cooling performance per unit mass compared with silica gel. However, when compared with the COP value of nearly 0.5 obtained by Xu et al. under the same 60 °C hot-water condition, it is clear that the COP in this study is much lower. Therefore, significant improvement is required in terms of COP. Reducing the heat capacity of the heat exchanger applied to the adsorber and optimizing the coating thickness of the adsorbent on the heat exchanger surface would be appropriate directions for enhancement.

4. Conclusions

To utilize low-temperature waste heat—such as the heat discharged from data centers—for cooling, an adsorption heat-pump system incorporating Al-MOF was developed and its thermal performance was investigated. To maximize the heat and mass transfer performance of the Al-MOF, the adsorbent was applied onto a copper fin-tube heat exchanger using a dip-coating method. Under outdoor conditions of 30 °C, the fabricated adsorption heat-pump system was able to produce chilled water at 20 °C using a low-grade heat source of 55 °C. The resulting SCP was 144.7 W/kg, which is higher than typical values obtained with silica gel. However, the COP was relatively low at 0.278, indicating that further improvements—such as reducing the thermal mass of the adsorber's heat exchanger and optimizing the coating thickness of the adsorbent—will be necessary in future work.

Acknowledgements

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