



## Special Feature: Advanced Thermal Management Technology for Developing the High-efficiency Vehicle

Research Report

### Development of a Compact Adsorption Heat Pump System for Automotive Air Conditioning System

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**■ABSTRACT■** Adsorption heat pump (AHP) system is one of the key technologies. We have been developing AHP system utilizing the exhaust heat from the engine coolant system, which can meet the requirements in the automotive application. However, AHP systems have not been used in automotive applications because of its low volumetric power density of the adsorber. In order to improve the volumetric power density of the adsorber, we suggest a compact adsorber which is characterized by honeycombed composite plates of an adsorbent with thermal conductive filler bonded to a plate-type heat exchanger. In the suggested adsorber, the adsorption and desorption rate and the packing density were 1.33 times and 1.36 times larger than a reported coating-type adsorber respectively. The volumetric power density of our adsorber is comparable to that of a mechanical compressor for on board air conditioning system. The developed compact adsorber can contribute to reducing the size and total cost of the AHP system. This technology is to be applicable to the AHP systems not only for automotive application, but also for large-scale air conditioning systems (e.g. factory air conditioning system).

**■KEYWORDS■** Adsorber, Adsorption Heat Pump, Heat and Mass Transfer, Adsorption, Adsorption Material

#### 1. Introduction

Because most of the low-temperature (less than 100°C) heat produced by current automotive systems is discharged as waste, engineers are focusing on adsorption heat pump (AHP) systems as one of the key technologies for utilizing this waste heat.<sup>(1,2)</sup> When fully developed, AHP systems are expected to reduce air conditioning system energy consumption to approximately 30% of their current levels. However, AHP systems have not been practically used to date, because the volumetric power density of current adsorbers is too low for automotive applications. Herein, we report on the development of a compact AHP system designed to utilize (80-100°C) exhaust heat from automotive engine coolant systems that can meet automotive application requirements.

In a previous report, the use specifications for onboard AHP systems were studied. That study determined that the volumetric power density of the adsorber and coefficient of performance (COP) would need to be higher than 850 W/L and 0.55, respectively.<sup>(3)</sup>

Considering the conditions for onboard use, water and silica-alumina-phosphate 34 (SAPO-34) have been selected as the refrigerant and adsorbent, respectively. If the targets for both the power density and COP are achieved, it is possible that the benefits of the new system will not only be improvements to automobile fuel economy, but also include a decrease in AHP system manufacturing costs.

The volumetric power density of the adsorber is proportional to its sorption rate, packing density, and latent heat. The sorption rate is primarily determined by three stages: (a) overall particle ad/desorption rate, (b) packed bed mass transfer, and (c) packed bed heat transfer (**Fig. 1**). When using small diameter (1-3 mm) SAPO-34 as the adsorbent, the overall particle ad/desorption rate has little effect on sorption. Hence, to develop a high power density adsorber system, it is crucial to minimize the heat and mass transfer resistance. Previous research has shown that these factors could be reduced by using a coating method applying a thin layer of adsorbent.<sup>(4,5)</sup> However, such thin layers lead to a lower adsorber packing densities.

Therefore, if this issue could be resolved, the resulting technology could be applicable to large-scale air conditioning systems (such as factory air conditioning systems) as well as automotive applications.

Volumetric cooling power (VCP) is determined by the following equation:

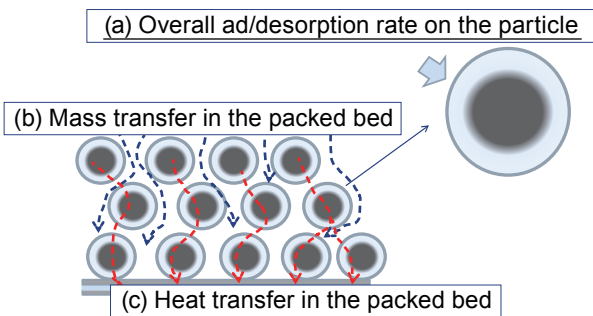
$$VCP = \frac{w \times \Delta H}{2 \times t \times V}, \tag{1}$$

where  $w$ ,  $t$ ,  $V$ , and  $\Delta H$  are the adsorption amount, adsorption time, adsorber volume, and the latent heat, respectively. The target zone for the cycle time and the adsorption amount based on Eq. (1) is shown in Fig. 2, along with the reported performance of an adsorber prepared by the coating method using SAPO-34. The figure shows that the goal of 850 W/L can be achieved

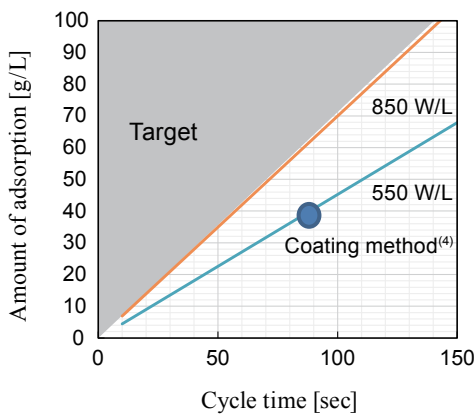
by an increase in the amount of adsorption and a decrease in the adsorption time.

In order to improve the volumetric power density of the adsorber, it is necessary to increase the product of adsorption rate and packing density. Increasing the coating layer thickness and decreasing its porosity can improve the packing density, but Dawoud reported that a coating layer thickness would also increase adsorption time due to both low water vapor diffusivity and the low thermal conductivity of the coating layer.<sup>(5)</sup> Our proposed compact adsorber is characterized by honeycombed composite plates fabricated from an adsorbent along with a heat conductive additive that is bonded to a plate-type heat exchanger, as shown in Fig. 3.

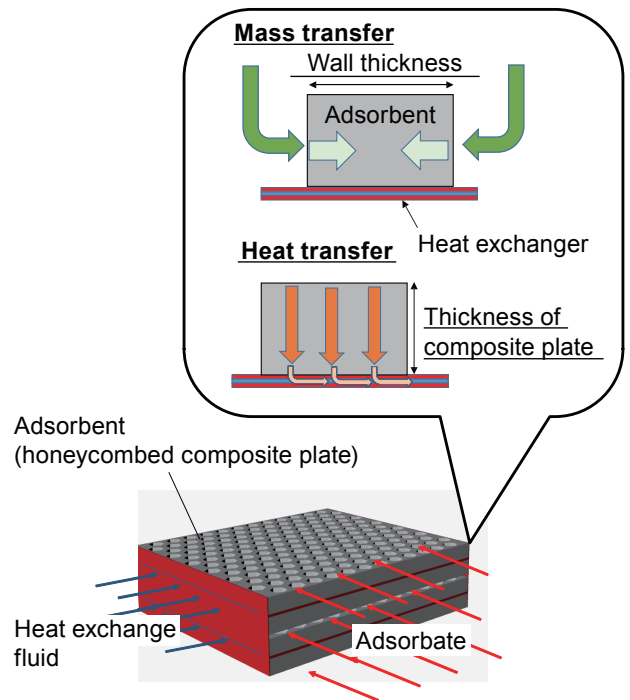
In our proposed adsorber, heat and mass transfers can be controlled independently. More specifically, the heat transfer resistance is controlled by the effective thermal conductivity and the composite plate thickness, the mass transfer resistance is controlled by the effective diffusion coefficient and the honeycomb composite plate wall thickness, and the packing density is controlled by the honeycombed composite plate aperture ratio. Additionally, we found that the mass transfer resistance could be reduced by decreasing



**Fig. 1** Schematic illustrations of (a) overall particle ad/desorption rate, (b) packed bed mass transfer, and (c) packed bed heat transfer.



**Fig. 2** Target zone for the cycle time and the adsorption amount aiming at the goal of 850 W/L.



**Fig. 3** Schematic illustrations of the proposed adsorber concept.

the wall thickness of the honeycomb composite plate, and that the packing density could be increased by decreasing the hole width. However, it needs to be noted that the decrease in the wall thickness is limited by manufacturability concerns and a sufficient hole width is necessary to permit an acceptable mass transfer rate.

We began this study by designing the honeycomb structure of the composite plate. In its final form, the composite plate is manufactured by extrusion with carbon fibers added to increase heat conductivity. The adsorption rate of the fabricated composite plate was then measured by a volumetric method under experimental conditions that ensured it was not affected by heat transfer, and the results were compared with the reported value of coating method.<sup>(3)</sup> The composite plate was then attached to a heat exchanger with microchannels to create the adsorber, which was connected to an evaporator, after which the adsorption rate was measured and compared with that of the coating method.<sup>(2)</sup> The performance of the completed apparatus was then evaluated in relation to the goal set in the previous study.<sup>(3)</sup>

## 2. Adsorber Design

The aperture ratio  $x$  of the honeycombed composite plate is calculated by the following equation:

$$x = \frac{(b/a)^2}{1 + 2(b/a) + (b/a)^2}, \quad (2)$$

where  $a$  and  $b$  are the wall thickness and the hole width of the honeycombed composite plate, respectively, as shown in Fig. 4.

Figure 5 shows the aperture ratio calculated by Eq. (2), varying  $b/a$  from 0 to 2. When  $a$  is equal to  $b$ , the aperture ratio is 0.25. After considering the need for a diffusion coefficient that could be measured by the reported method, the wall thickness was designed so that the water vapor diffusion in the wall is not the rate-determining step.<sup>(4)</sup> In this study, the wall thickness design was set at 300  $\mu\text{m}$ , using the diffusion coefficient of  $7.7 \times 10^{-5} \text{ m}^2/\text{s}$ . The optimum hole width of the honeycombed composite plate and the optimum gap width between the honeycombed composite plates ( $e$  in Fig. 4) were designed to ensure that the diffusion in the holes and the gap were also not the

rate-determining step. However, diffusion estimation becomes complex when the vapor is as dilute as seen in this study. The hole width is 300  $\mu\text{m}$ , which results in an aperture ratio of 0.25. The gap width between the honeycombed composite plates in our design was set at 500  $\mu\text{m}$  based on the estimation of the pressure loss due to vapor flow.

The heat exchanger thickness design ( $c$  in Fig. 4) was set at 500  $\mu\text{m}$  in order to take into consideration of the heat exchange power and the pressure loss in the heat carrier flow. The honeycombed composite plate thickness ( $d$  in Fig. 4), which was designed to take into consideration the thermal conductivity of the composite plate, was increased by the addition of the heat conductive additive. In this apparatus, the addition of carbon fiber (10 vol%) improved the composite plate heat conductivity to 5 W/(m·K), thereby allowing thicker plates and thus higher

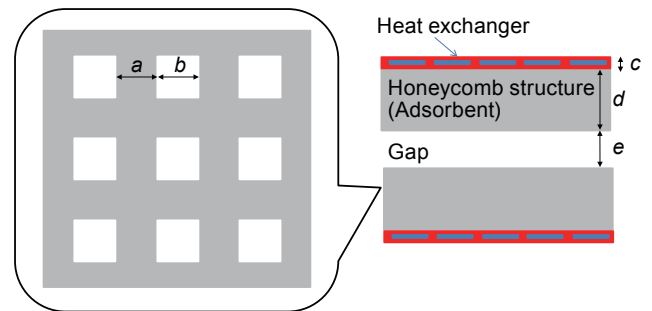


Fig. 4 Schematic illustrations of the structures of the honeycombed composite plate (left) and the adsorber comprising the composite plates and heat exchangers.

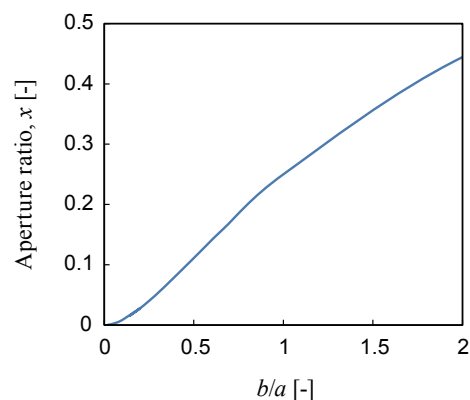


Fig. 5 Aperture ratios calculated by Eq. (2) with varying  $b/a$  value.

volumetric power density. In our design, composite plate thickness was set at 2.25 mm. The parameters of the adsorber are summarized in **Table 1**.

### 3. Experimental Setup

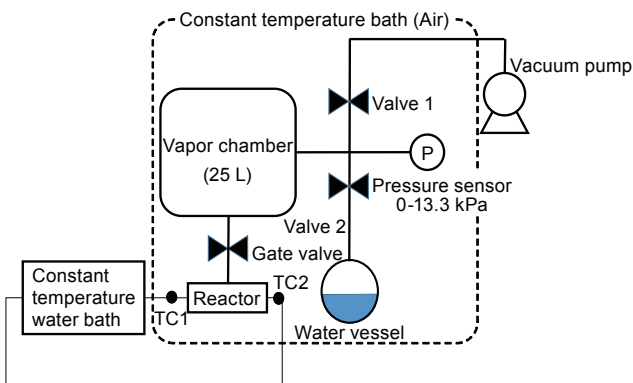
#### 3.1 Evaluation of the Composite Plate

##### 3.1.1 Experimental Apparatus

**Figure 6** shows a schematic drawing of the volumetric gas adsorption measuring apparatus used in this study. This apparatus consists of a chamber, a water vessel, a pressure gauge (ULVAC, Inc., CCMT-100D), two water shut valves, a gate valve, and a thermochemical reactor. The thermochemical reactor was connected to a constant temperature water bath in order to maintain the reactor at a constant temperature. The whole apparatus was installed inside a thermostatic chamber to establish isothermal conditions. **Figure 7** shows a schematic drawing of heat exchanging structure of the thermochemical reactor.

**Table 1** Adsorber parameters.

Parameter			
a	Wall thickness of the honeycombed structure	[ $\mu\text{m}$ ]	300
b	Side length of the square hole	[ $\mu\text{m}$ ]	300
c	Thickness of the heat exchanger	[ $\mu\text{m}$ ]	500
d	Thickness of the plate	[mm]	2.25
e	Gap width between the honeycomb plates	[ $\mu\text{m}$ ]	500



**Fig. 6** Schematic drawing of a volumetric gas adsorption measuring apparatus.

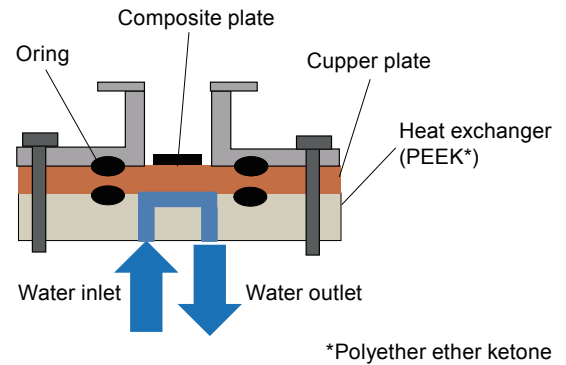
##### 3.1.2 Volumetric Method

The amount of adsorption is measured based on the change of pressure of the vapor chamber using the volumetric method.<sup>(3,5)</sup> The vapor pressure changes are monitored by the pressure gauge in the apparatus during sorption process (**Fig. 8**).

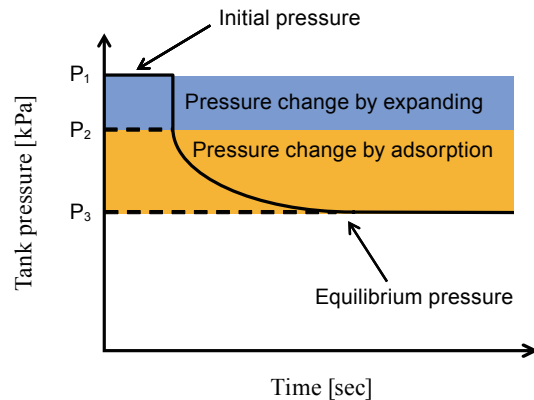
The adsorption ratio of water vapor  $X$  can be defined by the following equation:

$$X = \frac{P_t - P_3}{P_2 - P_3} \quad (3)$$

In this equation,  $P_t$ ,  $P_2$ , and  $P_3$  are the pressure at each time, the initial pressure, and the equilibrium pressure, respectively, as shown in Fig. 8.



**Fig. 7** Schematic drawing of heat exchanging structure of the thermochemical reactor.



**Fig. 8** Schematic illustrations of a vapor pressure change monitored by the pressure gauge in the apparatus during the sorption process.

### 3. 1. 3 Composite Plate Preparation

As stated above, we used SAPO-34 as an adsorbent in our apparatus. The adsorption isotherm is shown in Fig. 9. The honeycombed composite plate was formed by using an extrusion machine with the blending ratio shown in Table 2. It was then calcinated in air at 270°C for 5 hours to remove binder 2, which hinders vapor diffusion. The calcinated composite plate dimensions are 10 × 10 × 2.25 mm. The thermal conductivity of the plate was about 5 W/(m·K). The plate was bonded to a copper plate with binder 1. The copper plate thickness was set at 5 mm so that the temperature difference caused by the adsorption heat would be less than 2°C.

### 3. 1. 4 Experimental Conditions

Before the measurements, all the samples were pretreated at 90°C for 0.5 hours under vacuum conditions. The thermostatic chamber was maintained at 55°C. The temperature of the thermochemical reactor was kept at 35°C in an isothermal bath. The initial tank pressures were set at 1000, 1500, 2000, 2500, and 3000 Pa.

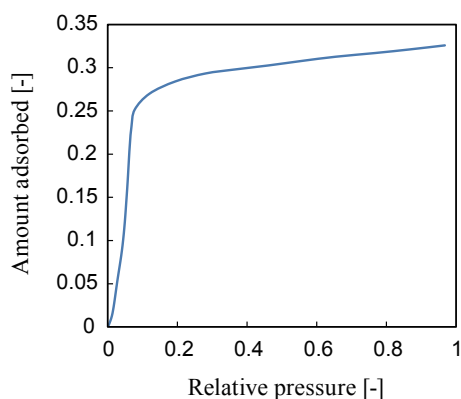


Fig. 9 Adsorption isotherm of the SAPO-34 at 25°C.

Table 2 Honeycombed composite plate blending ratio.

Constituent	Wt%
SAPO-34	60
Carbon fiber	30
Graphite	10
Binder1 (SBR)	2.5
Binder2 (methylcellulose)	10

### 3. 2 Adsorber

#### 3. 2. 1 Experimental Apparatus

Figure 10 shows a schematic drawing and photograph of the adsorber. As stated in the design section, the heat exchanger and honeycombed composite plate thicknesses were set at 0.5 mm and 2.25 mm, respectively. The honeycombed composite plate was bonded to the heat exchanger wall by binder 1.

The adsorption rate of the adsorber was measured by the apparatus shown in Fig. 11. This device consists of an evaporator, a gate valve, and two isothermal baths.

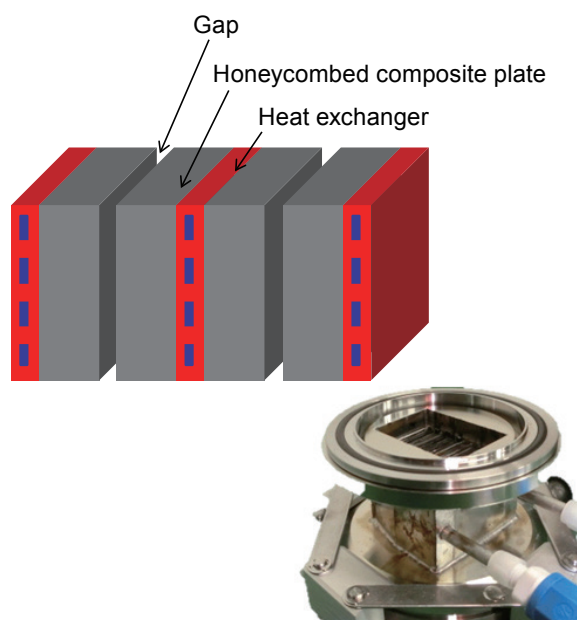


Fig. 10 Schematic drawing (left) and photo (right) of the adsorber.

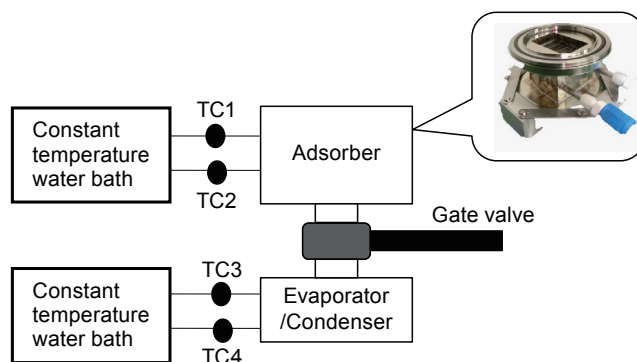


Fig. 11 Schematic illustrations of measurement apparatus for the adsorber.

adsorber to ensure that a sufficient amount of water vapor is supplied.

### 3. 2. 2 Experimental Conditions

**Table 3** shows the experimental conditions in which the effect of the evaporator temperature is examined. For adsorption test, both adsorber and condenser temperatures were set at 35°C, which correspond to an expected coolant temperature at the outlet of automobile radiator. For desorption test, adsorber temperature was set at 95°C, which corresponds to an expected coolant temperature at the outlet of automobile engine.

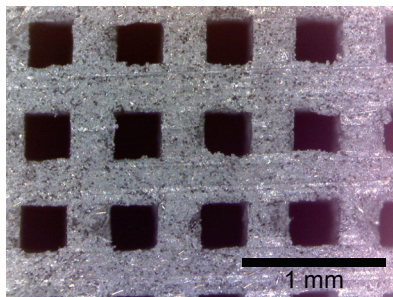
## 4. Results and Discussions

### 4. 1 Composite Plate and Adsorber

**Figure 12** shows a photograph of the extrusion-formed honeycombed composite plate with the wall thickness

**Table 3** Experimental conditions for adsorber evaluation.

Temperature of the evaporator [°C]	10	15	20
Flow rate of the water into evaporator [L/min]	0.8		
Temperature of the adsorber for adsorption [°C]	35		
Flow rate of the water into adsorber [L/min]	5		
Temperature of the condenser [°C]	35		
Flow rate of the water into condenser [L/min]	0.8		
Temperature of the adsorber for desorption [°C]	95		
Core volume of the adsorber [cc]	51		
Theoretical amount of adsorption $w$ [g/L-core]	64	68	70
Adsorption time [sec]	60		

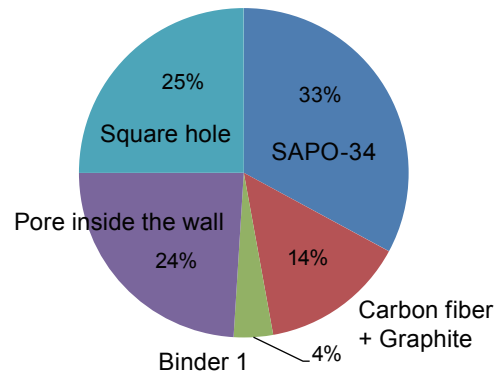


**Fig. 12** Photo of the extrusion-formed honeycombed composite plate.

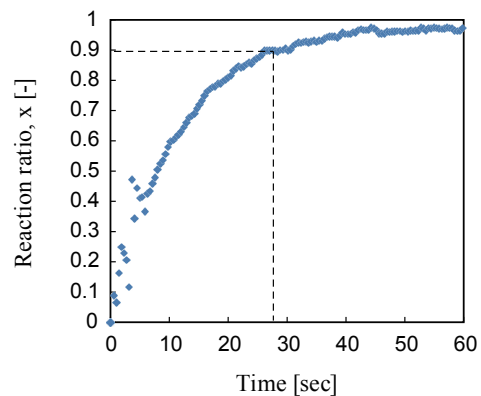
and honeycomb structure hole width set forth in the design described above. Specifically, the wall thickness, hole width, and SAPO-34 packing density were 300 μm, 300 μm, and 0.43 g/cc, respectively. **Figure 13** shows the volume ratios of the composite plate constituents. Materials comprise as little as half of the whole volume, and the rest is space: honeycomb hole or pore inside the wall. Thus, the packing density can still be increased by further optimizing the parameters listed in Table 1 or extrusion conditions. The packing density of the adsorber core, including the composite plates, the gap between the composite plates, and the heat exchanger was 0.32 g/cc. This value is 1.36 times that of the coated-type adsorber, 0.24 g/cc.<sup>(2)</sup>

### 4. 2 Evaluation by Volumetric Method

**Figure 14** shows the change of adsorption ratio over



**Fig. 13** Volume ratios of the constituents of the composite plate.



**Fig. 14** Change of adsorption ratio over time during the experiment with the initial pressure of 1500 Pa.

time during the experiment with the initial pressure of 1500 Pa. The adsorption rate  $r_{AD}$  [1/s] is defined by the following equation:

$$r_{AD} = \frac{1}{t_{AD}}, \quad (4)$$

where  $t_{AD}$  is adsorption time, which is defined as the time when the adsorption ratio reaches  $X = 0.9$ , as shown in Fig. 14.

**Figure 15** shows the rates of adsorption  $r_{AD}$  in experiments at different initial pressures. Here, it can be seen that the adsorption rate decreased with decreases in the initial pressure. However, even when the initial pressure was as low as 1000 Pa, the adsorption rate was 0.018 1/s. This adsorption rate is more than 2 times that of the coating method,<sup>(5)</sup> which was measured under 866 Pa water vapor. We can compare these adsorption ratios because the pressure conditions are similar to each other; initial pressure 1000 Pa decreased to 829 Pa in this study. These results indicate that not only was the diffusion resistance decreased by the reduction in the honeycomb composite plate wall thickness, but also that the heat transfer resistance was decreased by the increase in the honeycomb composite plate thermal conductivity that resulted from the addition of carbon fiber.

### 4.3 Adsorber Evaluation

**Figure 16** shows the temperature difference of the water, the heat carrier, between the inlet and outlet

of the adsorber. The temperature difference increases significantly with the evaporation temperature. It is considered likely that the equilibrium temperature was increased by the higher pressure of water vapor supplied at higher temperature by the evaporator.

The adsorption ratio  $X(t)$  is calculated from the result shown in Fig. 16 by the following equations:

$$X(t) = \frac{Q_{AD}(t)}{Q_{TH}}, \quad (5)$$

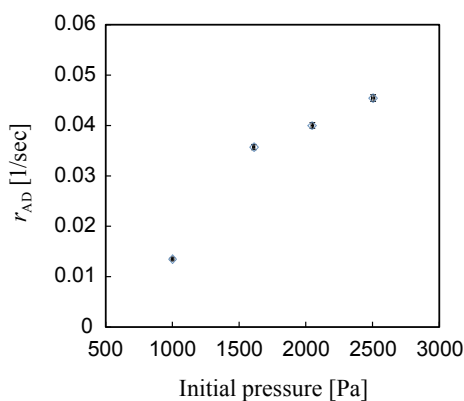
$$Q_{AD} = m_{HC} \cdot c_{pHC} \cdot \Delta T_{AD}, \quad (6)$$

$$Q_{AD}(t) = \int_0^t Q_{AD} dt, \quad (7)$$

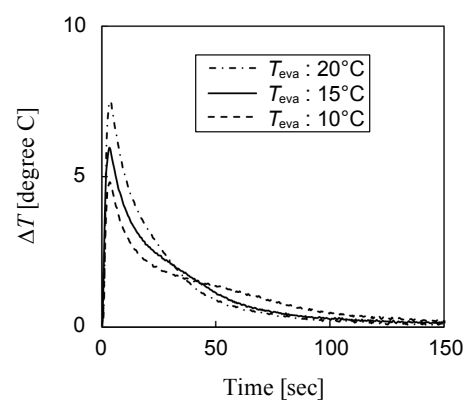
$$Q_{ideal} = w_{ideal} \cdot \Delta H_{AD}, \quad (8)$$

where  $Q_{AD}(t)$ ,  $Q_{TH}$ ,  $X(t)$ ,  $t$ ,  $C_{pHC}$ ,  $\Delta H_{AD}$ ,  $w$ , and  $\Delta T_{AD}$  are the sum of adsorption heat, the theoretical adsorption heat, the reaction rate, the time, the specific heat of water, the adsorption heat, the amount of loaded adsorbent, and the temperature difference of water between the inlet and the outlet of the adsorber, respectively. In this study, the value of  $\Delta H_{AD}$  is the same as that given in the previous report.<sup>(6)</sup>

**Figure 17** shows the adsorption ratio within 60 s calculated from the temperature difference of the water between the inlet and the outlet of the adsorber, as described by Eqs. (5) to (8). When the temperature



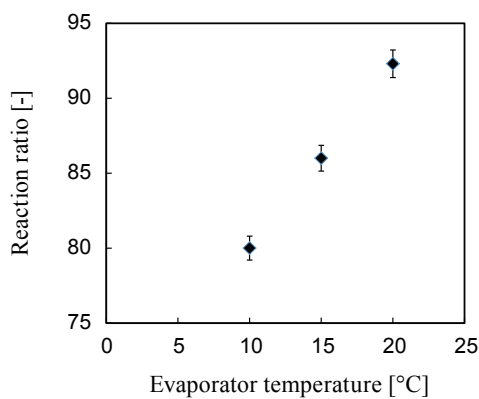
**Fig. 15** Rates of adsorption  $r_{AD}$  in experiments with different initial pressures.



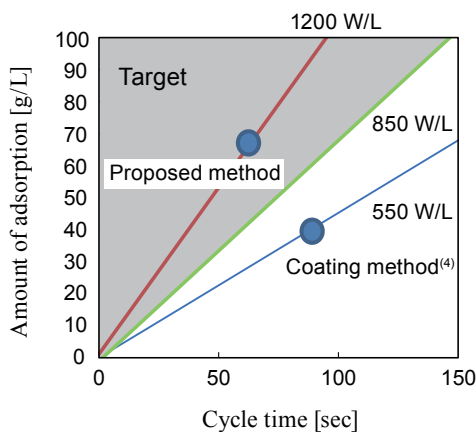
**Fig. 16** Temperature difference of water, the heat carrier between the inlet, and the outlet of the adsorber.

of the evaporator was 15°C, the adsorption ratio reached 86% within 60 s. Compared with the result of the volumetric method, the adsorption rate was as low as half, which indicates that the heat transfer resistance in the heat exchanger is so high that it affects the adsorption rate. Accordingly, it will be necessary to decrease not only the thermal resistance in the honeycombed composite plate but also the thermal resistance in the heat exchanger.

From the results of the adsorption rate and the packing density of the adsorber, the VCP is calculated by Eq. (1). The VCP is shown by a line in **Fig. 18** with a circle indicating the experimental result when the evaporator temperature is 15°C. Compared with the coating method,<sup>(2)</sup> the adsorption rate and adsorber packing density have been improved as much as 1.33-fold and 1.36-fold, respectively. The VCP of



**Fig. 17** Adsorption ratio within 60 s with varying initial pressure.



**Fig. 18** Target zone for the cycle time and the amount of adsorption aiming at the goal of 850 W/L.

the suggested adsorber achieved 1000 W/L, which is comparable to the VCP of electric compressors.

Future study will involve improvements to the adsorption ratio within 60 s under the severe conditions required for onboard use. For example, the adsorption ratio needs to be maintained over 90% under conditions where the evaporator and the adsorber temperatures are lower and higher, respectively. Other parameters that were not considered in this study include the hole width of the honeycombed composite plate and the gap between the honeycombed composite plates. These will also need to be optimized to further improve our proposed device.

## 5. Conclusions

Herein, we reported on a compact adsorber for AHP systems that is characterized by honeycombed composite plates of adsorbent with a conductive carbon fiber heat additive bonded to the plate-type heat exchanger. In our experiments, the adsorption rate of the composite plate was measured by a volumetric method under experimental conditions where the adsorption rate was not affected by the heat transfer. Our experimental results show that the adsorption rate of our proposed adsorber is 2-fold higher than that achievable via the coating method. The adsorber, which is composed of the composite plate and the heat exchanger, was connected to an evaporator and its adsorption rate was measured and compared with that of the coating method. The results show that the adsorption rate and packing density of our proposed adsorber were improved as much as 1.33-fold and 1.36-fold, respectively, when compared with the coating method.

The VCP of the proposed adsorber was measured at 1000 W/L, which corresponds favorably to the VCP of electric compressors. It is believed that our developed compact adsorber can contribute to reducing the size and total cost of AHP systems and could be applicable to not only automotive applications but also large-scale air conditioning systems (such as factory air conditioning systems). On the other hand, when compared with the results of the volumetric method, we can see that the adsorption rate of our apparatus is just 50%, which indicates that heat transfer resistance in the heat exchanger remains excessive. According, in our future studies, we will need to both decrease the thermal resistance in the honeycombed composite



plate and also decrease the thermal resistance in the heat exchanger.

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Figs. 1-18 and Tables 1-3

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