

天然メソポーラス材料を用いた低コスト吸着式ヒートポンプの研究開発
 (その 21) 太陽熱吸着ヒートポンプの熱力学的シミュレーションによる性能分析

Research and Development of Low-Cost Adsorption Heat Pump
 Using Natural Mesoporous Material

21th: Thermodynamic Simulation on Performance of Solar Adsorption Heat Pump System

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In this research, the heat and mass transfer coefficients required to operate the model are experimentally estimated. The heat exchangers filled with the traditional A-type silica gel and the natural mesoporous material called Wakkanai Siliceous Shale (WSS) composite adsorbent are used, and their filled density is divided into two levels. In terms of the mass transfer, the temperature of the cooling water is varied to reflect thermal effects on the mass transfer. The overall heat transfer coefficient of each heat exchanger is experimentally estimated as the adsorbent temperature changes from 80°C to 30°C. Lastly, effects of the climate conditions of major cities of Japan on the AHP system are analyzed targeting the case that the regeneration water is heated by a solar collector.

1. Introduction

Due to being able to utilize low level heat sources lower 100°C from waste heat and solar energy, adsorption heat pumps (AHP) are considered as effective systems that provide cooling with less energy consumption. Since the entire performance of AHP systems is strongly dependent on not only heat transfer but also mass transfer characteristics of the adsorbate into the adsorbent, numerous researches on the adsorber or adsorbent have been conducted to improve adsorption behaviors.

Large temperature jump (LTJ) and large pressure jump (LPJ) are the most representative methods. In the LTJ method, the adsorbent temperature is adjusted at a certain pressure to promote adsorption, whereas in the LPJ method, the adsorption pressure is controlled. In previous researches of our team, adsorption dynamic characteristics of the coated adsorbent layers ¹⁾ and filled adsorbent in a lab scale heat exchanger ²⁾ were analyzed. In this study, the performance characteristics of a solar powered AHP applying adsorbers, which are filled by A-type silica gel or WSS impregnated with 20 wt.% of lithium chloride with different filling density, are analyzed by numerical modeling. The climate conditions of Sapporo, Japan (43°N, 141°E) obtained from the meteorological administration of

Japan are applied.

2. Mathematical modeling equations

2.1 Adsorption isotherm and kinetic equations

Equilibrium adsorption amount of WSS+LiCl 20 wt.% were numerically fitted using Eq. (1) and (2). The average and maximum deviations between the measured and calculated equilibrium loading of WSS + LiCl 20 wt.% were 0.0081 and 0.06 g/g, respectively ($R^2 = 99.24$).

Here, P_i show the pressure of each adsorption site, n is the number of molecules per site, N_{mi} is the density of the receptor site, and E_{ai} is the molar adsorption energy of gas in the site i ³⁾. The isotherm equations of A-type silica gel were Eq. (3) ~ (5). An average and a maximum deviation of the balanced load of the measurement and calculation of the A-type silica gel are 0.0048 and 0.0164 g/g, respectively ($R^2=99.58$). The equilibrium adsorption amounts of both materials were measured at four temperature levels of 30 to 50 °C, as shown in Figure 1 and 2.

Adsorption uptake of each bed is calculated based on a linear driving force model as shown in Eq. (6). The overall mass transfer coefficient (K_m) was experimentally estimated in our previous research ²⁾.

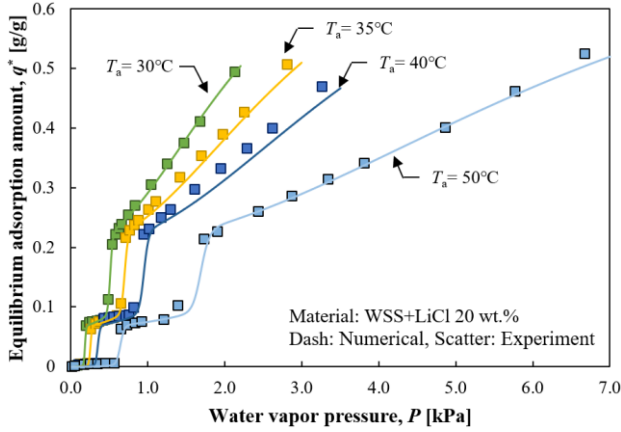


Figure 1. Water vapor sorption isotherms of WSS+LiCl 20 wt.%

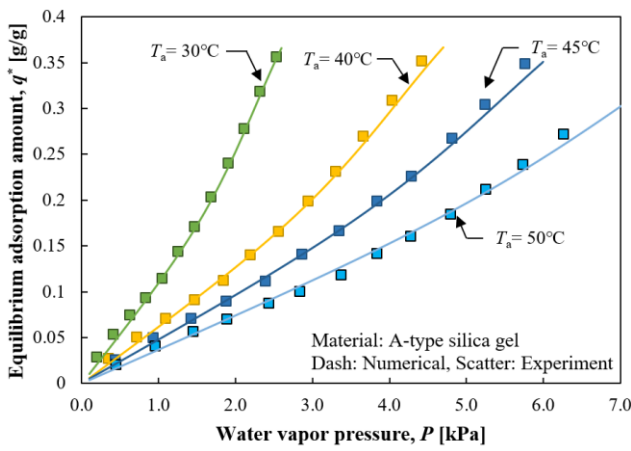


Figure 2. Water vapor sorption isotherms of A-type silica gel

$$q^* = \sum_{i=1}^4 \frac{n_i N_{M_i} \left(\frac{P}{P_i}\right)^{n_i}}{1 + \left(\frac{P}{P_i}\right)^{n_i}} \quad (1)$$

$$P_i = P_{\text{sat}} \exp\left(\frac{\Delta E_{a,i}}{RT_a}\right) \quad (2)$$

$$\frac{q^*}{q_0} = \frac{A \phi \exp\left(\beta \frac{P}{P_s}\right) \frac{P}{P_s} + C \frac{P}{P_s}}{\left\{1 + \phi \exp\left(\beta \frac{P}{P_s}\right) \frac{P}{P_s}\right\}^n} \quad (3)$$

$$\beta = \exp\left(\frac{E_c}{RT}\right) \quad (4)$$

$$A = \frac{[1 + \phi \exp(\beta)]^n - C}{\phi \exp(\beta)} \quad (5)$$

$$\frac{dq}{dt} = K_m(q^* - q) \quad (6)$$

2.2 Energy equations for ad/desorption models

A mathematical model assuming uniform temperature and concentration profile throughout the adsorption material is presented in Eq. (7) ~ (12). For the adsorption bed 1, which is initially in the desorption mode, the bed temperature (T_b) and outlet temperature of its water side ($T_{b,w,o}$) can be calculated by

Eq. (7) ~ (9).

$$C_{\text{tot}} \frac{dT_{a1}}{dt} = M_a \frac{dq}{dt} \Delta H(T_{a1}) + \dot{Q}_1 \quad (7)$$

$$C_{b1,w} \frac{dT_{b1,w,o}}{dt} = \dot{m}_{b,w} c_{p,w} (T_{b1,w,i} - T_{b1,w,o}) - \dot{Q}_1 \quad (8)$$

$$\dot{Q}_1 = \varepsilon_{b1} \dot{m}_{b1,w} c_{p,w} (T_{b1,w,i} - T_{a1}) \quad (9)$$

In a similar way, those of adsorption bed 2 which is initially in the adsorption mode are calculated by Eq. (10) ~ (12).

$$C_{\text{tot}} \frac{dT_{a2}}{dt} = M_a \frac{dq}{dt} \{\Delta H(T_{b2}) - c_{p,v}(T_{a2} - T_{\text{evap}})\} - \dot{Q}_2 \quad (10)$$

$$C_{b2,w} \frac{dT_{b2,w,o}}{dt} = -\dot{m}_{b2,w} c_{p,w} (T_{b2,w,o} - T_{b2,w,i}) - \dot{Q}_2 \quad (11)$$

$$\dot{Q}_2 = \varepsilon_{b2} \dot{m}_{b2,w} c_{p,w} (T_{a2} - T_{b2,w,i}) \quad (12)$$

3. Simulation results and discussions

3.1 Basic Adsorption Heat Pump systems

Figure 3 and Figure 4 show comparisons of the cooling capacity based on the filled density for both adsorbents. A significant difference between the cooling-capacity distributions of the A-type silica gel and WSS composite was observed. The A-type silica gel exhibited a rapid decrease in its cooling capacity because it quickly reached the saturated state. The reduction in the cooling capacity for the WSS composite was moderate during the adsorption cycle. Additionally, the adsorbent with a lower filling density exhibited a steeper decrease in the cooling capacity. Therefore, the rate of reduction of the cooling capacity was proportional to the mass transfer rate.

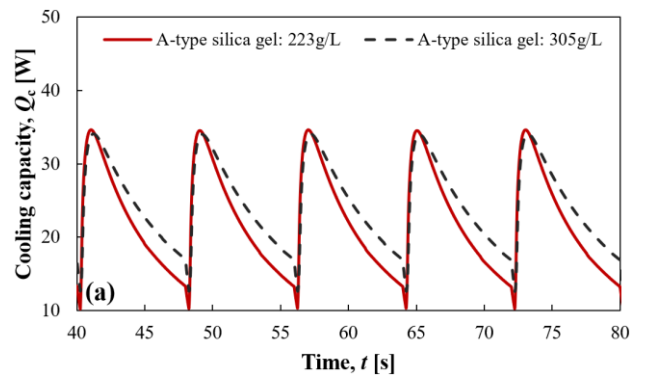


Figure 3. Comparison of cooling capacity according to filled density: A-type silica gel

Figure 5 and Figure 6 depict the variations in the specific cooling power (SCP) and COP, respectively, with respect to the half cycle time. The COP should be considered when evaluating an AHP, as well as other heat-pump systems. Additionally, the

SCP is an important performance indicator of an AHP and represents the attainable cooling capacity based on the unit mass of the adsorbent. The SCP values of the materials with lower filling densities were higher than those of the materials with higher filling densities. This implies that the adsorbent was used more efficiently in the heat exchanger with the lower filling density. The general trends of the SCP resembled and were dependent on the cooling capacity. WSS+LiCl 20 wt.% (329 g/L) exhibited the smallest SCP variation (relatively constant value) with respect to the half cycle time. As the cycle time increased, the sensible heat loss that occurred when the mode was switched from adsorption to desorption accounted for a relatively small portion among the entire load. Hence, the COPs of the systems employing the adsorbents tended to increase when the adsorption time increased. The COP for the case of the WSS composite was improved by 6–17% compared with that for the A-type silica gel, indicating the effectiveness of the WSS composite

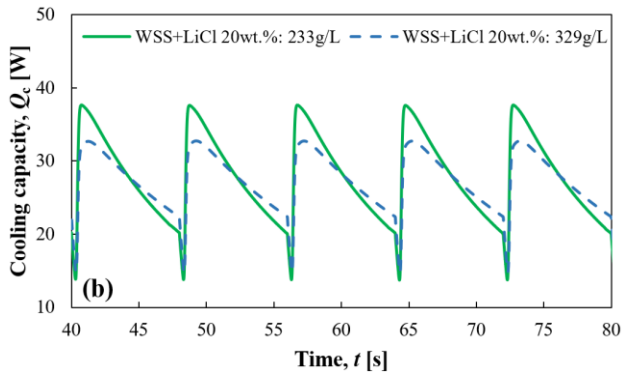


Figure 4. Comparison of cooling capacity according to filled density: WSS+LiCl 20 wt.%

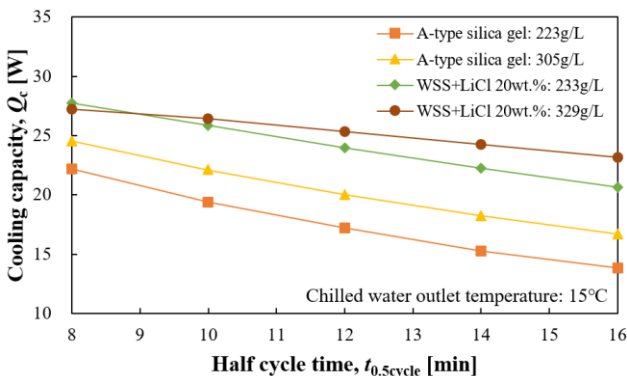


Figure 5. Effect of half cycle time on cooling capacity

3.2 Solar adsorption heat pump systems

The energy balance absorbed by the collector is established by following Eq. (13) and (14), where $F_R \tau \alpha$ is intercept efficiency of the collector [-], $F_R U_L$ is the first-order

coefficient [W/m²K]. The term on the left side refers to input energy to the collector which is proportional to the solar radiation amount. The terms on the right side refer to temperature variation rate of the stored water, heat loss amount from the collector and heat transfer amount to the AHP system. Coefficients regarding the solar collector were derived from the research of Koronaki et al. ⁴⁾.

$$F_R A_{SC} I(\tau \alpha) = C_{tw} \frac{dT_{tw}}{dt} + U_L A_{SC} (T_{tw} - T_{amb}) + \dot{Q}_{tw} \quad (13)$$

$$\dot{Q}_{tw} = \dot{m}_{b,w} C_{p,w} (T_{b,w,i} - T_{b,w,o}) \quad (14)$$

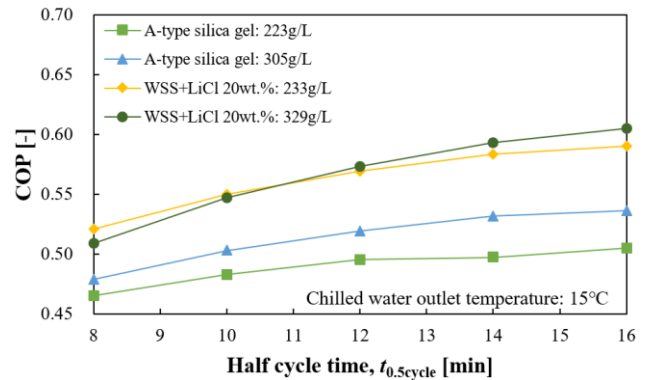


Figure 6. Effect of half cycle time on cooling capacity

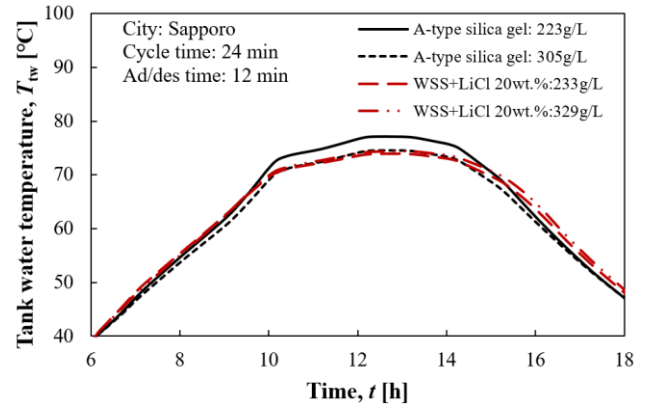


Figure 7. Variation of regeneration water temperature

Figure 7~9 show daily variation of regeneration water temperature, cooling capacity and COP of the system with different filled density and adsorbent materials. At the beginning of the day, COP tended to be low because the heat loss occurring when the system undergoes switching its mode from adsorption and desorption takes relatively the larger portion from the entire heat consumption amount at this period. For this reason, COP became higher as the obtainable temperature of hot water increases. Cooling capacity also tended to increase as the obtainable cooling capacity increases.

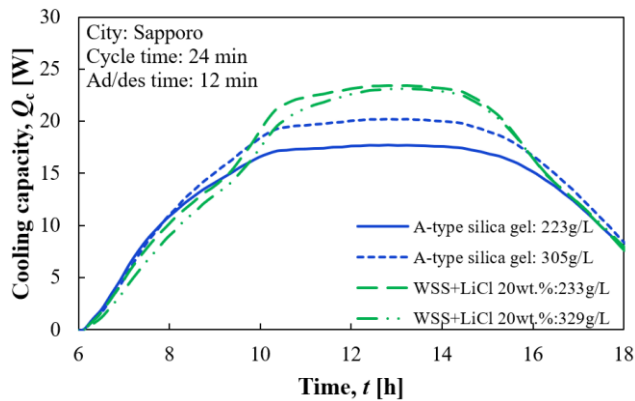


Figure 8. Variation of cooling capacity during the daytime

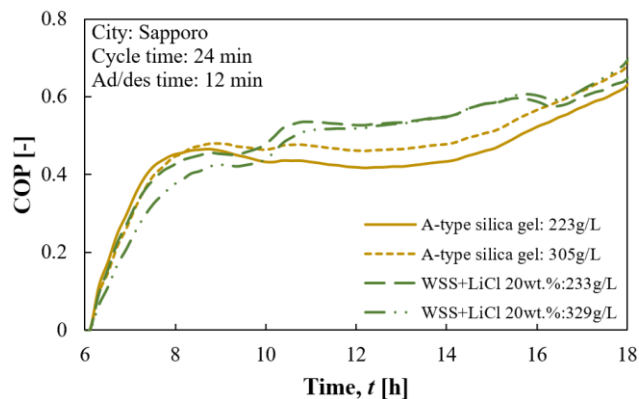


Figure 9. Variation of COP during the daytime

4. Conclusions

The experimentally obtained heat and mass transfer coefficients were substituted into a mathematical model for a more accurate and practical estimation of the AHP performance. The cooling capacity and SCP tended to decrease as the adsorption time increased because of the decreasing adsorption rate. The COP tended to increase with an increase in the adsorption time. The decrements and increments of the parameters of the adsorbents differed owing to their different adsorption dynamics and equilibrium characteristics. Therefore, the optimization of the cycle time, considering the adsorption dynamics and equilibrium characteristics of the adsorbents, is necessary. In future studies, the analysis on long term-operations (i.e., during daytime) will be conducted based on this zero-dimensional AHP model, thermally supported by a solar collector. This appears to be promising because of the advantages of fast and simple calculations. Additionally, the system performance as well as energy and exergy analyses according to various operating parameters will be provided in future studies.

Finally, the WSS composite material exhibited a COP that was 6–17 % higher than that of the A-type silica gel. This

indicates the effectiveness of the WSS composite compared with the frequently used A-type silica gel.

Nomenclature

	Effective area of valve [m ²]		
C	Thermal capacity [J/K]	C_p	Specific heat [J/g K]
I	Solar radiation [W/m ²]	K_m	Overall mass transfer [s ⁻¹]
M	Mass of dry adsorbent[g]	\dot{m}	Mass flow rate [g/s]
P	Pressure [Pa]	Q	Heat capacity [W]
q	Uptake [g/g]	q^*	Equilibrium uptake [g/g]
T	Temperature [K]	t	Time [s]
ε	Heat transfer efficiency [-]	ΔH	Heat of adsorption [J/g]
ρ	Density [kg/m ³]		

Subscript

Amb	Ambient	b	Bed
c	Cooling	i	Inlet
o	outlet	v	Vapor
w	Water	1~2	Bed number

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