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# Optimized Performance of One-Bed Adsorption Cooling System

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## ABSTRACT

The study aimed at the reduction of system size of adsorption cooling systems for refrigeration and air-conditioning applications. To simplify the system, we investigated one-bed configuration of adsorption cooling system. In general, one-bed adsorption cooling system would result in a large temperature fluctuation at chilled water outlet. To overcome that drawback and to maximize the cooling capacity, the cycle time, namely, pre-heating, desorption, pre-cooling, and adsorption times, of one-bed adsorption cooling system was optimized. In case of two-bed adsorption cooling system, two adsorbers operates in reverse phase each other, which means that the degree of freedom for cycle time optimization is two. In case of one-bed adsorption cooling system, four processes can be independently optimized. In our study, activated carbon-ethanol pair was chosen as the adsorbent-refrigerant pair because of a high adsorption capacity of activated carbons against ethanol. Using adsorption isotherms and kinetic data of activated carbon-ethanol pair measured by our research group, a lumped parameter model of one-bed adsorption cooling system was developed. The four parameters of cycle time were optimized using global optimization method, and the optimal time settings were effectively found. The results showed the effect of cycle time optimization on the cooling performance of one-bed adsorption cooling system.

## 1. INTRODUCTION

Adsorption refrigerators and heat pumps are environmentally benign technologies, and they are intensively studied since 1970s along with a rise of global scale energy and environmental issues such as oil crisis, ozone depletion, and global warming. Many of the adsorption refrigeration and heat pump systems are in a two-bed configuration, where two adsorbent beds perform a cycle of adsorption and desorption processes out of phase (Boelman et al., 1995; Chua et al., 1999). Two-bed adsorption cooling systems are mainly used in industrial applications and large scale buildings and the cooling capacity of them is typically larger than 100 kW. On the other hand, solar adsorption cooling systems or ice-makers are equipped with a single bed in

most cases because it is operated by a daily cycle (Louajari et al., 2011; Hassan et al., 2011; Umair et al., 2014).

In our study, a one-bed configuration of adsorption cooling system was investigated so that the system size could be reduced. A main difference between the proposed one-bed system and existing one-bed solar adsorption cooling system is that the proposed system is operated by a short time cyclic operation, similar to the cycle time of two-bed adsorption cooling systems.

## 2. SIMULATION OF ONE-BED ADSORPTION COOLING SYSTEM

### 2.1 Outline of the system

A one-bed adsorption cooling system, which consists of an adsorber, a condenser and an evaporator, was investigated in this study. The schematic of the system is illustrated in Figure 1. During the adsorption process, the adsorber is connected with the evaporator and the condenser is isolated. The adsorber is cooled by the cooling water to adsorber and the chilled water flows in the evaporator, which is cooled by the evaporation heat of refrigerant. The cooling water to the condenser is kept flowing so that the temperature of the condenser is maintained. The amount of liquid refrigerant in the evaporator can be maintained by controlling flow rate of condensed refrigerant flow from the condenser to the evaporator. After the adsorption process, the adsorber is disconnected with the evaporator and heated to a certain temperature by hot water, which is the pre-heating process. Then, the adsorber is connected with the condenser for the desorption process. During the desorption process, the adsorber is heated by hot water and the condenser is cooled by the cooling water. The evaporator is isolated but the chilled water is kept flowing to avoid temperature rise in evaporator. Finally in the pre-cooling process, the adsorber is disconnected with condenser and it is cooled to a certain temperature by the cooling water.

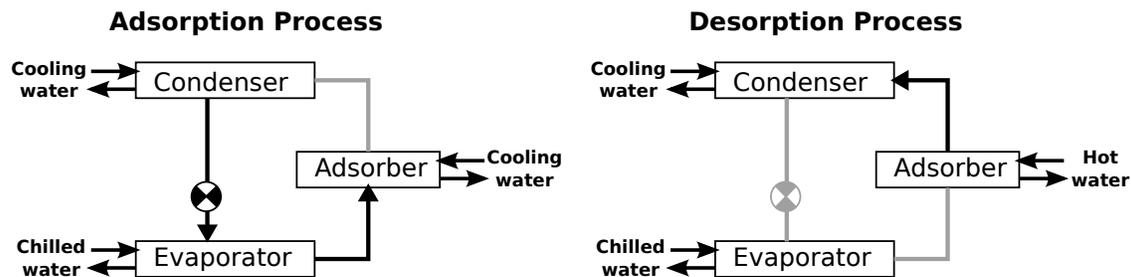


Figure 1: Schematics of one-bed adsorption cooling system

With the one-bed configuration, the time length of four processes, namely, adsorption, pre-heating, desorption, pre-cooling processes can be independently selected. The cycle time of the two-bed adsorption cooling system consists of two parameters, which are adsorption/desorption time and pre-heating/pre-cooling time, because two adsorbers change their processes at the same timing. On the other hand, the one-bed adsorption cooling system has four independent processes, which means that the cycle time setting has more freedom compared with that of the two-bed configuration.

### 2.2 Mathematical model

Performance of the one-bed adsorption cooling system was predicted by using lumped parameter model. The adsorption uptake was given by Eq.(1).

$$\frac{dw_b}{dt} = \frac{15D_p}{r_p^2} (W_b - w_b) \quad (1)$$

$D_p$  is given by the Arrhenius equation as a function of adsorbent temperature (Sakoda and Suzuki, 1984).

$$D_p = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (2)$$

Considering the energy balance during the adsorption process, temperatures in adsorber, condenser, and evaporator are given by Eqs.(3)–(5), respectively.

$$(M_s c_s + M_s c_{r1} w_b + M_b c_b) \frac{dT_b}{dt} = m_{ca} c_{ca} \epsilon_{ca} (T_{ca,i} - T_b) + [Q_s + c_{rv} (T_e - T_b)] M_s \frac{dw_b}{dt} \quad (3)$$

$$(M_{c,r1} c_{r1} + M_c c_c) \frac{dT_c}{dt} = m_{cc} c_{cc} \epsilon_{cc} (T_{cc,i} - T_c) \quad (4)$$

$$(M_{e,r1} c_{r1} + M_e c_e) \frac{dT_e}{dt} = m_{ch} c_{ch} \epsilon_{ch} (T_{ch,i} - T_e) - [L_r - c_{rl} (T_c - T_e)] M_s \frac{dw_b}{dt} \quad (5)$$

The left hand side of these equation shows temperature change of thermal mass, and the first term of the right hand side represents the heat given/taken by heat transfer media. The second term in the right hand side of Eq.(3) and (5) expresses the heat transfer due to latent heat. The latent heat term of adsorbed was modified by taking the sensible heat of refrigerant vapor into consideration. Similarly, evaporator energy balance takes into account the heat given by the refrigerant liquid coming from the condenser. The equations for pre-cooling process can be derived with  $\frac{dw_b}{dt} = 0$  in Eqs.(3) and (5).

Similar to the adsorption process, the energy balance equations of heat exchangers during the desorption process are given in Eqs.(6)–(8).

$$(M_s c_s + M_s c_{r1} w_b + M_b c_b) \frac{dT_b}{dt} = m_{h} c_{h} \epsilon_{h} (T_{h,i} - T_b) + Q_s M_s \frac{dw_b}{dt} \quad (6)$$

$$(M_{c,r1} c_{r1} + M_c c_c) \frac{dT_c}{dt} = m_{cc} c_{cc} \epsilon_{cc} (T_{cc,i} - T_c) - [L_r + c_{rv} (T_b - T_c)] M_s \frac{dw_b}{dt} \quad (7)$$

$$(M_{e,r1} c_{r1} + M_e c_e) \frac{dT_e}{dt} = m_{ch} c_{ch} \epsilon_{ch} (T_{ch,i} - T_e) \quad (8)$$

During the desorption process, the sign of  $\frac{dw_b}{dt}$  is negative. The pre-heating process can be derived with  $\frac{dw_b}{dt} = 0$  in Eqs.(6) and (7).

### 2.3 Adsorbent and refrigerant

The adsorbent and refrigerant pair in our study are activated carbon powder and ethanol. We have measured adsorption isotherms and kinetics by thermogravimetric method (El-Sharkawy et al., 2014). The adsorption isotherm was reproduced by Dubinin-Astakhov equation given by Eq.(9).

$$W = W_0 \exp\left[-\left(\frac{A}{E}\right)^n\right]$$

$$A = RT \ln\left(\frac{P_0}{P}\right) \quad (9)$$

where,  $W_0 = 1.2$  kg/kg,  $n = 1.8$ , and  $E = 6426$  J/mol for the present adsorbent.

The intra-particle diffusion coefficient was given in the form of the Arrhenius equation, and  $D_0/r_p^2 = 1.61 \times 10^{-2} \text{ s}^{-1}$ , and  $E_a = 10,365$  J/mol.

## 2.4 Validation of the model

The lumped parameter model was used in many simulation studies on adsorption cooling systems, and the validity of the model was already shown in some studies, for instance, Saha et al. (1995); Alam et al. (2003). Our mathematical model followed these precedent studies, and COP and cooling capacity of a two-bed adsorption chiller with silica gel and water pair were also predicted and compared between our model and the experimental results from a literature (Miyazaki et al., 2014). The results showed that the cooling capacity predicted by our model was reasonably close to the experiment. On the other hand, a discrepancy between the model prediction and the experiment was observed in COP. One of the main reason of difference in COP would be heat losses occurred in the experimental machine, and therefore, the model prediction would show an ideal performance of the system.

Although the comparison between the mathematical model and the experiment was performed for two-bed configuration, it could be applicable to one-bed configuration because the adsorber was governed by the same fundamental equations of heat and mass transfer as those of two-bed configuration. We are now carrying on experimental study on one-bed adsorption cooling system with activated carbon-ethanol pair. Validation of the model using our own configuration of heat exchanger will be available in the near future.

## 3. OPTIMIZATION OF CYCLE TIME

The optimum cycle time settings for adsorption, pre-heating, desorption, and pre-cooling processes were investigated by a global optimization method, Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 2001). The PSO mimics a behavior of swarm, such as a school of fish, to seek its feed using a group of particles. The particles have information on their best position achieved in its history, and exchange information with neighbors. We have successfully applied the PSO to the optimization of cycle time of adsorption cooling systems (Miyazaki and Akisawa, 2009).

The objective function was specific cooling power (SCP) and four process times were the variable. The simulation program of adsorption cooling system was developed on Matlab, and a PSO toolbox on Matlab was used for optimization. The optimization was performed under the temperature conditions given in Table 1.

**Table 1: Conditions of heat transfer fluid**

Hot water	80°C
Cooling water to adsorber	30°C
Cooling water to condenser	30°C
Chilled water	14°C

The optimization results showed that the SCP was maximized with time settings given in Table 2. The maximum SCP was 140 W/kg. It was shown that the adsorption time should be longer than desorption time to maximize the cooling output. Unbalanced adsorption and desorption time cannot be used with two-bed configuration. The freedom of time settings for four process times is one of advantage of one-bed configuration, and the results confirmed that the adsorption and desorption time have to be in different time settings to maximize the SCP. This is because of the difference in adsorption kinetics depending on adsorber temperature. In general, the adsorption speed is faster with higher temperature.

**Table 2: Optimization results**

Adsorption time	920s
Pre-heating time	50s
Desorption time	640s
Pre-cooling time	40s
SCP	140 W/kg
COP at the maximum SCP	0.48

Figure 2 shows a comparison of chilled water outlet temperature between the optimum time settings given in Table 2 and two fixed time settings with 640s for adsorption/desorption time and 40s for pre-cooling/pre-heating time and 920s for adsorption/desorption time and 40s for pre-cooling/pre-heating time. The first 640s or 920s are the desorption time, so there is no cooling effect. With the time setting of 640s for both adsorption time and desorption time, the chilled water outlet temperature was slightly lower than that of the optimum time settings because the initial condition of adsorber to start adsorption process was different, but the average cooling power through the cycle was lower than that of the optimum time settings. with the 920s for both adsorption and desorption time, a lower chilled water outlet temperature was obtained, but the average cooling power was also low in this case because the period of no cooling effect was longer than that of the optimum time settings. The SCPs of 640s for adsorption/desorption and 920s for adsorption/desorption were 136 W/kg and 135 W/kg, respectively, and COPs with these time settings were 0.44 and 0.50, respectively.

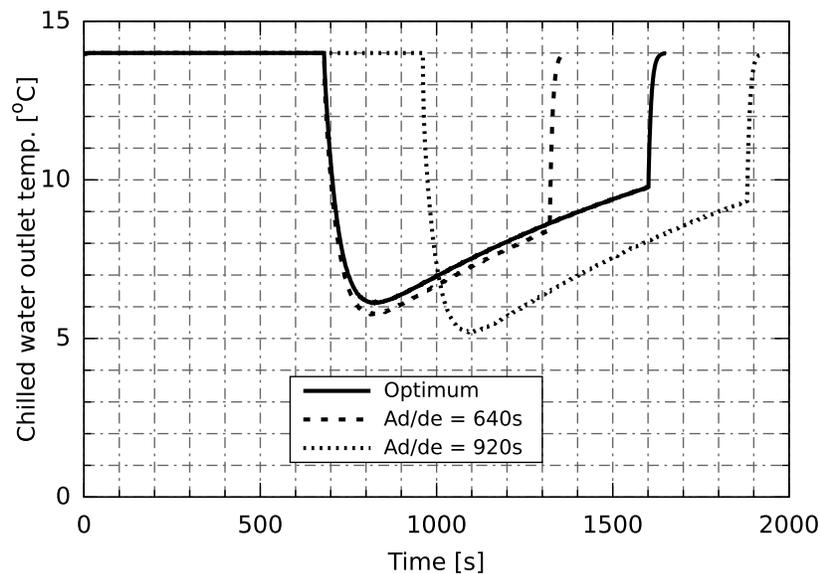


Figure 2: Comparison of chilled water outlet temperature

#### 4. CONCLUSIONS

A one-bed configuration of adsorption cooling system was investigated with simulation. Adsorption isotherm and adsorption kinetic data for activated carbon powder-ethanol pair were used in the analysis. The time settings of four processes of adsorption cycle, namely, adsorption, pre-heating, desorption, and pre-cooling processes, were optimized to achieve maximum specific cooling power. The results showed that the time length of adsorption process should be longer than that of the desorption process for the maximum SCP. The SCP of 140 W/kg with COP of 0.48 was predicted by simulation with the temperature conditions of 80°C for hot water, 30°C for cooling water, and 14°C for chilled water.

#### NOMENCLATURE

$c$	specific heat	[J/(kg·K)]
$D_0$	pre-exponential constant	[m <sup>2</sup> /s]
$D_p$	intra particle diffusion coefficient	[m <sup>2</sup> /s]
$E$	characteristic energy	[J/mol]
$E_a$	activation energy of adsorption	[J/mol]
$L_r$	evaporation heat of refrigerant	[J/kg]
$m$	mass flow rate	[kg/s]

$P$	pressure	[Pa]
$P_0$	saturation pressure	[Pa]
$Q_s$	adsorption heat	[J/kg]
$R$	universal gas constant	[J/(mol·K)]
$r$	radius	[m]
$T$	temperature	[K]
$W$	equilibrium adsorption uptake	[kg/kg]
$W_0$	maximum adsorption uptake	[kg/kg]
$w$	adsorption uptake	[kg/kg]

### Greek Symbols

$\epsilon$	heat exchanger effectiveness	[-]
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### Subscript

b	adsorbent bed
c	condenser
e	evaporator
ca	cooling water to adsorber
cc	cooling water to condenser
ch	chilled water
h	hot water
i	inlet
p	adsorbent particle
rl	refrigerant liquid
rv	refrigerant vapor
s	sorption material

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