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PERFORMANCE ANALYSIS OF A SILICA GEL/WATER ADSORPTION CHILLER

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Abstract A conventional silica gel/water adsorption chiller has been analyzed numerically. A novel non-dimensional mathematical model has been presented to analyze the design effect of different components of an adsorption chiller. The design parameters of this system are characterized by the number of transfer unit, NTU, and the inert material alpha number, α of different components of the system. Results show that the number of adsorber transfer unit, NTU_a has the most influential effect on the system performance, which is followed by the evaporator number of transfer unit, NTU_e. It is also observed that coefficient of performance (COP) and non-dimensional specific cooling capacity increase with the increase of NTU_a and NTU_e, but decrease with the increase of inert material alpha number.

Introduction

In order to enhance the utilization of environment friendly energy systems, one of the major concerns is to develop HCFC-free refrigeration/heat pump systems, which utilize waste heat or renewable energy as the driving sources. Adsorption cooling systems are promising for providing a safe alternative to HCFC-base refrigeration devices. From this context, a number of researchers have investigated the possibility of adsorption heat pumping/refrigeration systems driven by waste heat or by renewable energy sources. Among them, the representative examples are: Sakoda and Suzuki (1984), Techarnev and Emerson (1988) for solar cooling, Chua et. al. (1999), Saha et. al. (2000) and Alam et. al. (2001) for waste heat utilization.

Many researchers have investigated the performance analysis of adsorption heat pump/cooling systems on different operating conditions. The design effect of an adsorber has also been studied by Zheng et el. (1995) and Alam et el. (2000a,b). A conventional adsorption heat pump/cooling unit consists of four major components, namely, adsorber, desorber, condenser and evaporator. The system performance may deteriorate seriously if one of the major units of an adsorption cooling system is not designed optimally. All the parametric studies for conventional adsorption chiller up to now have been conducted based on a fixed design, i.e. in dimensional form. To predict the optimum design conditions of the adsorption system, the model should be defined in non-dimensional form. From this context, a non-dimensional simulation model has been presented to investigate the design effect of the different component of an adsorption chiller in the present study.

The primary objective of this study is to analyze the effect of different components' NTU of an adsorption chiller on the system performance (COP and cooling capacity). This article not only provides the fundamental understandings of a conventional adsorption chiller but also gives useful guidelines for determining optimum design and operating conditions of a conventional adsorption chiller.

Mathematical Model

The basic conventional adsorption chiller consists of two pairs of heat exchangers, namely an evaporator, an adsorber, a condenser and a desorber as shown in Fig.1. The working principle of conventional chiller is elsewhere available in the literature of Saha et. al. (1995) and Alam (2001). In the present study, it is assumed that the temperature and pressure are uniform throughout the whole adsorber. It is also assumed that the system has no heat loses to the environment i.e., well insulated. According to these assumptions, the dynamic behavior of heat and mass transfer inside the different components of the adsorption chiller can be written as:

2.1 Energy balance in adsorber/desorber

The energy balance in the silica-gel bed can be written as;

$$\begin{aligned}\frac{d}{dt}\left\{\left(W_s C_s + W_s C_s q + W_{hex} C_{hex}\right) T_b\right\} &= W_s \cdot Q_{st} \cdot \frac{dq}{dt} \\ &+ \delta[\{\gamma(T_b - T_{con}) - (1-\gamma)(T_b - T_{eva})\} \cdot W_s \cdot C_w \cdot \frac{dq}{dt} \\ &+ \gamma\, \dot{m}_{hot} C_w \left(T_{hotin} - T_{hotout}\right) + (1-\gamma)\dot{m}_{cool} C_w \left(T_{coolin} - T_{coolout}\right)\end{aligned} \quad (1)$$

where, δ takes the value 1 or 0 depending whether the valves between the adsorbent beds and condenser/ evaporator are open or not and γ equals to either 1 or 0 depending whether the concerning bed roles as desorber or adsorber. The outlet temperature of hot water and coolant can be expressed as;

$$T_{w,out} = T_b + \left(T_{w,in} - T_b\right)\cdot \exp\left(-\frac{U_{hex} A_{hex}}{\dot{m}_w C_w}\right) \qquad (2)$$

2.2 Energy balance in condenser/evaporator

The condenser/evaporator heat exchanger energy balance equation can be written as;

$$\begin{aligned}\frac{d}{dt}\left\{\left(W_{ref,hex}C_{ref,hex} + W_{w,ref}C_w\right)T_{ref}\right\} &= \xi\{-L\cdot W_s \frac{dq_{ad}}{dt} \\ &+ W_sC_s(T_{con/eva} - T_{eva/con}) - W_sC_w(T_{ad} - T_{ref})\frac{dq_{ad}}{dt}\} \\ &+ \dot{m}_{con}C_w(T_{con,in} - T_{con,out})\end{aligned} \qquad (3)$$

where, $\xi=1$ or 0 depending whether the desorber/adsorber is connected with condenser/evaporator or not. The heat transfer fluid (cooling/chilled water) heat balance equation can be written as;

$$T_{ref,out} = T_{ref} + \left(T_{ref,in} - T_b\right)\exp\left(-\frac{U_{ref} A_{ref}}{\dot{m}_{ref} C_{ref}}\right) \qquad (4)$$

2.3 Adsorption equilibrium

The adsorption equilibrium for silica-gel/water vapor can be expressed by the following correlation;

$$q = A(T_s)\left(P_{sat}(T_v)/P_{sat}(T_s)\right)^{B(T_s)} \qquad (5)$$

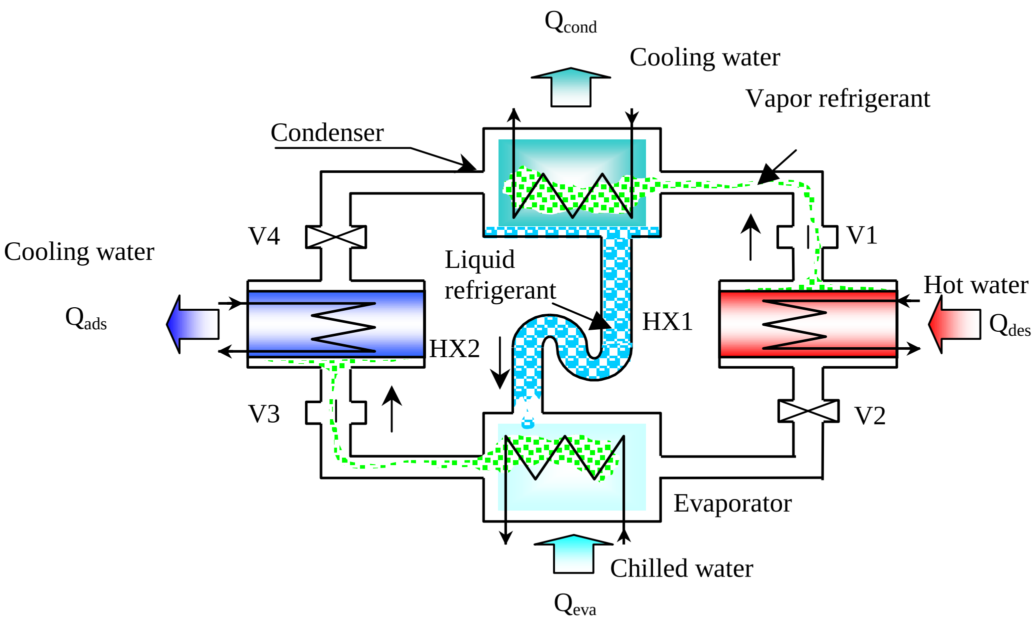

Fig.1. Schematic diagram of the basic adsorption chiller.

where, $A(T_s)$ and $B(T_s)$ are the function of silica gel temperature as discussed by Saha et al. (1995).

2.4 Normalization

The set of equations (1)—(4) has been normalized by introducing following transformations,

$$\theta = \frac{T - T_{cool}}{T_{hot} - T_{cool}}, \quad \tau = \frac{t}{t_{cycle}} \text{ and } \bar{q} = \frac{q}{q_{\max}} \qquad (6)$$

In the non-dimensional form, the energy balance equation for adsorber/desorber can be expressed as;

$$\begin{aligned}&\left(1 + \alpha_{r-s}\bar{q} + \alpha_{b,m-s}\right)\omega\frac{d\theta_b}{d\tau} = \omega\beta\frac{d\bar{q}}{d\tau} + \delta\omega[\{\gamma\left(\theta_b - \theta_{con}\right) \\ &- (1-\gamma)(\theta_b - \theta_{eva})\}\alpha_{r-s}\frac{d\bar{q}}{d\tau}] + \gamma\left(1-\theta_b\right)\left(1 - \exp\left(-NTU_a\right)\right) \\ &- Mr_{hot-cool}\cdot(1-\gamma)\theta_b\left(1 - \exp(-NTU_a / Mr_{cool-hot})\right)\end{aligned} \qquad (7)$$

In the similar way, the energy balance for condenser and evaporator can be rewritten as,

$$\begin{aligned}&\left(\alpha_{r-s}\mu + \alpha_{ref,m-s}\right)\omega\frac{d\theta_{ref}}{d\tau} = \zeta[\{\left(\theta_{ad} - \theta_{ref}\right)\cdot\frac{d\bar{q}_a}{d\tau} \\ &- \lambda\frac{d\bar{q}_a}{d\tau}]\omega + Mr_{chill-hot}\left(\theta_{chillin} - \theta_{eva}\right)\left(1 - \exp\left(-NTU_e\right)\right)\end{aligned} \qquad (8)$$

The non-dimensional parameters used in this analysis are defined and presented in Table 1.

2.5 System performance equations

In terms of dimensionless parameters, the COP can be written as;

$$COP = \frac{Q_{eva}}{Q_{in}} = Mr_{chill-hot}\frac{\int_0^1(\theta_{chillin} - \theta_{chillout})d\tau}{\int_0^1(1-\theta_{hotout})d\tau} \qquad (9)$$

and the non-dimensional cooling capacity can be expressed as:

Table 1. List of Non-Dimensional Parameters and Their Definitions.

Non-dimensional parameters	Mathematical expressions	Definitions
Mass flow ratio	$Mr_{ref-hot} = \frac{\dot{m}_{ref}}{\dot{m}_{hotw}}$	Ratio between mass flow of the reference heat exchanger and hot water mass flow.
Number of transfer unit	$NTU_{ref} = \frac{U_{ref} A_{ref}}{\dot{m}_{ref} C_w}$	Ratio of the overall heat transfer coefficient of the reference heat exchanger to the advection of energy in the fluid.
Inert material alpha number	$\alpha_{ref,m-s} = \frac{W_{ref,hex} C_{ref,hex}}{W_s C_s}$	Heat capacitance ratio of the inert mass in a reference heat exchanger to the dry adsorbent mass.
Refrigerant alpha number	$\alpha_{r-s} = \frac{C_r}{C_s} q_{\max}$	Specific heat capacitance ratio of the refrigerant to the adsorbent material.
Adsorbent beta number	$\beta = \frac{Q_{st} q_{\max}}{C_s (T_{hot} - T_{cool})}$	Heat ratio of the adsorption process to the required heat of adsorbent material to change its temperature from T_{cool} to T_{hot}.
Lambda number	$\lambda = \frac{L}{Q_{st}}$	Ratio of the latent heat evaporation to adsorption heat.
Refrigerant mu no.	$\mu = \frac{W_{evaw}}{W_s}$	Ratio of the refrigerant mass in evaporator to the dry adsorbent mass.
Switching frequency	$\omega = \frac{W_s C_s}{\dot{m}_{hotw} C_w t_{cycle}} = \frac{t_r}{t_{cycle}}$	Ratio of the required time to take the heat capacitance of adsorbent material by the heat transfer fluid to the switching time, t_{cycle}.

$$\text{NCC} = Mr_{chill-hot} \int_0^1 (\theta_{chillin} - \theta_{chillout}) d\tau \qquad (10)$$

while, NCC is defined as,

$$\text{NCC} = \frac{\text{cooling capacity}}{\dot{m}_{hot} C_w (T_{hot} - T_{cool})} \qquad (11)$$

3. Results and Discussion

The system of non-dimensional differential equations (7)-(8) has been solved numerically by finite difference approximation. The four thermodynamic steps were taken into consideration in the solution process. Two solution strategies have been employed during solution process, namely, the pressurization/depressurization process and the constant pressure process. During the pressurization/depressurization process, the mass transfer into the system is assumed to be constant, i.e., no vapor mass is allowed to enter/leave the system. The bed pressure can be calculated by checking the mass balance in the bed. The results obtained by the present simulation model compared well with experimental data of Saha et. al. (1995). A comparison of predicted and experimental outlet temperatures is shown in Fig. 2. The input data of temperature in the simulation procedure is taken as the average conditions of experiment as, T_{hotin}=85.2, T_{coolin}=30.1, $T_{chillin}$=13.9 and t_{cycle} taken 450s. Other values of non-dimensional parameters are calculated from the corresponding dimensional values of Saha et. al. (1995). From Fig. 2, it can be observed that the data from the present simulation model agree well with the experimental results. During the parametric investigation, desired parameter has been varied from a fixed value to a certain label until COP and NCC reach their asymptotic values. The base run parameters are furnished in Table 2. The effect of some most influential non-dimensional parameters on COP and NCC has been discussed in the following subsections.

The number of transfer unit, NTU is one of the most important design parameters of a heat exchanger. There are four heat exchangers in a conventional adsorption chiller, namely, adsorber, desorber, condenser and evaporator. In this subsection, the effect of adsorber/desorber NTU on COP and NCC has been discussed. In the present model, it is assumed that NTU of adsorber or desorber is identical. This is valid because, the heat transfer coefficient of adsorber and desorber can make identical by adjusting the flow rates of hot and cooling water. According to Saha et al. (1995), the heat transfer coefficients of adsorber and desorber are nearly same. Converting these values of heat transfer coefficient into NTU, the author of this study found that the adsorber/desorber NTU values are almost identical.

The effect of adsorber number of transfer unit, NTU_a on COP and NCC is depicted in Fig. 3. Both COP and NCC increase as NTU_a increases. It is well known that the higher the NTU is the better heat transport inside the adsorber reactor, which results in better performance. It may also be seen that the improvement of both COP and NCC values are marginal if NTUa is greater than 2. Therefore, the optimum value of NTUa is considered as 2.0 for the base run condition.

In an adsorbent bed heat exchanger, some materials e.g. aluminum and/or copper are used to separate the heat transfer fluid from adsorbent and to extend the heat transfer surfaces (e.g. fins). These materials are known as the inert material as they do not adsorb or desorb refrigerant vapor. In this study, these inert materials are characterized by a non-dimensional parameter, namely, inert material alpha number, α_{m-a} that is defined as the heat capacitance ratio of the inert mass to the adsorbent mass. The effects of adsorber/desorber and evaporator inert material alpha number on COP are depicted in Fig. 5.

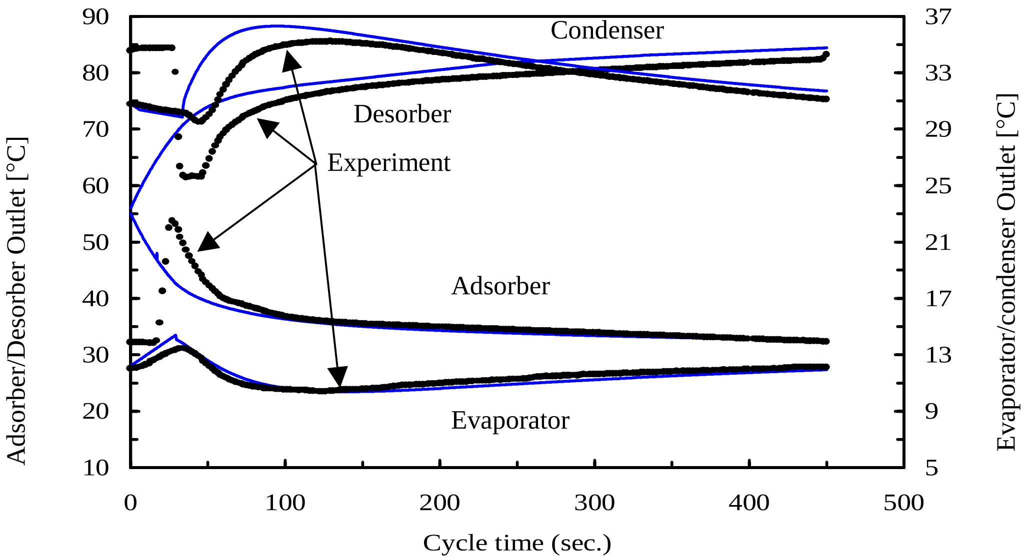

Fig. 2. Outlet temperature profiles of different components.

Table 2. Base Run Parameters.

$Mr_{cool-hot}$=1.23	$\alpha_{b,m-s}$=1.87
$Mr_{con-hot}$=1.0	$\alpha_{con,m-s}$=0.23
$Mr_{chill-hot}$=0.5	$\alpha_{eva,m-s}$=0.12
NTUa=2.0	Q_{st} = 2800 kJ/kg
NTUc=1.0	L = 2500 kJ/kg
NTUe=2.0	q_{max} = 0.34 kg/kg

Evaporator number of transfer unit, NTUe is defined as the ratio of heat transfer at the interface of chilled water/tube to the advection of energy in chilled water. Figure 4 depicts the influence of evaporator number of transfer unit, NTUe on COP and NCC. Increasing NTUe is equivalent to increase in convective heat transfer between the chilled water and tube wall relative to energy supplied by the input chilled water, that result in higher cooling output and better performance. It is also seen that increasing NTUe is no longer valuable when NTUe is greater than 2.0. Therefore, the optimum value of NTUe for the base run case has been taken as 2.0.

It can be seen that COP improves with the decrease of $\alpha_{a,m-a}$. The reason is that the more inert material is added to the adsorber/desorber, the more energy is needed to heat or cool the structure, which is responsible for lowering system performance. It may also be seen that an increase in evaporator inert

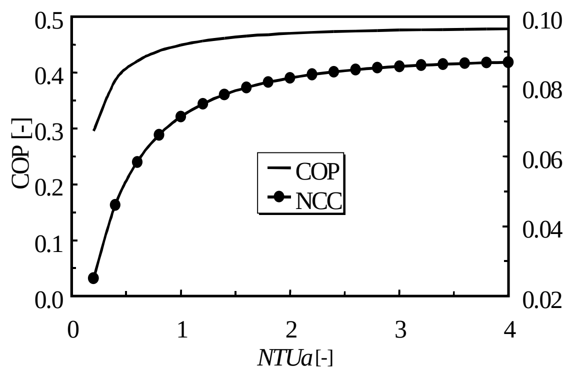

Fig. 3. Effect of adsorber number of transfer unit, *NTUa* on COP and NCC.

material alpha number, $\alpha_{e,m-a}$ leads to the decrease in

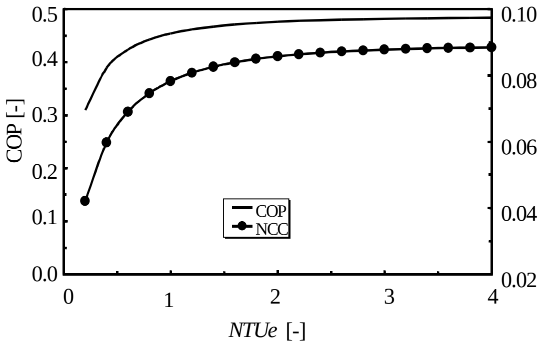

Fig. 4. Effect of evaporator number of transfer unit, NTUe on COP and NCC.

system performance, but this effect is negligible. Therefore, it may be concluded that the amount of inert mass should be minimized to achieve maximum performance.

CONCLUSIONS

A new simulation model has been presented to investigate the performance of a conventional adsorption chiller. The simulation model data show good agreement with the experimental results. The following conclusions can be drawn from the present parametric study;

(i) Both COP and NCC are sensitive to the adsorber/desorber number of transfer unit, NTUa that is followed by the evaporator number of transfer unit, *NTUe*. Condenser number of transfer unit, *NTUc* has less influence on both COP and NCC.

(ii) Among the inert mass of different heat exchanger, the inert mass in adsorber/desorber has the strongest effect. System performances improve with the reduction of inert material in the adsorber/desorber heat exchangers.

(iii) The overall performance of a conventional adsorption chiller can be improved by optimizing the design and operating parameters. The optimum values of the different *NTU* for the base run case

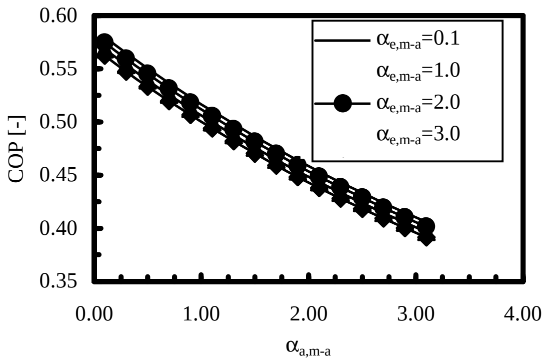

Fig. 5. Effect of inert material alpha number on COP.

are;

NTUa=NTUe=2.0, NTUc=1.0

(iv) The present model depicts dynamic behavior of heat and mass transfer of the adsorption refrigeration system well and this model can be utilized to determine the optimum design conditions of a real adsorption chiller. Further study on adsorber/desorber heat exchanger design in different configuration is needed to find the effect of heat exchanger design on the system performance of an adsorption heat pump/ refrigeration systems.

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NOMENCLATURE

A	: area [m^{2}]
C	: specific heat [kJ/(kg.K)]
CC	: cooling capacity [kW]
COP	: coefficient of peformance [-]
L	: latent heat of vaporization [kJ/kg]
$\dot{m}$	: mass flow [kg/sec.]
Mr	: mass flow ratio [-]
NCC	: non-dimensional cooling capacity [-]
NTU	: number of transfer unit [-]
P	: pressure [kPa]
Q	: heat transfer [kJ]
Q	: concentration [kg/kg]
Q_{st}	:heat of adsorption [kJ/kg]
T	:temperature [K]
t	:time [sec.]
U	:heat transfer coefficient [kW/(m^2.K)]
W	:weight [kg]

Greek letters,

$\alpha_{b,m-a}$	:bed inert material alpha no. [-]
$\alpha_{con,m-a}$	:condenser inert material alpha no. [-]
$\alpha_{eva,m-a}$	:evap. inert material alpha no. [-]
α_{r-a}	: refrigerant alpha no. [-]
β	:adsorbent beta no. [-]
δ	:flag which governs con./eva. transients [-]
γ	:flag which governs silica-gel bed transients [-]
λ	:refrigerant lambda no. [-]
μ	:refrigerant mu no. [-]
θ	:non-dimensional temperature [-]
τ	:non-dimensional time [-]
ω	:switching frequency [-]
ξ	:flag which governs cond. transients [-]
ζ	:flag which governs eva. transients [-]

Subscript

A	: adsorber, adsorption
B	: silica gel bed
con	: condenser
cool	: cooling water
d	: desorber, desorption
eva	: evaporator
hex	: heat exchanger
hot	: hot water
in	: inlet
out	: outlet
r	: refrigerant
s	: silica gel
sat	: saturation
v	: vapor
w	: water