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NUMERICAL STUDY OF AN ADVANCED ADSORPTION CHILLER WITH DIFFERENT MASS ALLOCATION - EFFECT OF COOLING SOURCE

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Abstract

The performance of three-stage chiller with different mass allocation among upper, middle and bottom beds has been investigated numerically to determine the influence of the cooling source temperature on cooling capacity, COP, and chilled water outlet temperature. It is found that the chiller can be driven effectively by the waste heat of temperature 50°C with the heat sink at environment temperature (22-40^{o}C). Results show that cooling capacity can be improved with the optimum allocation of adsorbent mass to the bottom beds than that to the upper two beds. The improvement in Coefficient of Performance (COP) values, however, is less significant. It is also seen that the improvement in cooling capacity is more significant for the relatively lower cooling source temperature.

Keywords: Adsorption chiller, Three-stage, Re-heat scheme, Silica gel, Water

1. Introduction

To provide thermal comfort, air-conditioning (heating or cooling) is required in large areas of the world. The increased use of these technologies consumes energy [1] and is responsible for the emission of greenhouse gases which have ozone depletion potential [2-4]. It is vital to cut the primary energy consumption and launch renewable energy for sustainable development of global energy. A reliable, low cost, high efficiency thermally-driven heat pump for residential and commercial heating and cooling has been the focus of considerable international research for many years. To achieve this objective, the use of waste heat or renewable energy should be increased in energy conversion processes especially in cooling process. Heat driven sorption (adsorption/ desorption) cycle is one of the promising candidates to utilize waste heat at near environment temperature by Kashiwagi et al. [5]. So that waste heat below 100^{0}C can be recovered, which is highly desirable. Three stage adsorption chiller with silica gel-water pair as adsorbent/ adsorbate is considered that can use low temperature heat source (50-70^{o}C) with a near environmental temperature heat sinks (22-40^{o}C).

In this study, silica gel–water has been selected as the adsorbent/ refrigerant pair because of the low regeneration temperature of silica gel and the high latent heat of vaporization of water.

Additionally, this working pair is non-toxic. The present research investigates with the utilization of unexploited, near ambient temperature waste heat between 50 and 70°C as the driving heat source with a cooling source at (22-40°C). The influences of heat transfer fluid temperature on cooling capacity, COP and chilled water outlet temperature are determined by a cycle simulation computer program. Performances are also compared with that of the conventional three-stage chiller. In the present treatment, the performances of the proposed chiller which operational strategy is shown in Table 1.

2. Working Principle of Three-Stage Chiller

Most of the advanced cycles in adsoprion refrigeration/ heat pump are proposed to achieve high COP (Coefficient Of Performance) and/ or SCP (Specific Cooling Power) values. Few cycles, however, are proposed to utilize relatively low temperature waste heat. Multi-stage advanced adsoprtion cycle is the cycle that can use low temperature (45~60°C) heat source with near environmental temperature heat sinks (30°C). If chilled water at 7°C is to be obtained with conventional adsorbent-refrigerant pair such as silica gel-water, a conventional single stage cycle will not be operational with such a low temperature waste heat. The reason is that the regenerating temperature lift of 15~30K is too small for an evaporating temperature lift of 23K to be spanned by raising the pressure in one single stage. In order to overcome the technical difficulty intrinsic in operating a refrigeration cycle, with such a small regenerating temperature lift, a three stage adsorption cycle is proposed and designed by Boelman and Kashiwagi [6]. The chiller produced 1kW of cooling (chilled water at 12°C in, 7°C out), with a 5 minute adsorption/desorption cycle. The COP of 0.17 is reported. In the three stage advanced cycle, the regenerating temperature lift of the adsorbent can be small because the refrigerant evaporating temperature (or pressure) lift is split into three smaller temperature lifts (Fig. 2). Pressure thus rises into three progressive steps from evaporation to condensation level; to achieve this, the introduction of two additional pairs of sorbent beds is necessary (Fig.2). Although the operating pressure levels are different, adsorption/ desorption temperatures are kept equal for the three beds. Hence, each of three pairs of beds must be cooled and heated in parallel, which in principle triplicates the heat input required to drive the chiller. The increased need for driving heat input, however, is less pronounced for temperatures such as 50°C heat source with 30°C heat sink, since the heat losses inherent in batched cycle operation decrease with smaller temperature lifts Boelman and Kashiwagi [6]. To describe the cycle of the system, it is assumed that *Hex*2, *Hex*4 and *Hex*6 are in cooling position at temperature T_c while *Hex*1, *Hex*3 and *Hex*5 are in heating position at temperature T_h. At the beginning of the cycle all valves are closed. The desorbers (*Hex*2, *Hex*4 and *Hex*6) are heated by hot water while absorbers (*Hex*1, *Hex*3 and *Hex*5) are cooled by cooling water. During a short intermediate process (30s for this system) no adsorption/ desorption occurs.

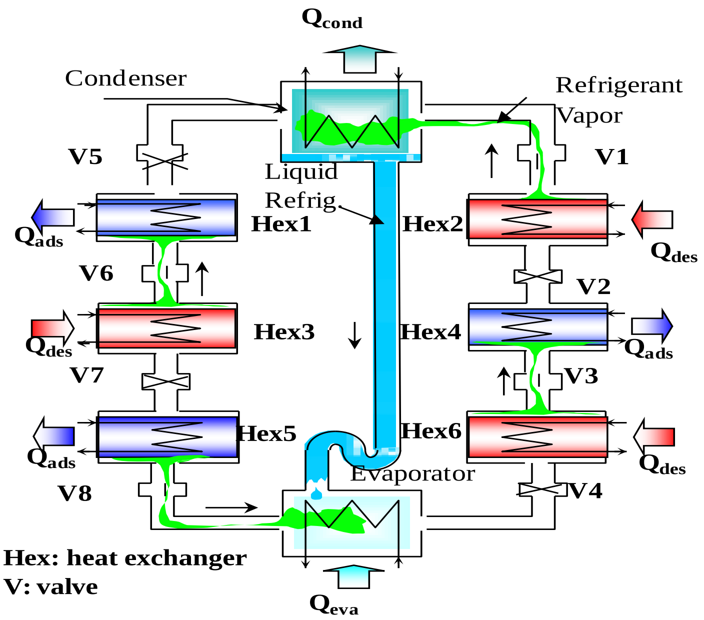
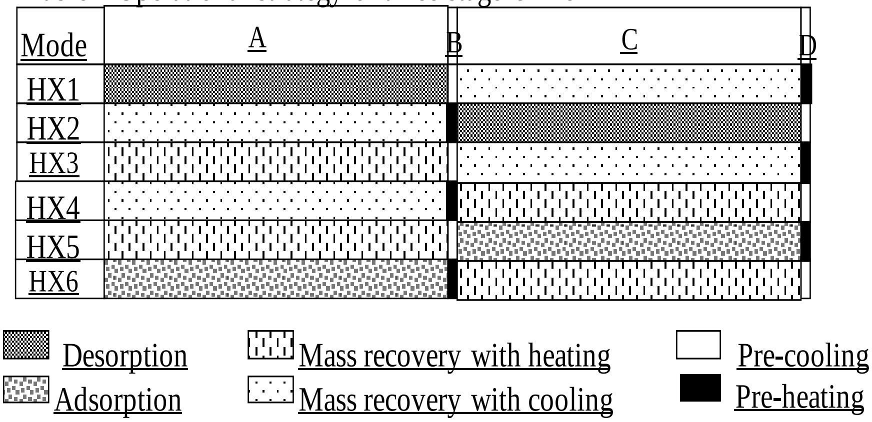


Fig. 1 Schematic diagram of the three-stage adsorption chiller.

After this short period, valves 2, 4, 5 and 7 are opened to allow refrigerant to flow from *Hex*2 to *Hex*1, from evaporator to *Hex*3, *Hex*4 to condenser, *Hex*6 to *Hex*5. When refrigerant concentrations in the adsorbers and desorbers are at near their equilibrium level, the flows of hot and cooling water are redirected by switching the valves so that the desorber can change it mode into adsorber and adsorber into desorber. The adsorption/desorption process can be continued by changing the direction of hot and cooling water flow. The standard operational strategy of three stage chiller is shown in Table 1 and standard operating condition is shown in Table 2.

Table 1 Operational strategy of three stage chiller



Mode	A	B	C	D
HX1	▓	□	░	■
HX2	░	■	▓	□
HX3	▥	□	░	■
HX4	░	■	▥	□
HX5	▥	□	▒	■
HX6	▒	■	▥	□

▓ Desorption
▒ Adsorption
▥ Mass recovery with heating
░ Mass recovery with cooling
□ Pre-cooling
■ Pre-heating

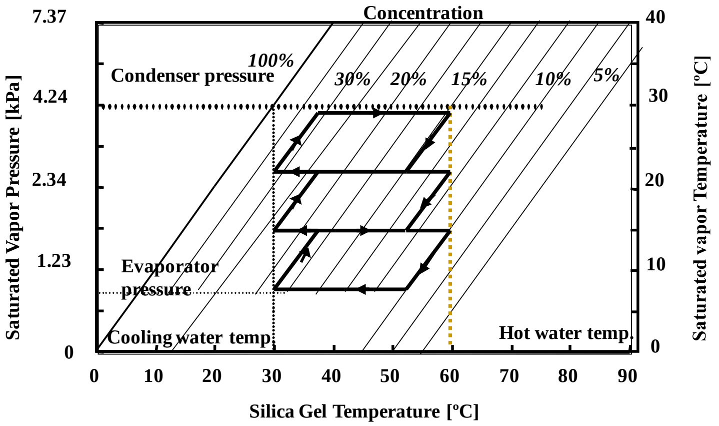


Fig.2 Conceptual P-T-X diagram of three stage adsorption chiller

3. Mathematical Formalsm

The heat transfer and energy balance equations for the adsorbent beds can be described as follows:

$$T_{out} = T + (T_{in} - T)\exp\left(-\frac{UA_{hex}}{\dot{m}_w c_w}\right) \tag{1}$$

$$\begin{aligned} &\frac{d}{dt}\left\{\left(W_s C_s + W_s C_w q + W_{hex} C_{hex}\right) T\right\} = \\ &W_s Q_{st}\frac{dq}{dt} - \delta . W_s C_w \begin{Bmatrix} \gamma\left(T - T_{eva}\right) + \\ \left(1-\gamma\right)\left(T - T_{wv}\right) \end{Bmatrix} \frac{dq}{dt} + \\ &\dot{m}_w C_w \left(T_{in} - T_{out}\right) \end{aligned} \tag{2}$$

Where, δ is either 0 or 1 depending whether the adsorbent bed is working as a desorber or an adsorber and γ is either 1 or 0 depending on whether the adsorbent bed is connected with the evaporator or another adsorbent bed. The heat transfer and energy balance equations for the evaporator can be described as:

$$T_{chill,out} = T_{eva} + (T_{chill,in} - T_{eva})\exp\left(-\frac{UA_{eva}}{\dot{m}_{chill} c_{chill}}\right) \tag{3}$$

$$\frac{d}{dt}\left\{\left(W_{eva,w}C_w + W_{eva,hex}C_{eva,hex}\right)T_{eva}\right\} = -LW_s\frac{dq_{ads}}{dt} - W_sC_w\left(T_{con} - T_{eva}\right)\frac{dq_{des}}{dt} + \dot{m}_{chill}C_{chill}\left(T_{chill,in} - T_{chill,out}\right) \tag{4}$$

The heat transfer and energy balance equations for the condenser can be written as:

$$T_{cond,out} = T_{cond} + (T_{cw,in} - T_{cond})\exp\left(-\frac{UA_{cond}}{\dot{m}_{cw}c_w}\right) \tag{5}$$

$$\frac{d}{dt}\left\{\left(W_{cw,w}C_w + W_{cond,hex}C_{cond,hex}\right)T_{cond}\right\} = -LW_s\frac{dq_{des}}{dt} - W_sC_w\left(T_{des} - T_{cond}\right)\frac{dq_{des}}{dt} + \dot{m}_{cw}C_w\left(T_{cw,in} - T_{cw,out}\right) \tag{6}$$

The mass balance for the refrigerant can be expressed as:

$$\frac{dW_{eva,w}}{dt} = -W_s\left(\frac{dq_{des-cond}}{dt} + \frac{dq_{eva-ads}}{dt}\right) \tag{7}$$

where, the subscripts *des*-*cond* and *eva*-*ads* stand for the refrigerant vapor flow from desorber to condenser and evaporator to adsorber, respectively. The silica gel/ water property model is similar to the model used by Khan et al. [7]. The adsorption equilibrium equation for silica gel/water pair is taken as:

$$q^* = \{0.8\times[P_s(T_w)/\ P_s(T_s)]\}/\{1+0.5\times[P_s(T_w)/\ P_s(T_s)]\}$$

4. System Performance Measurement

The cooling capacity and COP of the three-stage adsorption chiller can be described as:
Cooling Capacity

$$= \dot{m}_{chill}C_w\int_0^{t_{cycle}}\left(T_{chill,in} - T_{chill,out}\right)dt\bigg/t_{cycle}$$

$$\text{COP} = \frac{\dot{m}_{chill} C_w \int_0^{t_{cycle}} \left(T_{chill,in} - T_{chill,out}\right) dt}{\dot{m}_{hot} C_w \int_0^{t_{cycle}} \left(T_{hot,in} - T_{hot,out}\right) dt}$$

Table 2: Standard operating condition

	Temperature (°C)	Flow rate (kg/s)
Hot water	60	0.4
Cooling water	30	0.4(ads)+0.34(cond)
Chilled water	14	0.11
Cycle time	810ads/des, 600mr, 30ph/pc	

Ads/des = adsorption/desorption, mr = mass recovery, ph/pc = pre-heat/pre-cool

5. Results and Discussions

Three-stage adsorption chiller is designed to utilize the low temperature thermal heat from the industries or from renewable energy sources. The simulation techniques are applied to determine the effect of driving cooling source temperature on chiller performance and the results are also compared with those of the conventional three-stage chiller. Cycle time is an important parameters for the scheme. Due to fixed design of the chiller, all design parameters for each adsorbent bed are considered equal.

Driving Cooling Source Temperature Effect on Cooling Capacity:

Fig. 3 shows the effect of cooling water inlet temperatures on cooling capacity. The cooling capacity increases steadily as the cooling water inlet temperature is lowered from 40°C to 22°C. This is due to the fact that lower adsorption temperatures result in larger amounts of refrigerant being adsorbed and desorbed during each cycle. For the proposed three stage chiller using optimum mass allocation, the cooling capacity and COP value reach 4.1728kW and 0.2305 respectively, with 55°C driving source temperature in combination with a coolant temperature of 22°C.

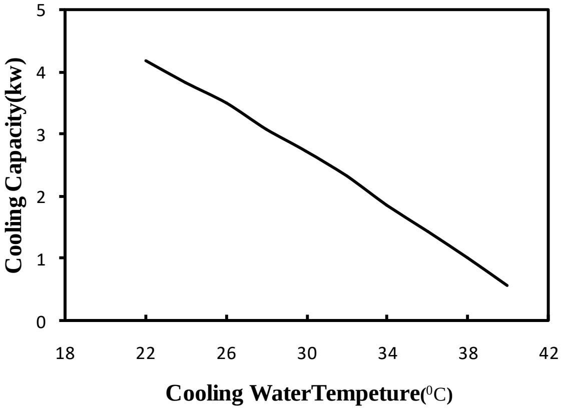


Fig. 3: Effect of cooling source temperature on cooling capacity

Driving Cooling Source Temperature Effect on COP:

The effect of different mass allocation ratios of the beds (upper : middle : Lower) and varying cooling source temperature on COP are illustrated in Fig. 4. The simulated COP values also increase with lower cooling water inlet temperature. It can be seen that the improvement in COP with addition of more silica gel in lower beds is significant. It is seen that the optimum condition (12 : 16: 20 ratios), provides better COP value for low heat source temperature below 65°C, however, it provides slightly lower COP values for relatively high heat source temperature (above 65°C). Therefore, it may be claimed that in terms of COP, the three-stage is not beneficial. It is already mentioned that the proposed chiller is designed for low temperature waste heat source.

Due to the nature of waste heat, the COP of the machine is not important, only the output, for the present case cooling capacity is important. Therefore, if a three-stage machine is designed with (12 : 16 : 20) = (upper :middle: bottom) ratios, the chiller can provide better cooling capacity even the cooling source temperature decreases from 40°C to 22°C.

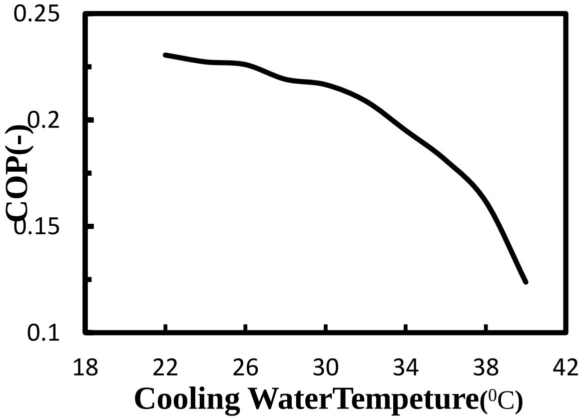


Fig. 4: Effect of cooling source temperature on COP

Driving Cooling Source Temperature Effect on Chilled Water Outlet Temperature:

The effect of cooling water inlet temperatures on average chilled water outlet temperature is presented in Fig. 5. It is observed here that chilled water outlet temperature decreases steadily as the cooling water inlet temperature is lowered from 40°C to 22°C.

In an adsorption chiller, the chilled water for air-condition purposes is obtained from the outlet of the chilled water. Generally, less chilled water outlet temperature is expected, while the requirement of cooling capacity is high. The chilled water outlet temperature, however, affects cooling demand of the demand side. Therefore the requirement of chilled water outlet temperature is very important. From this context, the effect of cooling source temperature as well as mass allocation ratios are presented in Fig.5. It may be seen that the chiller with different level cooling source temperature provides different level chilled water outlet temperature even the other operating conditions are the same. It can be also seen that the higher is the cooling source temperature; the highrer is the chilled water outlet temperature. From the same figure, it is also observed that there is an optimum value of mass ratios (12 : 16 : 20) to achieve lowest temperature chilled water outlet. If a proposed three-stage chiller is designed in optimum condition, i.e. mass ratio at (12 : 16 : 20) = (upper : middle : bottom), the chiller will provide the best cooling capacity as well as also provide low temperature chilled water outlet. Therefore, it could be claimed that adsorption chiller with near 22^{o}C cooling source temperature provides relatively low temperature chilled water, while low evaporating temperature affects the cooling capacity. Therefore, it is desirable to compare cooling capacities in the same evaporating temperature.

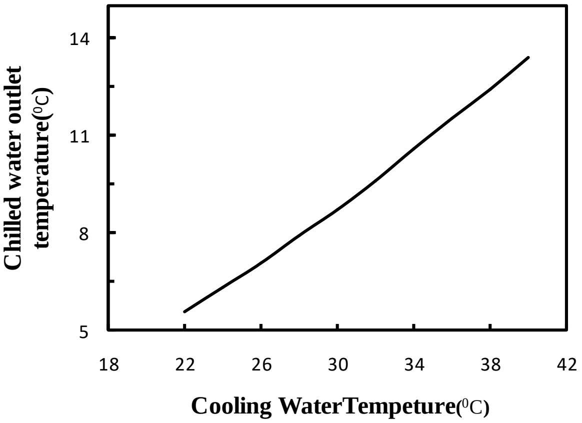


Fig. 5: Effect of cooling source temperature on the calculated average chilled water outlet temperature

6. Conclusions

The performance of a three-stage adsorption chiller with different mass ratios is investigated numerically. A finite difference iterative technique is used in the analysis for the solution procedure. Through analysis, calculations can be drawn as follows by allocating optimum mass ratios (12 : 16 : 20) = (upper : middle : bottom). As the cooling source temperature decreases, Cooling Capacity (CC) and COP increase. However, chilled water outlet is decreased. Comparing with the performance of the study by Saha et al. [8], the cooling capacity has improved by 6% while the cooling water temperature is at 30°C. Finally, it may be concluded that if a three-stage chiller with different mass allocation is designed at (12 : 16 : 20) = (upper : middle : bottom) ratios, the chiller can perform better in terms of cooling capacity than that of conventional three-stage chiller (16 : 16 : 16) = (upper : middle : bottom) even the cooling source temperature is fluctuated between 22°C and 40°C.

Nomenclature

A	area (m^2)
C	specific heat ($Jkg^{-1}K^{-1}$)
L	latent heat of vaporization (Jkg^{-1})
$\dot{m}$	mass flow rate (kgs^{-1})
P_s	saturated vapor pressure (Pa)
q	concentration (kg / kg)
q^*	concentration equilibrium (kg / kg)
Q_{st}	isosteric heat of adsorption (Jkg^{-1})
T	temperature (K)
t	time (s)
U	heat transfer coefficient ($Wm^{-2}K^{-1}$)
W	weight (kg)

Subscripts

ads	adsorber, adsorption
cond	condenser
chill	chilled water
cw	cooling water
des	desorber, desorption
eva	evaporator
Hex(SE)	heat exchanger
hw	hot water
in	inlet
out	outlet
s	silica gel
se	sorption element
w	water
wv	water vapor

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