410 リヒート二段型吸着サイクルの性能シミュレーション

Performance Simulation of Reheat Two-Stage Adsorption Cycle

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There has been a great progress in Adsorption Refrigeration Cycle research. Many researchers have introduced their methods to discover and improve cycle performance. This paper will present a new adsorption cycle known as Reheat Two-Stage, which has been evaluated numerically. The study aims to examine the possibility of improving adsorption cycle performance which uses low temperature heat source and environmentally friendly refrigerant. This paper will describe the cycle working principle and discuss the results obtained from simulations. The cycle performance is analyzed using cooling capacity and coefficient of performance (COP). The results show that cycle performance is extremely sensitive to driving heat source temperature. The results also show that cycle time and mass recovery time are influential factors on performance. This paper will also compare the performance of this cycle with Single-Stage and Two-Stage cycles.

Keywords: Single Stage, Two-Stage, Reheat Two-Stage Adsorption Cycle, mass recovery, cooling capacity, COP.

1. Introduction

In recent years, many researchers have proposed and investigated many kinds of adsorption refrigeration systems. The use of refrigerant, which is environmentally friendly and low temperature heat source, gets more and more attention. The silica gel-water pair is well suited to temperature below 100°C. Saha et al. [1-4] proposed adsorption chiller with silica gel-water pairs, driven by low temperature heat source. They introduced Two-Stage and Three-Stage adsorption systems. The systems are driven by heat source temperature below 60°C. Pons and Poyelle [5] proposed internal mass recovery to achieve relatively high cooling power. Furthermore, Akahtira et al. [3] and Alam et al. [4] showed that mass recovery process in conventional adsorption cycle improves cooling capacity for relatively low heat source temperature. Subsequently, Alam et al. [4] proposed advanced adsorption chiller that enables to exploit heat source temperature between 50-90°C and to produce effective cooling. In this analysis, cooling capacity and COP are used to find out cycle performance and to compare the proposed cycle with other cycles.

2. Working Principle of Reheat Adsorption Cycle

Fig. 1 Conceptual P-T-X Diagram of Reheat Two-Stage Adsorption Cycle

Fig. 2 One Pair Bed Scheme

Reheat Adsorption Cycle is similar to that of Two-Stage Adsorption Chiller. The evaporating pressure lift is divided into two consecutive pressure lifts by introducing four adsorbent beds. It aims to exploit low temperature heat source. Thus, the evaporating pressure (temperature) will be lifted, as shown in Fig. 1.

To explain the working principle of this cycle, suppose a pair of bed namely HEX 1-HEX 2 (Fig. 2) works as adsorber and desorber in turns. At the end of each half-cycle, one bed (HEX 1) is cold and the other one (HEX 2) is hot. Simultaneously, HEX 1 is at low pressure (P_e) and must be pressurized up to the condenser pressure; HEX 2 is at high pressure (P_c) and must be depressurized down to the evaporator pressure. To pressurize and depressurize, vapour is transferred from desorber to adsorber. In conventional mass recovery cycle, this process is known as Mass Recovery Process.

Adsorption/desorption process will occur automatically due to a difference in beds pressure. HEX 1 pressure increases while HEX 2 pressure decreases. Both HEX pressures reach the same point. To provide more cooling capacity, desorber temperature (HEX 2) is still at high temperature or continuing heating process. Refrigerant release is still occurring from HEX 2 to HEX 1. It

causes HEX 2 concentration to decrease (point 7 in Fig. 1).

Afterwards HEX 1 is heated up by hot water and HEX 2 is cooled down by cooling water. During this process, refrigerant circulation is stopped by closing all refrigerant valves. When the pressures of HEX 1 and HEX 2 are nearly equal to the pressures of condenser and evaporator, the valve between HEX 1 and condenser (as well as valve between HEX 2 and evaporator) is opened, allowing the refrigerant to flow. To complete one cycle, the next process is the same as the previous half-cycle. Only, the position of HEX 1 is as desorber and HEX 2 is as adsorber.

As mentioned above, Reheat Two-Stage Adsorption Cycle is similar to that of Two-Stage Cycle. In Two-Stage, however, lower bed never interacts with condenser and upper bed never interacts with evaporator. All beds of the Reheat Cycle go through all processes and interact with condenser and evaporator one by one. To complete one cycle, one HEX passes through six steps: desorption, mass recovery with heating process, pre-cooling, adsorption, mass recovery with cooling process, and pre-heating.

When one pair of HEX is in mass recovery process or in pre-heating/cooling process, cooling capacity of the chiller will decline unless HEX is connected to evaporator. Consequently, another pair of HEX is required to achieve high cooling capacity and continuous cooling effect. Complete scheme of the proposed chiller can be seen in Fig. 3.

In this study, two cases of operational strategy are presented in Table 1. The difference between Case I and Case II is as follows. Case I consists of eight modes (A-H). When a pair of bed (e.g. HEX 1 and HEX 2) is in adsorption-desorption process, another pair of bed (e.g. HEX 3 and HEX 4) is completing mass recovery and pre-heating/cooling process. Case II consists of 10 modes (A-J). When a pair of bed is in adsorption-desorption process, another pair is completing mass recovery and pre-heating/cooling. When it is completed, the pair will undertake adsorption-desorption process simultaneously with the other pair (mode C and mode H). In conclusion, the difference between two cases is that in case II there are two pairs of bed undertaking adsorption-desorption process at the same time.

3. Simulation of Reheat Adsorption Cycle

The mathematical formalism of the cycle has been developed by Alam, et al (2003). The heat transfer and energy balance equations for the beds are follows:

$$T_{out} = T + (T_{in} - T) \exp \left(- \frac{U_{hex} A_{hex}}{\dot{m}_w C_w} \right) \quad (1)$$

$$\begin{aligned} \frac{d}{dt} \{ \dot{W}_s C_s + \dot{W}_s C_w q + \dot{W}_{hex} C_{hex} \} T = & \dot{W}_s Q_{st} \frac{dq}{dt} + \\ & - \delta \dot{W}_s C_s \{ \gamma (T - T_c) + (1 - \gamma) (T - T_e) \} \frac{dq}{dt} + \\ & \dot{m}_w C_w (T_{in} - T_{out}) \end{aligned} \quad (2)$$

Where, δ is either 0 or 1 depends on whether bed is working as desorber or adsorber and γ is either 1 or 0 depends on whether bed is interacting with evaporator or another bed. The energy balance for condenser can be expressed as:

$$T_{cwout} = T_c + (T_{cwin} - T_c) \exp \left(- \frac{U_c A_c}{\dot{m}_{cw} C_w} \right) \quad (3)$$

$$\begin{aligned} \frac{d}{dt} \{ \dot{W}_{cw} C_w + \dot{W}_{c,hex} C_{c,hex} \} T_c = & - L \dot{W}_s \frac{dq_{des}}{dt} \\ & - \dot{W}_s C_w (T_{des} - T_c) \frac{dq_{des}}{dt} + \dot{m}_{cw} C_w (T_{cwin} - T_{cwout}) \end{aligned} \quad (4)$$

Fig. 3 Four-Bed Reheat Adsorption Cycle Scheme

Table 1 Chiller Operational Strategy

Case I

	Mode							
	A	B	C	D	E	F	G	H
1	Desorption	Mass recovery with heating process	Pre-Heating	Adsorption	Mass recovery with cooling process	Pre-Cooling	Desorption	Mass recovery with heating process
2	Pre-Heating	Desorption	Mass recovery with heating process	Pre-Cooling	Adsorption	Mass recovery with cooling process	Pre-Heating	Desorption
3	Desorption	Mass recovery with heating process	Pre-Heating	Adsorption	Mass recovery with cooling process	Pre-Cooling	Desorption	Mass recovery with heating process
4	Pre-Heating	Desorption	Mass recovery with heating process	Pre-Cooling	Adsorption	Mass recovery with cooling process	Pre-Heating	Desorption

Case II

	Mode									
	A	B	C	D	E	F	G	H	I	J
1	Desorption	Mass recovery with heating process	Pre-Heating	Adsorption	Mass recovery with cooling process	Pre-Cooling	Desorption	Mass recovery with heating process	Pre-Heating	Adsorption
2	Pre-Heating	Desorption	Mass recovery with heating process	Pre-Cooling	Adsorption	Mass recovery with cooling process	Pre-Heating	Desorption	Mass recovery with heating process	Pre-Cooling
3	Desorption	Mass recovery with heating process	Pre-Heating	Adsorption	Mass recovery with cooling process	Pre-Cooling	Desorption	Mass recovery with heating process	Pre-Heating	Adsorption
4	Pre-Heating	Desorption	Mass recovery with heating process	Pre-Cooling	Adsorption	Mass recovery with cooling process	Pre-Heating	Desorption	Mass recovery with heating process	Pre-Cooling

1,2,3,4: Heat exchanger

Evaporator heat balance equation is:

$$T_{chill.out} = T_e + (T_{chill.in} - T_e) \exp \left(- \frac{U_e A_e}{\dot{m}_{chill} C_w} \right) \quad (5)$$

$$\begin{aligned} \frac{d}{dt} \{ \dot{W}_{ew} C_w + \dot{W}_{e,hex} C_{e,hex} \} T_e = & - L \dot{W}_s \frac{dq_{ads}}{dt} \\ & - \dot{W}_s C_w (T_c - T_e) \frac{dq_{des}}{dt} + \dot{m}_{chill} C_w (T_{chill.in} - T_{chill.out}) \end{aligned} \quad (6)$$

Performances of the Reheat Adsorption Cycle are examined by the following performance indices:

$$\text{Cooling Capacity} = \frac{\dot{m}_{\text{chill}} C_w \int_0^{t_{\text{cycle}}} (T_{\text{chill,in}} - T_{\text{chill,out}}) dt}{t_{\text{cycle}}} \quad (7)$$

$$\text{COP} = \frac{\dot{m}_{\text{chill}} C_w \int_0^{t_{\text{cycle}}} (T_{\text{chill,in}} - T_{\text{chill,out}}) dt}{\dot{m}_{\text{hot}} C_w \int_0^{t_{\text{cycle}}} (T_{\text{hot,in}} - T_{\text{hot,out}}) dt} \quad (8)$$

The parameters used in the simulation are presented in Table 2:

Table 2 Specification for Adsorber, Condenser and Evaporator

	Adsorber	Desorber	Evaporator	Condenser
Heat Transfer Coeff.	1000 W/m ² .K	750 W/m ² .K	5800 W/m ² .K	3900 W/m ² .K
Area of Heat Transfer Tube	0.061 m ² /kg. adsorbent	0.061 m ² /kg. adsorbent	2 unit x 3 m ²	2 unit x 1 m ²
Heat Capacity	1260 J/K/kg. adsorbent	1260 J/K/kg. adsorbent	260000 J/K	109000 J/K
Inlet Temp	30°C	50-90°C	14°C	30°C
Silica gel mass	16 kg/bed (Total: 16x 6 =96 kg)			

In the simulation, the equations are solved by finite difference approximation technique with time step 1s. In the beginning of the calculation, the initial values are assumed and finally adjusted by iteration process. The convergence criterion is taken as 10⁻³.

4. Results and Discussion

Some simulation results have been simulated numerically based on parametric analyses. Coefficient of Performance value obtained from the Reheat Adsorption Cycle increases as heat source temperature increases. This is caused by the difference between maximum and minimum concentration level. The difference expands as heat source temperature increases. Thus, greater amount of refrigerant will be adsorbed and desorbed. In other words, cooling capacity as well as COP (Fig. 4, 5) will improve if heat source temperature increases.

The result from Case I are interpreted in Fig. 4 and Fig. 5. These figures show that cycle time setting in an adsorption cycle is a performance influencing factor. Longer cycle time will provide better cooling capacity compared to shorter cycle time for relatively low heat source temperature. If the chiller is operated at relatively high heat source temperature, shorter cycle time will result in better cooling capacity than longer cycle time. However, there is an optimum cycle time for every heat source temperature which produces better cooling capacity. According Fig. 4, to get a better cooling capacity, cycle time above 3000 s should be chosen if heat source temperature is below 70°C; cycle time between 2000-3000s for interval heat source temperature 70-80°C, and cycle time between 1000-2000s for heat source temperature between 80-90°C.

Fig. 4 The Effect of Cycle Time on Cooling Capacity

Fig. 5 The Effect of Cycle Time on COP

Fig. 6 The Effect of Mass Recovery Time on Performance

In the P-T-X diagram (Fig. 1), it can be seen that concentration level at low heat source temperature changes rapidly as refrigerant saturation vapor pressure changes. Nevertheless, it changes slowly at relatively high heat source temperature. If the chiller is operated at long cycle time and at low heat source temperature, longer mass recovery time will be used effectively to transfer refrigerant vapor from adsorber to desorber. In other words, longer mass recovery process time for low heat source temperature is needed (than for relatively high heat source temperature) to adsorp/desorp refrigerant vapor from adsorbent bed. Consequently, cooling capacity will increase effectively. As previously mentioned, mass recovery process improves cooling capacity. Yet, it needs more desorption heat. Therefore, more heating is required to keep the desorber temperature at its highest level. If the chiller is operated at short cycle time, heat input to the bed is relatively higher than cooling output, causes low COP. It is well known that long cycle time always provides better COP value as described in Fig. 5.

Time setting influences performance. If pre-heating/cooling time is fixed, the adsorption-desorption time and mass recovery time are influential factors on performance. In this study, there are two modes of refrigerant valves arrangement, as described in

Fig. 7. Cooling Capacity Comparison among Reheat Adsorption Cycle, Single Stage and Two-Stage

Table 1. In case I, mass recovery time depends on fixed adsorption-desorption time. In case II, mass recovery time can be customized to find the best combination between mass recovery and adsorption-desorption time in a cycle. If mass recovery time is longer, the adsorption-desorption time will be shorter, vice versa. Fig. 6 shows the influence of mass recovery process time on performance. With fixed heat source temperature (70°C), fixed cycle time (2000s), and fixed average chilled out temperature (7°C), cooling capacity increases until certain point where the increase is relatively stable. It has been discussed before that the mass recovery process in the cycle generates more desorption heat, transferred from the desorber through desorbed vapor. As a result, COP decreases as mass recovery time increases. Fig. 6 also shows that an optimum mass recovery time can be chosen depends on cooling capacity and COP requirements.

The reheat cycle is proposed to obtain better performance than that of Single Stage and Two-Stage. Fig. 7 and Fig. 8 show performances comparison among Reheat Cycle, Single Stage and Two-Stage. According to these figures, cycle time is sensitive to heat source temperature. In this analysis, short cycle time is fixed at 1000s (including mass recovery time at 100s) while long cycle time is fixed at 5000s (including mass recovery time 1000s).

Cooling capacity obtained from the reheat adsorption cycle with long cycle time is better than that of single stage if heat source temperature is below 70°C (Fig. 7). However, short cycle time is required if heat source temperature is relatively high. Figure 7 also shows that cooling capacity with long cycle time provides almost the same cooling capacity provided by two-stage cycle. Nonetheless, COP value of reheat adsorption cycle with long cycle time is better than that of two-stage cycle. Single Stage COP is superior to Two-Stage and Reheat Two-Stage COP. Yet, if the chiller is designed for waste heat utilization, COP value is less crucial than cooling capacity. Moreover, Single Stage is difficult to produce low-chilled outlet at low heat source temperature.

5. Conclusions

The simulation program can be used to predict Reheat Adsorption Cycle performance. The simulation result shows that COP increases as heat source temperature and cycle time increase. For cooling capacity, the longer cycle time required for low heat source temperature, the better cooling capacity. The opposite mechanism applies to high heat source temperature. Nevertheless, the cooling capacity increases as heat source temperature increases.

The Reheat Two-Stage Cycle provides better cooling capacity than that of Single Stage and almost the same that of Two-Stage, even though the heat sources temperature fluctuates in the range of 50-90°C. However, longer cycle time is required for low heat source temperature (below 70°C) and short cycle time is required for relatively high heat source temperature.

Fig. 8. COP Comparison among Reheat Adsorption Cycle, Single Stage and Two-Stage

Nomenclature

A	: Area, [m ²]
C_p	: Specific heat, [kJ/kg.K]
$\dot{m}$	: Mass flow rate, [kg/s]
Q_{st}	: Heat of adsorption, [kJ/kg]
Q	: Concentration, [kg refrigerant/kg adsorbent]
T	: Temperature, [K]
t	: Time, [s]
U	: Heat transfer coefficient, [Kj/(m ² .K)]
W	: Weight, [kg]
Subscripts	
Ads	: Adsorption
c	: Condenser
$chill$	: Chilled water
des	: Desorber
e	: Evaporator
hex	: Heat exchanger
in	: inlet
out	: outlet
s	: silica gel
v	: vapour
w	: water

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