DEVELOPMENT OF HYBRID-TYPE ADSORPTION HEAT PUMP ADDING ELECTRICALLY OPERATED PUMP

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ABSTRACT

In Japan, a tremendous amount of heat energy below 373 K is discharged into atmosphere as waste heat, and it accounts for about 80 % of heat loss. Advanced utilization of such low temperature heat energy leads to establishment of a highly-efficient energy utilization system.

Adsorption heat pump (AHP) is very attractive technology for achieving the objective, because it can generate cold heat energy below 283 K for air conditioning by utilizing the low temperature heat energy as regeneration heat source of an adsorbent. However, heat output and COP of the conventional thermally-operated AHP decrease significantly as regeneration temperature.

We have proposed a hybrid type AHP aiding electrically-operated suction pump. In the proposed AHP, a mechanical booster pump (MBP) is incorporated into the thermally-operated silica gel/water type AHP as a suction pump, and works for promoting water vapor transportation between an adsorber and evaporator/condenser. We have studied effect of MBP power on heat output performance of AHP experimentally. It is demonstrated that the proposed AHP can achieve 1.6 times as large heat output performance as the thermally-operated AHP.

Key Words: ***adsorption heat pump, mechanical booster pump, silica gel, water vapor.***

1 INTRODUCTION

Energy consumption in Japan continues to grow consistently in spite of taking many energy conservation measures, and enormous expansion of energy consumption has been causing several fatal environmental and energy problems. We should notice that these problems affect not only our country but also the surrounding countries or all over the world. Under these circumstances, a tremendous amount of heat energy, which accounts for over 60 % of primary energy supply in Japan, is unused and discharged into atmosphere as waste heat. In particular, heat energy below 373 K accounts for about 80 % of its waste heat. Development of advanced utilization technologies of such low temperature heat energy is considered to be very effective to prevent the above serious issues.

Adsorption heat pump (AHP) system is considered to be one of the most leading technologies to utilize low temperature thermal energy, because it can generate cold heat energy around 280 K for air conditioning without any mechanical power by utilizing the low temperature heat as regeneration heat source of an adsorbent. Aiming to enhancement of cold-heat output of AHP system, many theoretical and experimental studies have been already conducted (Chahbani et al. 2004, Thorsten et al. 2002, Wu et al. 2002, Zwang et al. 2001, Watanabe et al. 1993, Watanabe et al. 1996, Fujisawa et al. 2002).

However, AHP system still has two serious problems for practical use. One is that cold heat output per unit volume of AHP is much smaller than that of an absorption heat pump; e.g. the silica gel/water type AHP needs more than 4 times as big apparatus volume as absorption heat pump. The other is that heat output and coefficient of performance (COP) decrease significantly in refrigeration mode of AHP with regeneration temperature; e.g. at 358 K, COP reaches about 0.65, whereas at 333 K, it decreases down to about 0.2.

As one of the solution to these problems, we have proposed an innovative adsorption heat pump, the hybrid AHP, which is integrated electrically-operated suction pump into the conventional thermally-operated AHP. In the proposed AHP, suction pump is expected to transport adsorbate vapor forcibly from adsorber to condenser in the desorption process, and to increase an adsorptivity of adsorbent in operation range of the AHP. Experimental studies on effect of heat output and COP on pump power was carried out by a lab-scale apparatus. The results have been evaluated by comparing that for the thermally-operated AHP.

2 OPERATION CONCEPT OF THE HYBRID AHP

Figure 1 shows adsorption isotherms of water vapor on silica gel and operation range of the thermally-operated and the hybrid AHP. The conventional thermally-operated AHP is driven by heat sources at T_L, T_M and T_H, where T_L is the temperature of generated cold heat, T_M is the ambient temperature and T_H is the regeneration temperature of adsorbent supplied as exhaust heat from factories, fuel cells, solar system and so on. The saturated vapor pressures corresponding to respective heat resources are defined as P_L, P_M and P_H. The thermally-operated AHP operates within the relative pressure range of ϕ_1 to ϕ_2 given by the following equations.

$$\phi_1 = P_M/P_H \quad (1)$$

$$\phi_2 = P_L/P_M, \quad (2)$$

where ϕ_1 and ϕ_2 represent the relative pressure at the equilibrium state of the desorption and the adsorption process respectively. In the thermally-operated AHP, ϕ_1 decreases with increasing T_H or decreasing T_M, and ϕ_2 increases with decreasing T_M or increasing T_L. The thermally-operated AHP runs on the condition of $\phi_1 < \phi_2$ and is theoretically expected to generate cold heat output proportional to difference in amount adsorbed between ϕ_1 and ϕ_2, Δq.

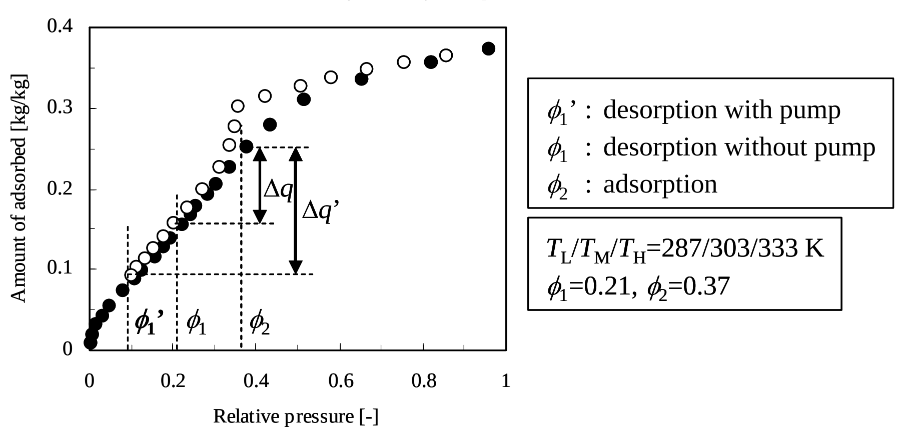

Fig. 1. Operation diagram of adsorption heat pump with/without pump

On the other hand, in the hybrid AHP, water vapor is forcibly transported from the adsorber to the condenser by suction pump during desorption process. Therefore, pressure of the adsorber in the hybrid AHP, P_M', becomes lower than that in the thermally-operated AHP, P_M, even if both AHPs operated under the same temperature of heat sources. The relative pressure for the hybrid AHP is newly defined as follows:

$$\phi_1' = P_M'/P_H \tag{3}$$

Since ϕ_1' is smaller than ϕ_1, the hybrid AHP can achieve wider operation range and higher adsorptivity than the thermally-operated AHP.

2 EXPERIMENT

2.1 Experimental Apparatus

Figure 2 shows a schematic drawing of the lab-scale hybrid AHP system with silica gel/water pair. This experimental setup consists of an adsorber, an evaporator/condenser and a mechanical booster pump (MBP). These were connected with each other as shown in Figure 2. Detailed drawing of the adsorber is shown in Figure 3. The adsorber had four separated rooms for changing the weight of adsorbent. In each room, four Fin-type Silica gel Tube modules (FST modules) were installed (Li et al.2004). The FST module is made up of copper heat exchanger tube (16 mm I.D., 400 mm in height) and copper fins cast to the tube (Figure 3). Silica gel (Fuji Silysia Chemical Ltd.), of average particle size of 412 μm, was packed between the fins and wrapped by stainless net. The fin pitch and fin length of the FST-module were 2.32 mm and 11 mm, respectively. The mechanical booster pump (ULVAC, Inc.; MBS-010 type) was used as suction pump for transporting water vapor. The MBP is an oil-free dry pump with a rate of exhaust volume of 12 m^3/h under reduced pressure condition. In the adsorber, pressure sensors were installed, and K-type thermocouples were also inserted in the seven points as shown in Figure 2. The amount of adsorbed water vapor was also measured by the level gage equipped in the evaporator/condenser.

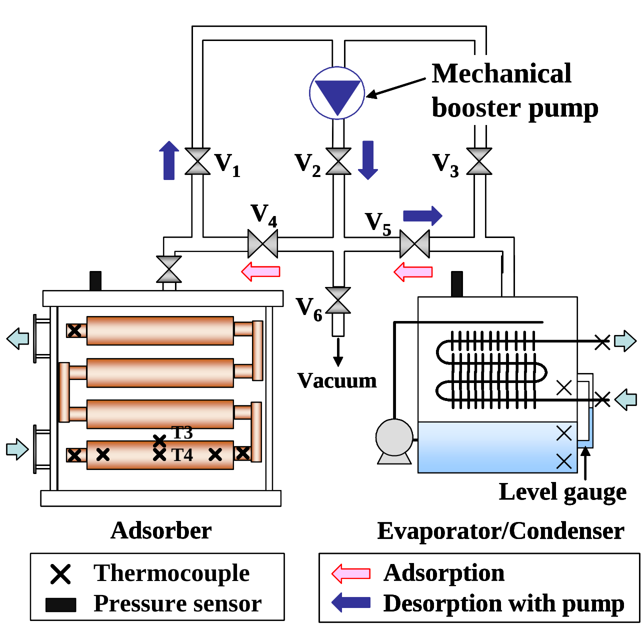

Fig. 2. Schematic drawing of the experimental apparatus

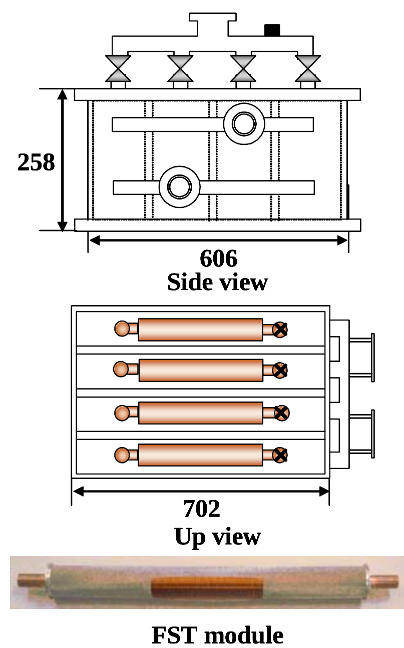

Fig. 3. Details of adsorber

2.2 Experimental Procedures

2.2.1 Adsorption process

The adsorber was evacuated at 353 K for 20 h. After the temperature in the adsorption column reached 303 K, the evaporator/condenser was set at 287 K. Then, V_4 and V_5 were opened to feed the water vapor into the adsorber. When amount of adsorbed water became quasi-equilibrium state, all valves were closed. In this paper, this process is defined as thermally-operated adsorption process.

2.2.2 Thermally-operated desorption process

After the thermally-operated adsorption process, desorption experiment was started. The temperatures in the adsorption and the evaporator/condenser were set at 333 K and 303 K, respectively. Then, V_4 and V_5 were opened to desorb water vapor from silica gel. After reaching equilibrium state, all valves were closed. In this paper, this process is defined as thermally-operated desorption process.

2.2.3 Desorption process aided with pump

After the thermally-operated adsorption process, desorption experiment was started. The temperature in the adsorption column and the evaporator/condenser were set at 333 K and 303 K as well as the thermally-operated desorption. Then, V_2 and V_3 were opened to start to exhaust the water vapor forcibly into the evaporator/condenser through the MBP. When there was no change in the water level of the condenser, all valves were closed. This process is defined as pump aided desorption process.

3 RESULTS AND DISCUSSION

3.1 Changes In Temperature Difference And Amount Adsorbed During Desorption Process

Figure 4 shows changes in temperature differences, ΔT, in the adsorber and amount of desorbed water, Δq, with time during desorption process with/without pump.

It can be seen that every temperature in the packed bed drops rapidly in both experiments as soon as the desorption has started. This results from absorbing the heat of adsorption. After reaching the maximum temperature difference, ΔT_{max}, within 3 min, it rises gradually to its initial temperature. After 60 minutes, every temperature in the adsorber returned to the initial temperature. Compared to the thermally-desorption process, temperature drops is great for the desorption with MBP except for an initial period of the experiment. It is considered that thermal energy continues to be absorbed for desorbing water vapor all through the desorption process with MBP.

Amount of desorbed in both experiments decreases by little and little with time, and reaches quasi-equilibrium state after 60 min. In an initial period, desorption rate for the hybrid AHP, which corresponds to change in amount desorbed, was a little smaller than that for thermally-operated AHP. However, after 60 minutes, desorption ratio achieves 80 % to desorption equilibrium for the pump aided desorption, whereas it reaches only 50 % for the thermally-operated desorption. It indicates that the hybrid AHP with MBP is able to improve the adsorptivity within the operation range about 1.6 times as large as the thermally-operated AHP.

Figures 5 and 6 show pressure profiles for the thermally-operated desorption and for the desorption aided with pump, respectively. In case of the thermally-operated desorption, as soon as the experiment has been started, pressure in the adsorber drops into that in the condenser. After then, there is little pressure difference between the condenser and the adsorber during the experiment. On the other hand, for the desorption aided with pump, it takes more time to equal to the pressure in the condenser. After reaching $P_{con.}$, the adsorber is getting lower pressure than the condenser since mechanical booster pump transports water vapor from the adsorber to the condenser forcibly. Pressure in the adsorber gradually decreases until 40 minutes and reached 2.1 kPa. It is concluded that further depressurized condition occurred by MBP enhanced desorption of water vapor.

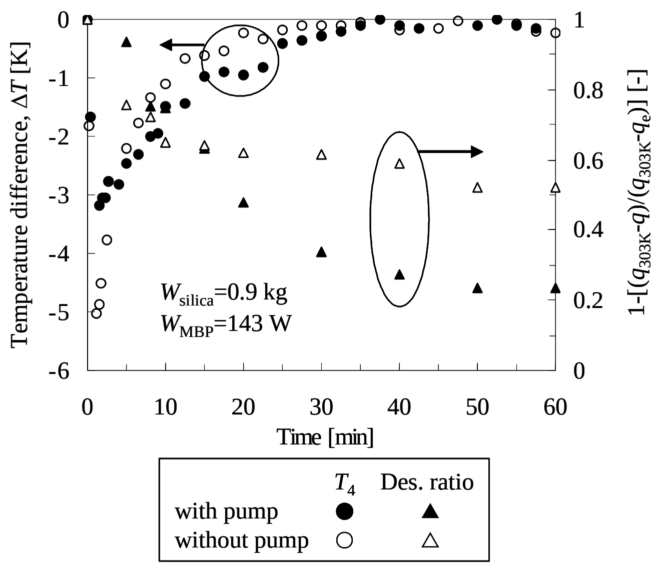

Fig. 4. Changes in temperature and amount desorbed during desorption with/without MBP

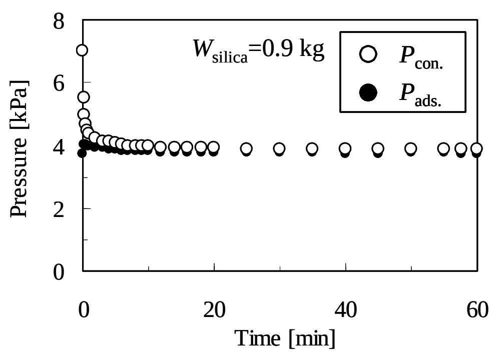

Fig. 5. Pressure profiles during thermally-operated desorption

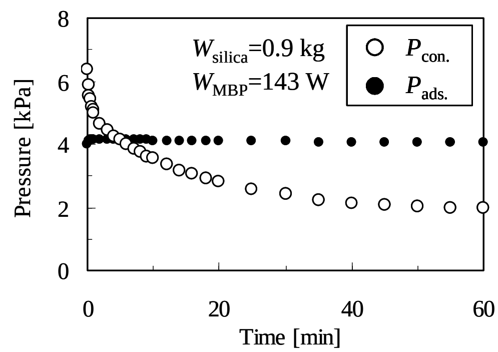

Fig. 6. Pressure profiles during desorption with MBP

3.2 Effect Of Pump Power On Desorption Rate

Figure 7 shows change in amount desorbed under the conditions of pump power changed to 103, 143 and 182 W. As shown in Figure 7, amount of desorbed water certainly increased with pump power, although pump power doesn't have much effect on the desorption rate within this experimental range. It is supposed that exhaust flow rate is too big in every pump power against the desorption rate. Further researches are required to clarify relationship between the pump power and the desorption rate and determine the optimized pump power.

In this paper, performance evaluation of the hybrid AHP is made from the viewpoints of heat output, Q_{output} [W], and coefficient of performance, COP [-] that are calculated as follows.

$$Q_{output} = \Delta q \cdot \Delta H_{eva} \cdot W_{silica} / \theta \tag{4}$$

$$COP_{MBP} = \frac{Q_{output}}{W_{MBP}} \tag{5}$$

, where ΔH_{eva} is the heat of evaporation of water [J/kg K], W_{silica} is the weight of packed silica gel [kg], θ is the adsorption/desorption time [s], W_{MBP} is electric power consumption of MBP [W] The adsorption/desorption time, θ, is defined as 5 min in this evaluation.

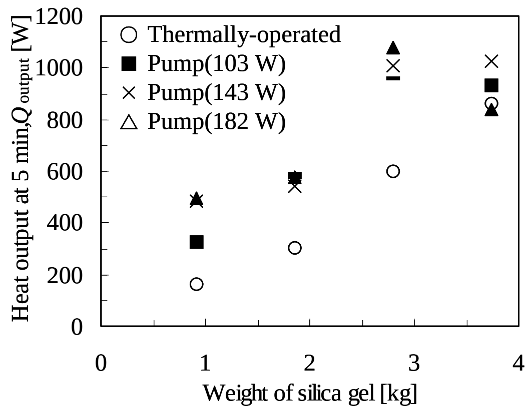

Fig. 7. Effect of pump power on heat output

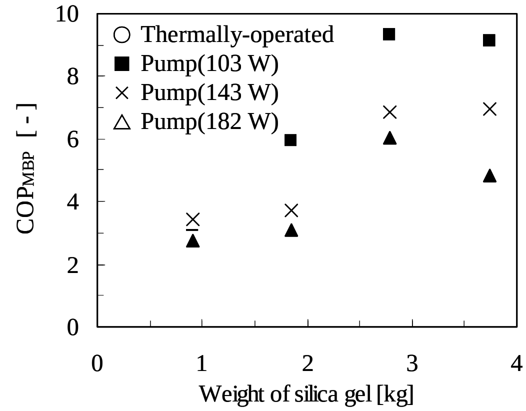

Fig. 8. Effect of pump power on COP_{MBP}

Q_{output} and COP_{MBP} under various experiment conditions are shown in Figure 8. In this figure, abscissa axis represents weight of the silica gel packed in the experimental apparatus. The weight has been changed by changing number of rooms connected to the condenser.

It can be seen that heat output for the hybrid AHP increases with the weight of silica gel, and it is largely similar to every pump power, since adsorption rate isn't affected so much by pump power as mentioned above. Within this experimental range, heat output for the hybrid AHP is about 1.6 times higher than that that for the thermally AHP. Heat output for the thermally-operated AHP increases in rough proportion to weight of silica gel. On the other hand, heat output for the hybrid AHP takes a maximum value of 980-1076 W at W_{silica}=2.8 kg. At W_{silica}= 3.7 kg, heat output of the hybrid AHP drops into 838-1027 W, and is almost the same as that of the thermally-operated AHP (863 W). This results shows that water vapor couldn't be transported sufficiently by the mechanical booster pump at W_{silica}=3.7 kg. It is suggested that when silica gel was packed 3.7 kg in weight, the MBP has an insufficient flow rate to amount of water vapor desorbed and transportation of water vapor is hindered by the MBP.

On the other hand, coefficient of performance indicates the opposite tendency of Q_{output}, i.e. COP increases with decreasing pump power. The reason is that heat output for the hybrid AHP is almost same even if pump power has been changed. In this experiment, the maximum value of COP_{MBP} is 9.2 at W_{silica}= 2.8 kg and W_{MBP}=103 W. These experimental results show that the capacity of the MBP using in the experiment was adequate when adsorbent capacity was about 2.80 kg.

4 CONCLUSION

For solving the problem of AHP that heat output and coefficient of performance (COP) decrease significantly with regeneration temperature, an innovative adsorption heat pump, the hybrid AHP has been proposed, which is integrated electrically-operated suction pump (MBP) into conventional thermally-operated AHP. Effect of MBP power on heat output of the silica gel/water type hybrid AHP was investigated experimentally by using a lab-scale apparatus. The following results were obtained.

Hybrid-AHP with MBP is able to improve adsorptivity within the operation range of the AHP about 1.6 times as large as the thermally-operated AHP. The hybrid AHP also can achieve about 1.6 times heat output at 5 min as much as the thermally-operated AHP. There is the optimized pump power on heat output and COP for the hybrid-AHP.

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