Development of Waste Heat Driven Multi-Bed, Multi-Stage Regenerative Adsorption Chiller

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Abstract

A multi-bed multi-stage adsorption chiller is proposed and studied. The chiller is automatically switching between conventional and multi-stage modes, and thus optimized for alternating temperatures of various heat sources.

An experimental prototype of our proposed chiller is built to investigate the performance of the chiller and to determine the driving heat source temperature levels of various modes of the chiller. The simulation codes of different modes are also developed to investigate the design and operating conditions of chiller. It is seen that the two-stage and three-stage mode of the chiller could run with very low heat source temperature (40-60°C). Though the COP (Coefficient of performance) of three-stage and two-stage mode is quit low, however, the system is effective to utilize low grade waste/renewable heat source, which finally contributes to mitigation of global warming. An advanced single stage called “mass recovery cycle” is also studied. It is proved that the single-stage cycle with mass recovery process improve the cooling capacity of the chiller.

The performance of adsorption chiller mainly depends on the heat and mass transfer characteristics of the adsorbent materials. The study also investigates the heat and mass transfer characteristics of adsorbent materials such as, silica gel and carbon fiber.

1. Introduction

Reduction of primary energy consumption is strongly required to mitigate global warming caused by fossil fuel consumption. To achieve this objective, the use of waste heat thermal energy or renewable energy should be increased in energy conversion process especially in refrigeration process. Thermally activated sorption technology is one of the possible alternatives to electric driven vapor compression refrigeration/heat pump system. At the moment, absorption (liquid vapor) refrigeration cycles are most promising technologies, however, the adsorption (solid vapor) cycles have distinct advantage over the other heat driven refrigeration cycle, in their ability to be driven by heat of relatively low, near-environmental temperature. Under the cycle, waste heat below 100°C can be recovered. Many adsorbent/adsorbate [1] pairs have been used in adsorption refrigeration/heat pumping system. Silica gel water adsorption chiller [2,3] is regarded as a candidate technology to utilize low temperature heat of 70-80°C. Many advanced cycles are proposed either to improve the COP values of the system and/or to improve their specific cooling
power (SCP). However, very few cycles are proposed to utilize relatively low heat source temperature. Even though the COP is low, multi-stage adsorption chillers enhance the possibility to convert low temperature heat of 50–60 °C into effective cooling. Conventional single stage chillers are already commercialized in Japan. It has, however, hurdles such as low COP and compactness. From such point of view to overcome the hurdles, this study aims at examining performance of new adsorption cycles with multi-bed and multi-stage theoretically and experimentally. Furthermore, it is basically important to understand the adsorption/desorption characteristics of adsorbent/adsorbate in order to improve the performance of the adsorption cycles. Investigating thermophysical properties of working pairs is also accomplished in this study, which will exploit appropriate materials for utilization of low temperature heat.

2. Performance of Multi-Bed, Multi-Stage Adsorption Chiller

2.1 Design of experimental facility

The chiller comprises one pair evaporator, one pair condenser and 3 pairs adsorbent beds. In the present design, three basic operational modes are included. The first mode will be to work as a high efficient conventional chiller; the second operational mode will be able to work as an advanced multi-stage adsorption chiller where available driving source temperature will be low as 50°C. The third mode will be able to work as advanced high cooling capacity adsorption chiller by recovering the internal refrigerant mass. The side and corner view of the chiller are presented in Figure 1.

![Figure1. Picture of the proposed multi-bed and multi-stage chiller](image)

2.2 Performance of multi-stage adsorption chiller

The study aims at designing a multi-bed multi-stage adsorption chiller that can be driven by waste/renewable heat source of temperature between 50 and 90°C with cooling source temperature at environment temperature. The chiller is designed such a way that it can be switched into different modes depending on the driving heat source temperature. Stage regeneration techniques have been applied to operate the chiller by relatively low temperature heat source. From the conceptual Dühring diagram (Figure 2) one can see that the conventional cycle is not operational with 50°C heat source temperature if the cooling source temperature is 30°C or more. In order to enable the practical utilization of these temperatures to adsorption chiller, multi-stage regenerative strategy can be applied. As can be seen from the Dühring diagram (Figure 2), the adsorption allows the regenerating temperature lift \((T_{des}-T_{ads})\) to be reduced by splitting the refrigerant saturated vapor temperature (or pressure) lift between evaporator and condenser \((T_{con}-T_{eva})\).
The study presents some experimental results of various modes of the proposed chiller. The performance of the different modes of the chiller is presented and compared to determine the optimum driving heat source temperature. The experimental results obtained from the different modes of the chiller are compared in Figure 3 and Figure 4. Figure 3 illustrates the effect of heat source temperature on SCP (cooling power per silica gel mass) of the different modes of the chiller. It should be noted here that the two-stage mode of the chiller is completely different from the conventional two-stage chiller. In conventional two-stage mode, only four beds are required to run the system, however, in the present case 6 beds are used. The upper two beds are used as upper cycle and lower four beds are used as lower cycle. From the Figure 3, it can be seen that three-stage chiller provides better SCP values if the heat source temperature is below 55 °C, single-stage mode provides better SCP value if the heat source temperature is relatively high (>75 °C). The experimental results also show that the chiller with two-stage mode provides best SCP values if the heat source temperature is between 55 and 75 °C. The effect of heat source temperature on COP of different modes obtained from experiment is presented in Figure 4. It can be observed that single stage mode provides better COP value comparing with single and three-stage modes if the heat source temperature is between 50 and 69 °C, while single stage mode provides better COP if the heat source temperature is greater than 69 °C.

Figure 2. Conceptual P-T-X diagram for conventional and multi-stage adsorption cycles

Figure 3. Effect of heat source temperature

Figure 4. Effect of heat source temperature
2.3 Dynamic simulation of adsorption cycle

A universal mathematical model describing the behaviors of current commercialized silica gel-water adsorbent is presented in this study. Comparing the previous study, this universal model comprises (i) a thorough and thermodynamically consistent representation of the heat and mass transfer processes of adsorbed phase, (ii) a realistic representation of the thermal mass capacity of the associated piping materials and fins, (iii) a distributed modeling of the reactor bed for the uptake and off-take processes, (iv) suitable for the circular bed and rectangular bed. The details of modeling are can be found in literature of Chua et al. [4].

The current formalism for single-stage cycle represents an improvement to the models of Saha et al. [2] and Chua et al. [3]. The data presented here are considered under same operating conditions as that in the above two literatures. In the model the total refrigerant inventory has been chosen to be 68.9 kg. The comparison of predicted and experimentally measured outlet temperatures is shown in Figure 5. One can observe that the current prediction agrees well with the experimental measurements.

![Figure 5. A comparison of prediction and experimental](image)

Figures 6 and 7 present the effects of cycle time on the COP and cycle-averaged chiller cooling capacity, respectively. It is clearly seen that the COP increases monotonically with the cycle time. The reason can be explained as follows. With a longer cycle time, the times of sensible heating or cooling during the same time interval will decrease compared with the short cycle time. This will lead to a favorable effect on the COP. The variation of cooling capacity is not monotonic. From 100s to 230s cooling capacity increases steeply, from 230s to 650s it is increase plateaus, and from 650s on, it begins to decrease. The low cooling capacity in a short cycle time is caused by the reduced adsorption, which is also related to the reduced desorption due to the insufficient heating of the desorber. At a certain cycle time, the maximum adsorption-desorption capacity will be achieved under the heating and cooling water temperatures. Extending the cycle time further will not bring any effect on useful refrigeration. Thus, beyond this optimal cycle time, average cooling capacity will decrease. It is worthy to utilize the effect of cycle time to partial load operation. This strategy results in two advantages, one is higher COP, the other one is easy control.

Figures 8 and 9 show the effect of hot water on chiller’s COP and cooling capacity, respectively. Higher hot water inlet temperature to chiller leads to higher COP and cooling capacity. Its effect is more pronounced for the cooling capacity as can be seen in Figure 9. It is noted that for 50°C hot water supply to the chiller, no cooling is produced by chiller should the condenser water temperature is higher than 28°C, i.e., cooling capacity tends to zero.
2.4 Enhancement by mass recovery process

The study investigates the performance of two-bed, silica gel-water adsorption refrigeration cycle with mass recovery process. The cycle with mass recovery can be driven by the relatively low temperature heat source. The process can be made just connecting the desorber and adsorber through a pipe; which allows the refrigerant vapor to enter from desorber to adsorber. Thus, the partial pressurization and depressurization in beds occur automatically. In the present study, a novel strategy in mass recovery cycle is proposed to improve the cooling capacity. In the new strategy, desorber keeps to be provided hot water and adsorber kept in cooling process by applying cooling water. The present strategy is completely different from the conventional mass recovery cycle as there is no heating and cooling process during mass recovery process in conventional mass recovery cycle. In the present strategy additional heating and cooling accelerated the desorption/adsorption process; thus the system provides the better cooling output. The figures also compare the COP and cooling capacity with those of single-stage cycle. From the figures, it is found that both mass recovery processes provide better COP and cooling capacity than those provided by single-stage cycle at the hot water temperature of 55°C. Moreover, Figure 10(b), it can be seen that cooling capacity of proposed mass recovery cycle is more than that of conventional mass recovery cycle; supply of hot/cooling water has the effect for increasing cooling capacity. In Figure 10(a), however, COP values of mass recovery cycle with heating/cooling are lower than those of conventional mass recovery cycle owing to supplying hot water during mass recovery process. That is, mass recovery process with heating/cooling enhances refrigerant circulation inside the adsorbent heat exchanger but brings out the generation of desorption heat more than cooling production; that is why COP value of proposed mass recovery cycle decreases. In the present study, it is assumed that heat source
is waste heat. That is, cost of input heat is free. Therefore, it is not serious problem that COP value is lower than that of conventional single-stage cycle. Improvement ratio of COP and cooling capacity for conventional single-stage cycle is high at heat source temperature lower than 60 °C. Therefore, mass recovery cycle has the advantage over single-stage cycle at especially low heat source temperature. Figure 10(c) presents the average chilled water outlet temperature of each cycle at each heat source temperature. From the figure, the chilled water outlet temperature of mass recovery cycle with heating/cooling is lower than that of other cycle, that is, mass recovery cycle with heating/cooling has better performance than the others.

3. Measurement of the Properties of Silica-gel-Water

The isotherm data of silica gel-water pair at low pressures (0-6000 Pa) and temperatures (303 – 338 K) is of great interest to designers of adsorption chillers. Accurate uptake (adsorb) and off-take (desorb) isotherm data at values of P and T similar to the operating conditions of an adsorption chiller could translate into economical gains in terms of (i) sizing of the adsorption beds and (ii) the better performances of adsorbent under batch-type operating conditions of such chillers.

Isotherm experiments on adsorbents are performed by either the direct or indirect method. The initial setup cost of the indirect method, such as the constant-volume-variable-pressure apparatus or CVVP in short, tends to be inexpensive but the results obtained may be subjected to higher experimental errors. In this report, we present an experimental set up for a direct method in which the isotherm data of silica gel-water pair are deemed to have an experimental error less than 2 %. To determine the isotherms of silica gel, we employ the Fuji-Davison type ‘A’ and type ‘RD’ silica gel as suitable adsorbent.

Figures 11 and 12 depict the experimental equilibrium data for the type ‘RD’ and ‘A’ silica gel with water vapor, respectively. The table 3 shows the values of raw data (in kg of adsorbate/kg of adsorbent) that were used to plot these isotherms at
the different temperature. Due to the system design, it is difficult for the CVVP system to achieve the measurement accuracy under the low pressure. However, the TGA method is suitable for high measurement accuracy at low pressure and temperature in the chamber could be maintained with high accuracy. Nevertheless, the testing result from both methods give good agreement, and this confirmation reinforces the design aspects of the adsorption chiller.

The performance of Type ‘RD’ silica gel water system employed by the adsorption chiller manufacturer, as described by the Henry’s isotherm[5], is also superimposed for comparison purposes. The data ranges of the manufacturer were obtained for temperatures from 328 to 358 K, and for system pressures from 1000 to 5000 Pa. However, the uncertainties of measurements are not available from the manufacturer. Apparently, the manufacturer is focusing more on the desorber conditions of adsorption chillers.

Table 3(a) Isotherm data for type RD silica gel

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<th>Temperature 323K</th>
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<td>TGA data</td>
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<td>7</td>
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Table 3(b) Isotherm data for type A

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<th>Temperature 323K</th>
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Figure 11. Isotherm data for water vapor onto the type ‘RD’ silica gel

Figure 12. Isotherm data for water vapor onto the type ‘A’ silica gel
Comparing the manufacturer’s data of type ‘RD’ silica gel with our experimental data for the same type of silica gel, the performance of type ‘RD’ silica gel-water system is found to be consistent in trend, as shown in Figure 11. A saturation limit of about 40% is observed from the experiments for the silica gel type ‘RD’. It is observed from Figures 11 and 12 that isotherms both type ‘RD’ and ‘A’ silica gel-water systems, exhibit signs of the onset of monolayer saturation at higher vapor pressures. It is noted that the saturation limit for vapor uptake of type “A” silica gel at an isotherm of 304 K is about 33%, which is lower than that of Type ‘RD’. Thus, the Tóth’s isotherm equation\([6,7]\) is found to fit the experimental data of both type ‘RD’ and type ‘A’ silica gel-water systems and therefore, this correlation is used to determine both the isotherm parameters as well as the isosteric heats of adsorption.

4. Evaluation of Activated Carbon-Ethanol Pair

Nowadays, adsorption heat pumps have received considerable attention as they are energy savers and environmentally benign. However, the main problem of adsorption heat pumps is the requirement of large heat transfer areas in the adsorber/desorber heat exchangers due to low thermal conductivity of the adsorbent bed which contains solid-porous adsorbents such as, zeolite, activated carbon fiber (ACF), or silica gel. The design of adsorbent bed heat exchanger also plays an important role to improve the performance. From this context, an experimental investigation of a plate-fin heat exchanger using ACF-ethanol as adsorbent/refrigerant pair has been conducted in the present study. Fin pitch, fin thickness and fin height are taken as 8 mm, 2 mm and 15 mm, respectively. In the present design the total length of the heat transfer fluid (HTF) path is taken as 5 m in order to obtain high temperature difference between HTF inlet and outlet. The picture of the adsorbent heat exchanger has been shown in Figure 13.

As can be seen from Figure 14, the heat transfer coefficient also peaks at around 50 s after the starting of the desorption mode after that it drops sharply. The average net desorption heat transfer coefficient during the first 80 s is around 1000 W/m\(^2\)\(\cdot\)K. However, the average net desorption heat transfer coefficient is as low as 5 W/m\(^2\)\(\cdot\)K during 500 to 2000 s which means that it is inevitable to choose short cycle time operations to enhance the performance.

![Figure 13. Photograph and specification of the plate-fin heat exchanger.](image)

![Figure 14. Net overall heat transfer coefficient during desorption mode.](image)

Conclusions

A multi-bed multi-stage adsorption refrigeration cycle has been studied extensively to produce effective cooling by utilizing relatively low temperature waste/renewable heat sources. In order to improve the performance of the adsorption cycles,
investigation on thermophysical properties of working pairs is also accomplished in this study. The following concluding remarks can be drawn:

- Though the COP is low, the multi-stage chiller produces cooling effectively even the temperature of the source is low, such as, 50 °C. Three-stage mode of the chiller provides better SCP values if the heat source temperature in below 55 °C, single-stage mode provides better SCP value if the heat source temperature is relatively high (>75 °C). The experimental results also show that the chiller with two-stage mode provides best SCP values if the heat source temperature is between 55 and 75 °C.
- Our proposed dynamic simulation model effectively predicts the performance of an adsorption chiller and it agrees well with experimental data.
- Mass recovery process with heating and cooling in single-stage mode improves SCP values significantly and the process is more effective for relatively low heat source temperature, specially at heat source temperature below 60°C.
- Experiment on different type silica gel water pair shows that a saturation limit of about 40% for the silica gel type ‘RD’. It is also observed that isotherms both type ‘RD’ and ‘A’ silica gel-water systems, exhibit signs of onset of monolayer saturation at regions of higher vapor pressures. However, the saturation limit for vapor uptake of type ‘A’ silica gel at an isotherm of 304 K is about 33%, which is lower than that of Type ‘RD’.
- The experiment on activated carbon-ethanol pair with plate fin heat exchanger shows that the average net desorption heat transfer coefficient during the first 80 s is around 1000 W/m²·K. However, the average net desorption heat transfer coefficient is as low as 5 W/m²·K during 500 to 2000 s which means that it is inevitable to choose short cycle time operations to enhance the performance.

References

Selected publications from the project


