



14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

An Experimental Study on the Chemisorption Heat Pump for Low Temperature Heat Source

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Abstract

Global interest in carbon neutrality is increasing for a sustainable society in response to the climate crisis. Various studies are being conducted for carbon neutrality, and among them, many studies related to unused energy are being conducted. Many studies focused on the waste heat recovery system regarding the use of unused energy. Recently, interest in a chemisorption heat pump capable of performing a cooling based on low-temperature thermal energy has increased. This research conducted an experimental study to understand the performance characteristics of a chemisorption heat pump consisting of a condenser, an evaporator, and two reactors based on a low-temperature heat source (40°C). Experiments were conducted for cases where the adsorption/desorption operation time was 20, 30, and 50 minutes, and the average cooling capacity, COP, and SCP were presented for each condition when performing six alternating operations. As adsorption/desorption operation time went up, average cooling capacity, SCP were reduced and COP was increased.

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Selection and/or peer-review under the responsibility of the organizers of the 14th IEA Heat Pump Conference 2023.

Keywords: Chemisorption Heat Pump; Waste heat recovery; Adsorbent; Adsorption; Desorption;

1. Introduction

There is a growing interest in carbon neutrality around the world. The governments of some countries around the world, including South Korea, have announced national plans to achieve carbon neutrality in 2050 [1]. Research institutions around the world are conducting research on the use of renewable energy, process efficiency improvement, and waste energy recovery to achieve carbon neutrality. Among these research topics, in the case of waste energy recovery, many studies have been conducted on waste heat recovery. One study showed the amount of waste heat in each EU country and each industry sector [2]. In most cases, thermal energy of more than 100°C is emitted in the form of waste heat, and most studies have focused on utilizing waste heat energy in this temperature band. In addition, since the technical difficulty is high to recover low-temperature thermal energy of about 40 to 50°C, relatively little research has been conducted on technologies that utilize low-temperature waste heat energy of about 40 to 50°C.

The chemisorption heat pump is a refrigeration cycle driven by thermal energy. Fig. 1 shows the basic principle and cycle diagram of chemisorption heat pump [3]. Relatively high-temperature (T_h) thermal energy is supplied to the desorption reactor, medium-temperature (T_m) thermal energy is discharged from the condenser and adsorption reactor, and low-temperature (T_l) thermal energy is supplied to the evaporator. A cooling effect occurs in the process of supplying low-temperature thermal energy to the evaporator. In order to drive the chemisorption heat pump, a high-temperature, medium-temperature, and low-temperature heat source is required, and the combination of this temperature is determined by a combination of a working fluid and adsorbent. According to Yang *et al.* [3], When the working fluid of the low-temperature driven chemisorption heat pump is NH_3 , NH_4Cl , PbCl_2 or NaBr are suitable as an adsorption material. Oliveira and

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Generoso [4] conducted an experiment using a chemical adsorption heat pump driven by about 70°C heat energy. Oro *et al.* [5] conducted an analysis study on a chemisorption heat pump using waste heat of about 70 °C discharged from the fuel cell. Pacho [6] conducted an analytical and experimental study on a chemisorption heat pump driven by thermal energy of 120°C. In addition to these studies, various studies were conducted on the chemisorption heat pump, such as cycle analysis and Clapeyron curve [7-11].

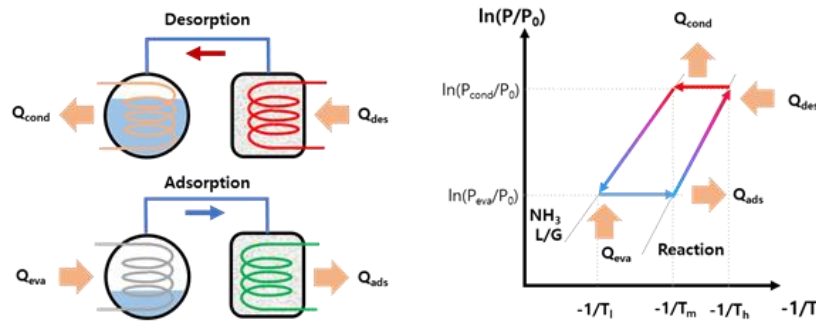


Fig. 1. Schematic and Cycle Diagram of Chemisorption Heat Pump [3].

In this study, a cooling cycle experiment was conducted by using a chemisorption heat pump consisting of an evaporator, a condenser, and two reactors. By performing the alternating operation, cooling performance, COP, and SCP (Specific cooling power) of the system according to the alternating operation time were measured.

2. Experimental Apparatus and Procedures

Fig. 2 shows schematic diagram of chemisorption heat pump. The chemisorption heat pump is operated alternately, and a total of four operation modes are repeated. Each operation mode is implemented using a valve in the system, and the valve's status under each operation mode is in shown in Table 1. In mode A, the working fluid is adsorbed and desorbed from the adsorbent in reactor 1 and reactor 2, respectively. Mode B is a preparation process for mode C, and the chillers connected to each reactor are changed. In mode C, the working fluid is adsorbed and desorbed from the adsorbent in reactor 2 and reactor 1, respectively. Mode D is a preparation process for mode A, and the chillers connected to each reactor are changed. In this study, experiment was conducted by setting T_h , T_m , and T_l to 40, 20, and 15°C, respectively. Chillers 1, 2, 3, and 4 supply cooling water of temperatures of 20°C, 40°C, 20°C, and 15°C to the system, respectively. Mode A, B, C, D were repeated as illustrated in Fig. 3, wherein Δt_1 was set to 20, 30, and 50 minutes, and Δt_2 was set to 5 minutes, and the experiment was conducted. During Mode B and D, Valve 5 was opened at the start of Mode B and D, and closed after 1 minute.

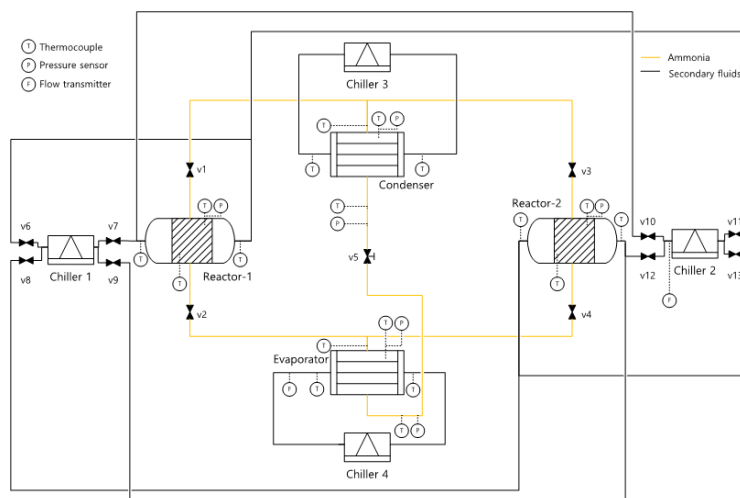


Fig. 2. Schematic Diagram of Chemisorption Heat Pump.

Table 1. Valve Position under each Operation Mode

Valve	1	2	3	4	5	6	7	8	9	10	11	12	13
Mode A	off	on	on	off	off	on	on	off	off	off	off	on	on
Mode B	off	off	off	off	on	off	off	on	on	on	on	off	off
Mode C	on	off	off	on	off	off	off	on	on	on	on	off	off
Mode D	off	off	off	off	on	on	on	off	off	off	off	on	on

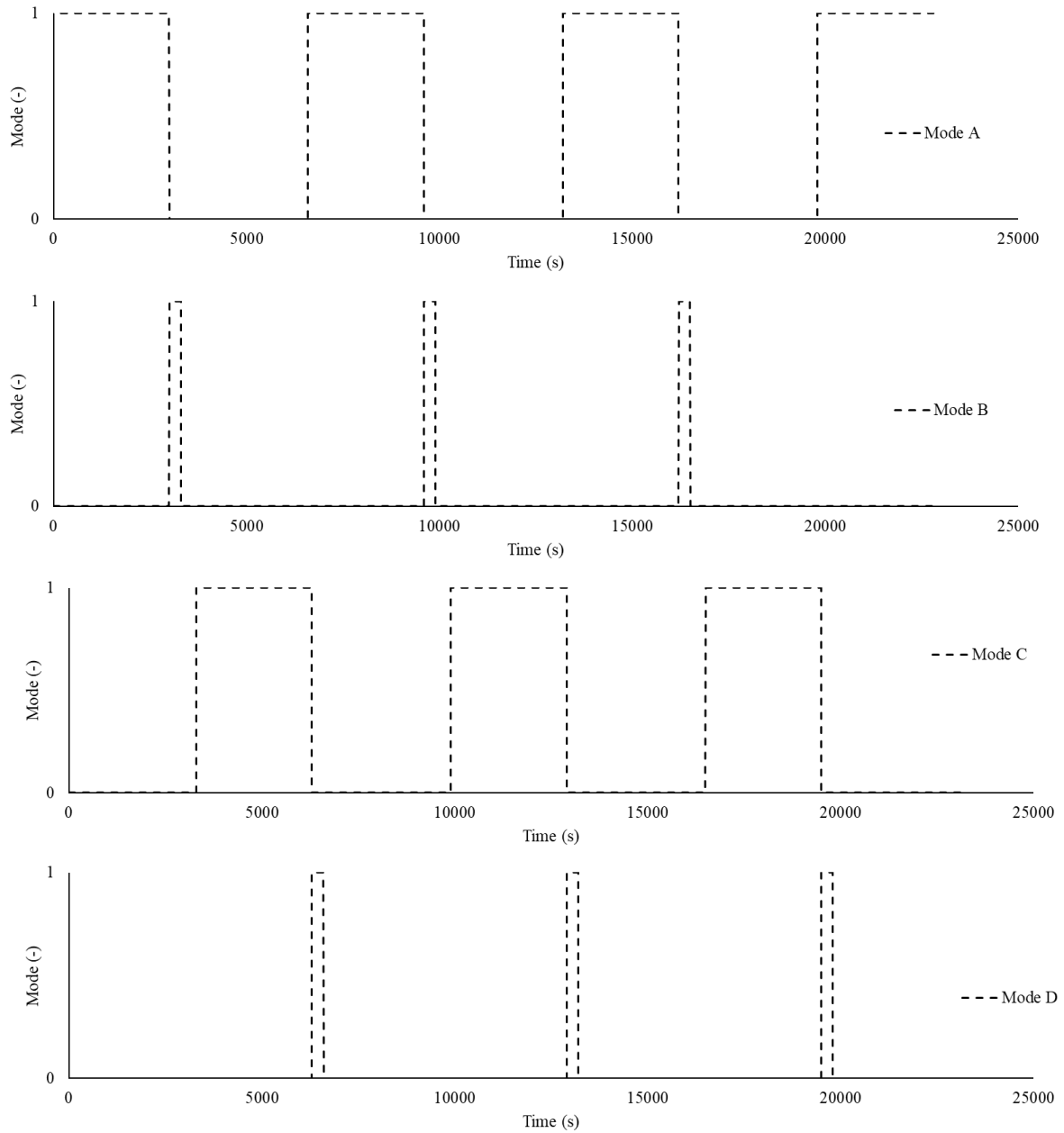


Fig. 3. Each Operation Mode over Time.

Temperature, pressure, and flow rate were measured using thermocouples, pressure transmitters, and flow meters, respectively, and the specifications of each instrument are as shown in the Table 2.

Ammonia was used as working fluid and NaBr was impregnated in Expanded-graphite and used as an adsorbent.

Table 2. Specification of each Instrument

Sensor	Model	Measurement Accuracy
Thermocouple	Omega T-type probe	$\pm 0.3^{\circ}\text{C}$
Pressure sensor	Sensys PSCH0030BCPG	$\pm 1.7 \text{ kPa}$
Flow meter	TCM3100-FA-SGSS-CSMS-	$\pm 0.1\%$ of reading

3. Experimental Results and Discussion

Figs. 4 ~ 9 show experimental results when Δt_1 was set to 30 minutes, and Δt_2 was set to 5 minutes. As shown in Fig. 3, Mode A and C were operated 4 and 3 times, respectively. If the alternating operation is repeated continuously, the initial conditions of modes A and C are constant. However, when the alternating operation is first started (0 second of Fig. 3), the initial condition of Mode A is different from the condition when the alternating operation is continuously repeated. Therefore, the data analysis was performed on the conditions under which the alternating operation was continuously performed. The experiment was performed by repeating modes A through D three times. This means that a total of 6 adsorption/desorption operations have been performed. Each adsorption/desorption preparation and adsorption/desorption operation are defined as one cycle, and the start and end of each cycle can be expressed like the black dotted line in Fig. 4. In the first, third, and fifth cycles in Fig. 4, the working fluid is adsorbed and desorbed in Reactors 1 and 2, respectively. In the second, fourth, and sixth cycles, the working fluid is desorbed and adsorbed in Reactors 1 and 2, respectively. The working fluid was moved from the desorption reactor to the condenser and condensed. Therefore, the pressure of the desorption reactor is slightly higher than the pressure of the condenser as shown in Fig. 4. Meanwhile, the working fluid evaporated from the evaporator moved to the adsorption reactor and was adsorbed into the adsorbent. Therefore, the pressure of the evaporator is slightly higher than that of the adsorption reactor. It can be seen that the pressure of each component shows a repetitive tendency and is maintained during the alternating operation. Fig. 5 shows cooling capacity of evaporator. Cooling capacity was calculated by using temperature difference and flow rate of secondary flow ($Q = \dot{m}C_p\Delta T$). In Fig. 5, the range 0 ~ 300 seconds is adsorption/desorption preparation operation, and after 300 seconds, it is adsorption/desorption operation. After adsorption/desorption preparation operation starts, the cooling capacity of the evaporator decreases to almost zero, and after adsorption/desorption operation starts, the cooling capacity increases rapidly and then gradually decreases. The cooling capacity was up to about 100 W. It can be found that the cooling capacity shows an almost constant tendency in 6 repeated cycles. Fig. 6 shows heat capacity supplied to desorption reactor. As shown in Figure 6, it can be seen that the heating capacity supplied to the desorption reactor increases rapidly after the start of the adsorption/desorption preparation operation and then gradually decreases. When the adsorption/desorption preparation operation starts, the cooling water of 40°C is instantaneously supplied to the reactor that had previously been supplied with cooling water of 20°C . Cooling water of 40°C is instantaneously supplied while the temperature of the structure (Stainless steel) of the desorption reactor is about 20°C , and the cooling water supplies thermal energy to increase the temperature of the desorption reactor structure. Therefore, the heating energy supplied to the reactor increases rapidly after the start of the adsorption/desorption preparation operation. After the temperature of the structure rises, the heat required for the desorption reaction is supplied to the reactor, and as the desorption reaction progresses, the desorption reaction slows down, so the heat supplied to the reactor gradually decreases over time. Olivera and Generoso [4] calculated COP of chemisorption heat pump based on the time averaged cooling capacity of evaporator and time averaged heating capacity supplied to reactor. In this paper, COP is obtained by dividing time averaged cooling capacity of evaporator by time averaged heating capacity supplied to reactor. Figs. 7 ~ 9 show time averaged cooling capacity of evaporator, time averaged heating capacity supplied to desorption reactor, COP of chemisorption heat pump. Average cooling capacity of evaporator is 73.2 (Cycle 1) ~ 87.3 (Cycle 6) W. Average heating capacity supplied to desorption reactor is 379.9 (Cycle 6) ~ 411.5 (Cycle 1) W. COP of chemisorption heat pump is 0.18 (Cycle 1) ~ 0.23 (Cycle 6) W.

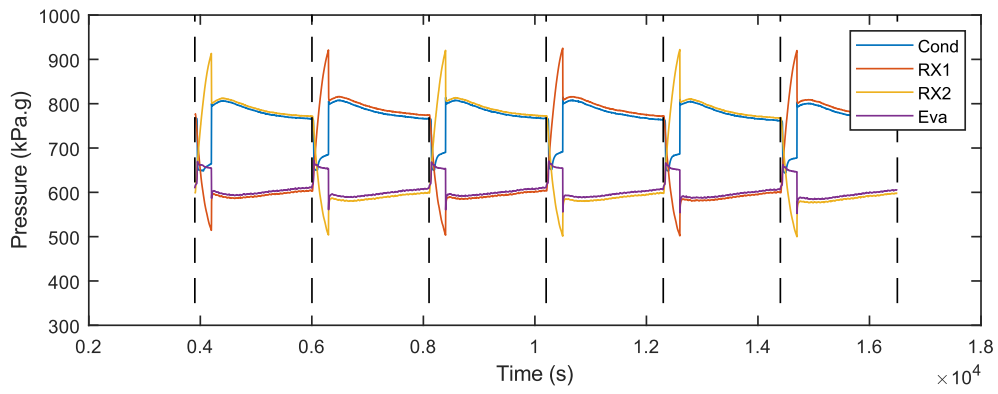


Fig. 4. Pressures of Cond (condenser), RX1 (Reactor 1), RX2 (Reactor 2) and Eva (Evaporator)

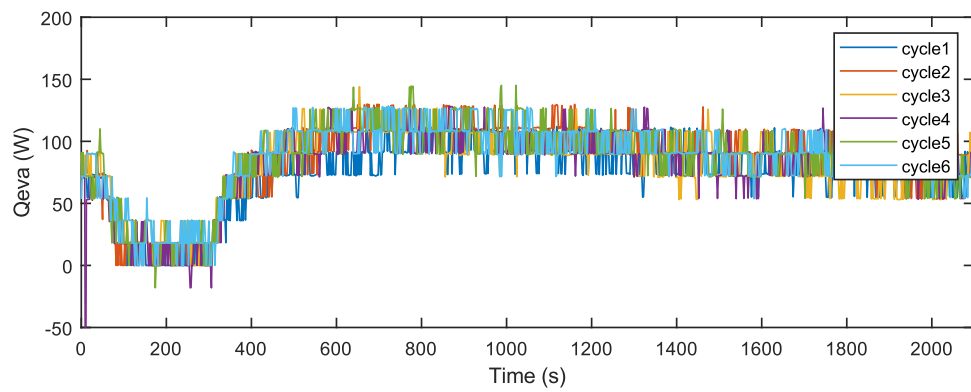


Fig. 5. Cooling Capacity of each Cycle

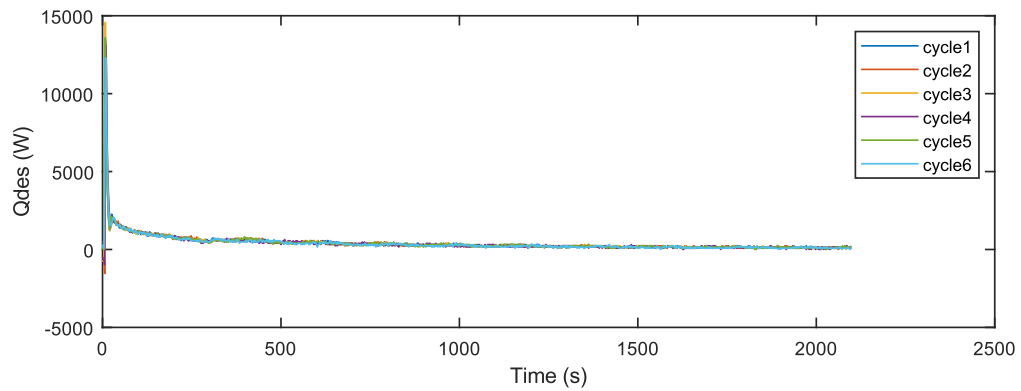


Fig. 6. Heating Capacity Supplied to Desorption Reactor of each Cycle

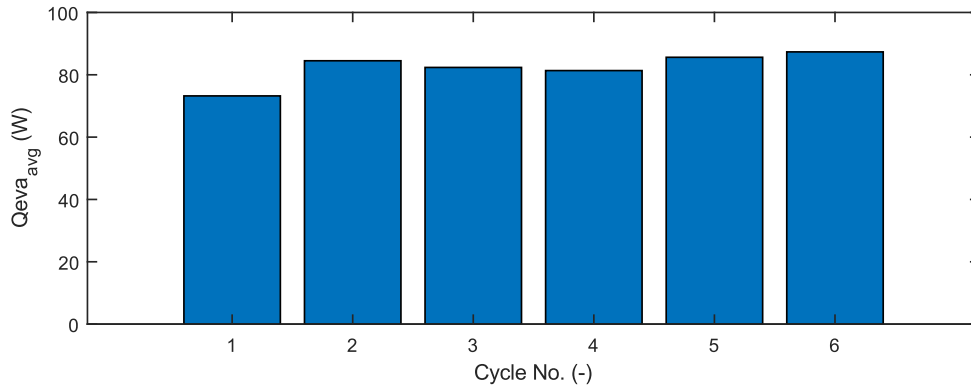


Fig. 7. Time Averaged Cooling Capacity of Evaporator

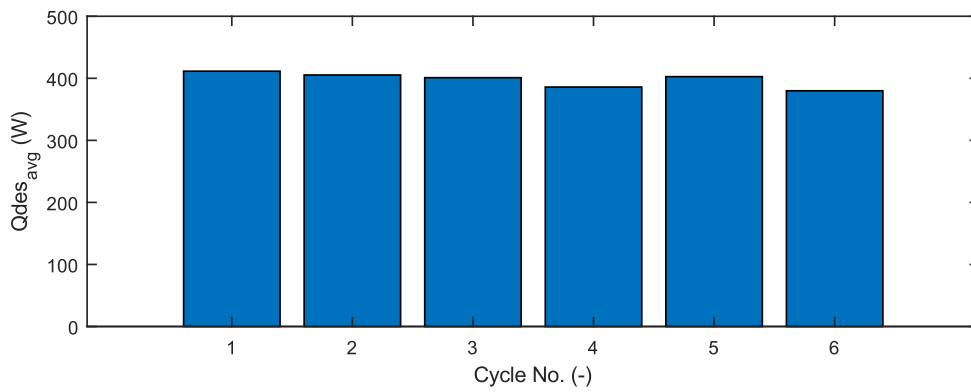


Fig. 8. Time Averaged Heating Capacity Supplied to Desorption Reactor

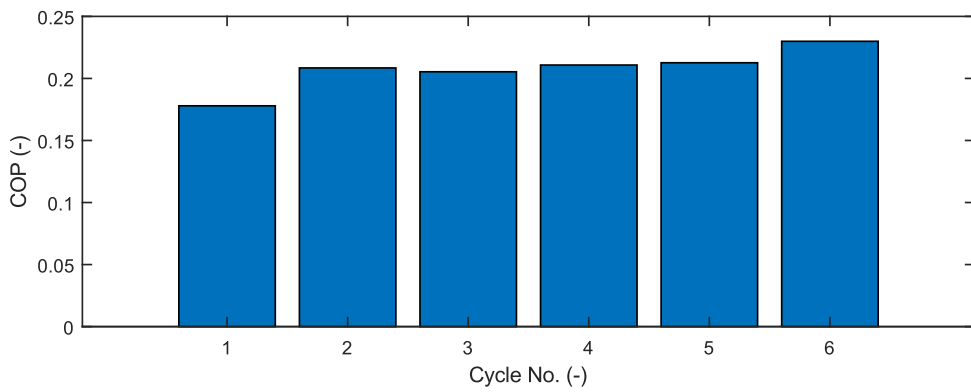


Fig. 9. COP of Chemisorption Heat Pump

As mentioned above, experiments were performed on conditions of 20, 30, and 50 minutes of adsorption/desorption operation time, respectively. Experiments were conducted twice each under the same conditions. Table 3 shows experimental results of each case.

Table 3. Experimental Results of Each Case

Case No.	Δt_1	$Q_{eva,avg}$ (W)	$Q_{des,avg}$ (W)	COP (-)	SCP (W/kg)
1	20	88.3	464.7	0.19	92.8
2	30	82.4	397.7	0.21	86.5
3	50	76.0	307.1	0.25	79.9
4	20	82.9	459.6	0.18	87.0
5	30	78.7	407.5	0.19	82.7
6	50	68.6	313.1	0.22	72.1

As shown in Fig. 5, Q_{eva} decreases as the adsorption/desorption operation time elapses. Thus, as Δt_1 increases, $Q_{\text{eva,avg}}$ and SCP decrease. Each time an alternating operation is performed, a large amount of heat energy is supplied to the reactor structure. Therefore, when the system is operated for a specific time span, the

COP is increased when the number of alternating operations is reduced. For this reason, as Δt_1 increases as shown in Table 3, COP increases.

4. Conclusion

An experimental study on the refrigeration cycle of chemisorption heat pump system is conducted. Experiment was conducted by using a system consisting of two reactors, a condenser, and an evaporator. Experiment was performed under conditions in which coolant of 40°C, 20°C, 20°C, and 15°C was supplied to the desorption reactor, the adsorption reactor, the condenser, and the evaporator, respectively. Experiments were performed on conditions of 20, 30, and 50 minutes of adsorption/desorption operation time. As adsorption/desorption operation time increases, average cooling capacity, SCP were decreased and COP was increased. Based on this study, it is possible to confirm the performance characteristics of the low-temperature driven chemisorption heat pump system according to the adsorption/desorption operation time.

Acknowledgements

This work was supported by Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MOTIE) (20212050100010, Chemisorption heat pump system using electrochemical compressor).

References

- [1] 2050 Carbon Neutral Strategy of the Republic of Korea: Towards a Sustainable and Green Society; 2020.
- [2] Michael P., George K., Andrea C., Umberto La C., Giorgio M., 2018. Industrial Waste Heat: Estimation of the Technically Available Resource in the EU Per Industrial Sector, Temperature Level and Country. *Applied Thermal Engineering* 138, p. 207-16.
- [3] Zhiyao Y., Ming Q., Kyle R. G., 2020. Ammonia-based Chemisorption Heat Pumps for Cold-Climate Heating Applications: A Comprehensive Review. *Applied Thermal Engineering* 179, 115674.
- [4] Rogério Gomes de O., Daniel João G., 2016. Influence of the Operational Conditions on the Performance of a Chemisorption Chiller Driven by Hot Water Between 65°C and 80°C. *Applied Energy* 162, p. 257-65.
- [5] Marcos Vinício O., Rogério Gomes de O.a, Edson B., 2018. An Integrated Solution for Waste Heat Recovery from Fuel Cells Applied to Adsorption Systems. *Applied Thermal Engineering* 136, p. 747-54.
- [6] Angeles Rivero P., 2015. Innovation in Carbon-Ammonia Adsorption Heat Pump Technology: a Case Study. Institute of Refrigeration.
- [7] Huashan B., Zhiwei M., Anthony Paul R., 2017. An Optimised Chemisorption Cycle for Power Generation Using Low Grade Heat. *Applied Energy* 186, p. 251-61.
- [8] Huashan B., Yaodong W., Anthony Paul R., 2014. Modelling of a Chemisorption Refrigeration and Power Cogeneration System. *Applied Energy* 119, P. 351-62.
- [9] Z.S. Zhou, L.W. Wang, L. Jiang, P. Gao, R.Z. Wang., 2016. Non-Equilibrium Sorption Performances for Composite Sorbents of Chlorides–Ammonia Working Pairs for Refrigeration. *International Journal of Refrigeration* 65, p. 60-8.
- [10] Ruzhu W., Liwei W., Jingyi W., 2014. Adsorption Refrigeration Technology: Theory and Application. 1st ed. John Wiley & Sons Singapore Pte. Ltd.
- [11] Liwei W., Guoliang A., Jiao G., Ruzhu W., 2021. Property and Energy Conversion Technology of Solid Composite Sorbents. 1st ed. Science Press Beijing.