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ABSTRACT

It is important to allow temperature and humidity to be individually controlled to ensure a comfortable ambient environment. Typically, vapor compression refrigeration cycles are widely used for conventional air-conditioners with high energy efficiency. The refrigeration cycle can also include cooling dehumidification, which involves eliminating airborne water vapor by condensing it on the evaporator surface. However, this operation may cause refrigeration cycle efficiency to decline and require a drain tube. Moreover, the humidification process requires an additional humidifier and a water supply. The scope for controlling humidity by desiccant is attracting increasing attention as a means of overcoming these issues. The desiccant can adsorb the water vapor directly from the air and this can reduce the energy consumption required to control humidity. Additionally, it can realize non-drain dehumidification and water-free humidification. Meanwhile, although hydrofluorocarbon (HFC) refrigerants are widely used for air-conditioners, most have considerable global warming potential. Worldwide, there is a need to shift to low-GWP refrigerants, for which natural refrigerants like carbon dioxide (CO_2) may prove promising candidates. In this research, a hybrid air-conditioning system using CO_2 refrigerant with a desiccant-coated heat exchanger (DCHE) was experimentally investigated. This system comprises a compressor, a four-way valve, indoor and outdoor units, and the DCHE module. The DCHE can function alternately as a gas cooler and evaporator by controlling the expansion valves installed in the system. The DCHE and the indoor heat exchanger manage the humidity and temperature control, respectively, which allows the system to realize sensible/latent heat-separation air-conditioning. Field testing was carried out in the field-test building resembling a real residential house and the system performance was examined under dehumidification and humidification modes.

1. INTRODUCTION

Solving issues related to greenhouse gas reduction and the targets under the Paris Agreement of the Montreal Protocol crucially depends on developing technologies to reduce CO_2 emissions across the board. In the residential sector, high airtightness, thermal insulation, and optimally energy-efficient equipment are needed. Air-conditioning impacts significantly on the residential environment, and has two aspects: temperature control (sensible heat treatment) and humidity control (latent heat treatment). Sensible/latent heat-separation air-conditioning, which controls these two aspects separately, can boost comfort and energy efficiency (Nishimura *et al*., 2014). For sensible heat treatment, high-efficiency air-conditioning is generally possible using a heat pump cycle. For latent heat treatment, meanwhile, humidity control via desiccant has been attracting increasing attention. A desiccant is a substance that directly adsorbs and desorbs water from the air. It can dehumidify by adsorbing water from indoor air and, conversely, humidify by desorbing water to the indoor air. Desiccant rotors and desiccant-coated heat exchangers (DCHEs) are examples of air-conditioning equipment that use desiccants. Because the adsorption/desorption heats can be directly processed by the refrigerant, DCHEs are expected to achieve higher performance when combined with heat pump cycles.

Regulations on the refrigerants used in heat pumps have been tightened given the impact on global warming, and CO_2 is considered one of the refrigerants with the lowest environmental impact (Bolaji and Huan, 2013). The authors have studied air-conditioners with DCHE and clarified their energy-saving performance (Higashi *et al.*, 2018). In this study, a latent-sensible heat-separation air-conditioning system using a heat pump cycle with CO_2 refrigerant and DCHE was prototyped. The DCHE performs humidity control, which allows the system to realize sensible/latent heat-separation air-conditioning. Field testing was carried out in a field-test building intended to emulate a real residential house, and the system performance was experimentally investigated in dehumidification and humidification modes.

2. HYBRID AIR-CONDITIONING SYSTEM

Fig. 1 shows the configuration of the hybrid air-conditioning system. The system comprises a compressor (COMP), a four-way valve (FWV), two heat exchangers (HEX1, HEX2), a desiccant-coated heat exchanger (DCHE), two variable-expansion valves (EXPV1, EXPV2) and an air fan (Fan).

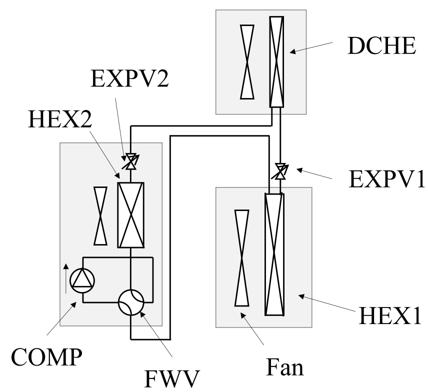
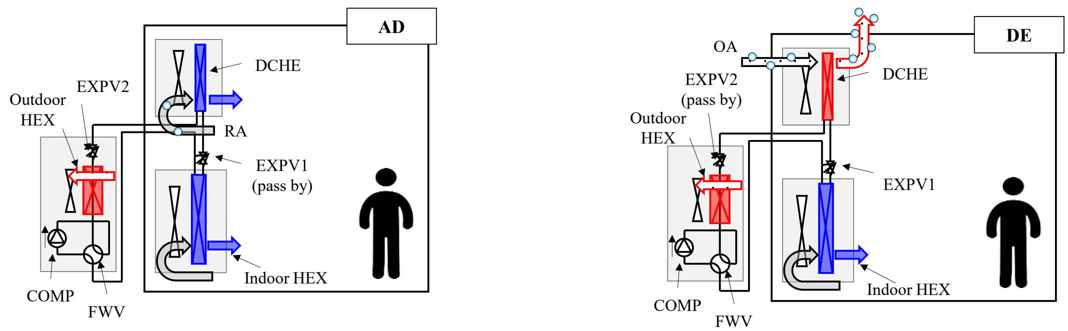


Figure 1: System structure
*HEX: heat exchanger, DCHE: desiccant-coated heat exchanger, COMP: compressor, EXPV: expansion valve, FWV: four-way valve

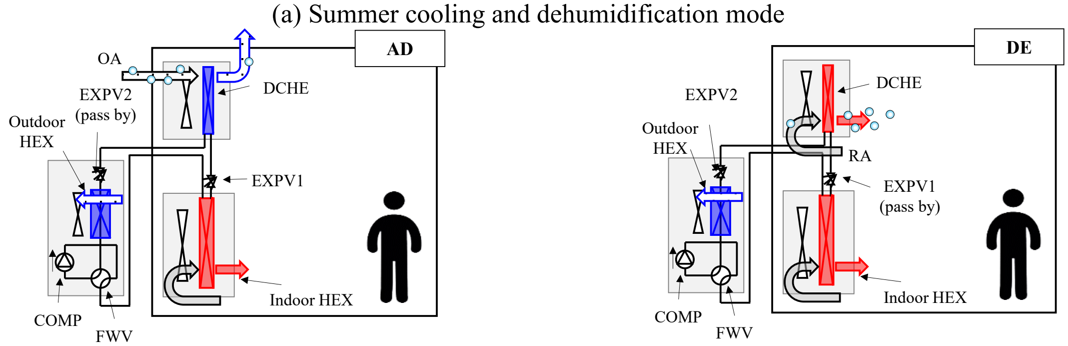
Fig. 2 shows the operation modes, Fig. 2 (a) the summer cooling and dehumidification mode, and Fig. 2 (b) the winter heating and humidification mode. This air-conditioner has two operation processes: adsorption (AD) and desorption (DE), in the summer and winter operation modes respectively.

In the summer cooling operation mode shown in Fig. 2 (a), the refrigerant flows clockwise, the indoor heat exchange (HEX1) functions as an evaporator, and the outdoor heat exchange (HEX2) as a gas cooler. The air is cooled by HEX1. During the AD process, EXPV1 is narrowed, EXPV2 is fully opened, and DCHE acts as an evaporator. The desiccant is cooled and adsorbs water from the indoor air. During the DE processes, EXPV1 is fully opened, EXPV2 is narrowed, while DCHE acts as an evaporator and the water is desorbed externally by heating the desiccant. Dehumidification by DCHE is performed by alternately repeating these adsorption and desorption processes. At this time, no condensed water is generated at the evaporator, making non-drain dehumidification feasible.

In the winter heating operation mode shown in Fig. 2 (b), the refrigerant flows counterclockwise, HEX1 works as a gas cooler and HEX2 as an evaporator. The indoor air is heated by HEX1. During the adsorption process, DCHE is an evaporator that adsorbs moisture from the outdoor air. During the desorption process, DCHE is a gas cooler and humidifies by desorbing the moisture into the room. Water-free humidification can be carried out without a water supply by utilizing the water in the outside air.



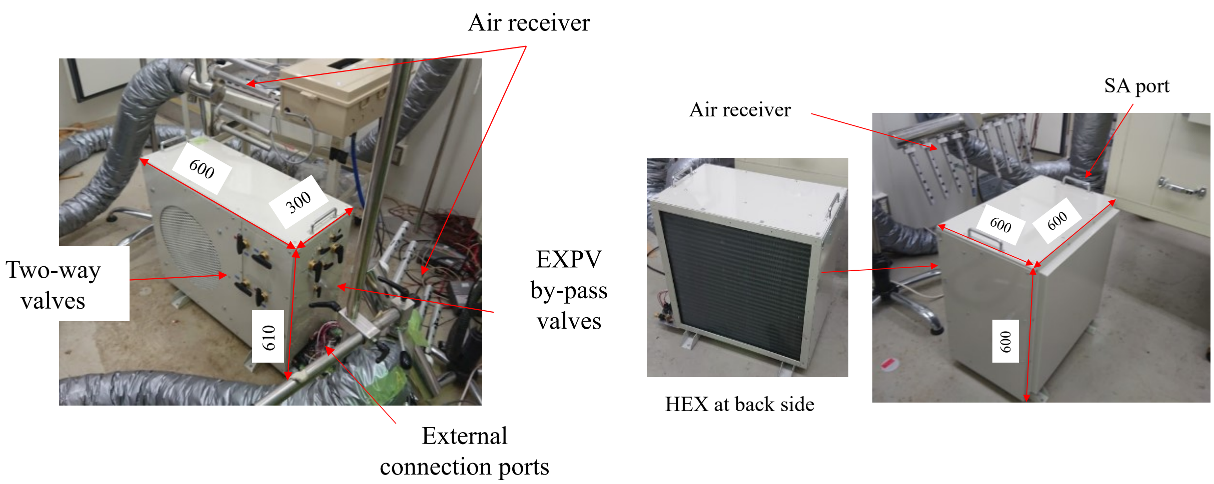
(a) Summer cooling and dehumidification mode



(b) Winter heating and humidification mode

Figure 2: Operating modes

Fig. 3 shows the prototype refrigeration cycle of the system, which comprises indoor and outdoor units. The outdoor unit, in turn, comprises a compressor, an outdoor heat exchanger, an air fan, and a variable-expansion valve. Four two-way valves are installed as alternatives to the four-way valve so that the refrigerant flow direction can be switched. The outdoor unit also includes an external connection port to connect a desiccant module described later. The indoor unit has an indoor heat exchanger and an air fan. The air is sucked in from the rear of the housing, traverses the heat exchanger, and is discharged from the front of the housing. Temperature and pressure sensors were installed in the refrigerant tubes at the inlet and outlet of the compressor, outdoor heat exchanger, indoor heat exchanger, and external connection.



(a) Outdoor unit (b) Indoor unit

Figure 3: Exterior of refrigeration cycle

Fig. 4 shows the desiccant module, which comprises a chamber for storing DCHE and an airflow path-switching section. The latter comprises slide boards, fixed boards, and motors that drive the slide boards. Moving these slide boards from side to side allows the air introduced to the DCHE to be switched (RA – DCHE – SA or EA – DCHE - OA). Four DCHEs, with a frontal area of 300 x 400 mm, were installed in the chamber. Fin-and-tube heat exchangers were used and 330g of polymer sorbent was coated on the heat exchangers. These DCHEs were connected to the external connection via refrigerant tubes as abovementioned.

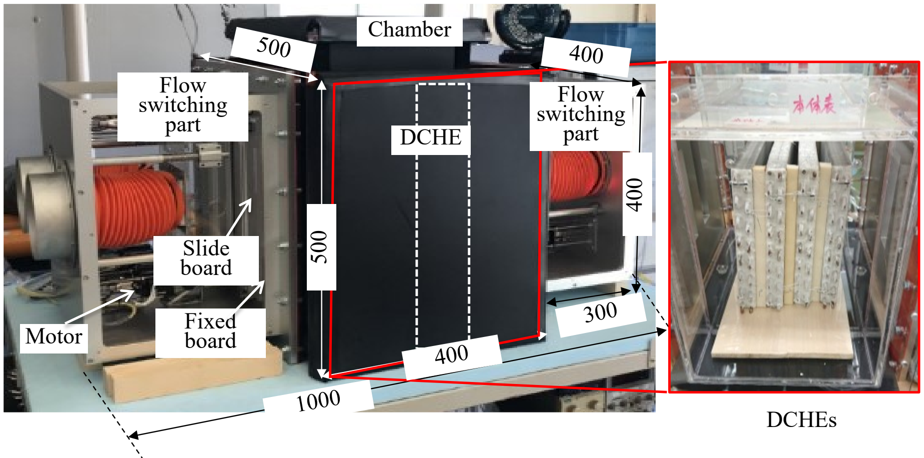


Figure 4: Desiccant module

3. EXPERIMENTAL RESULT IN CALORIMETER TEST ROOM

3.1 Methods

Before the field experiment, the performance of the hybrid air-conditioning system was experimentally investigated in a calorimeter test room, which was subdivided into two rooms, on indoor and outdoor sides respectively. The internal environment inside each room was controlled to ensure an arbitrary temperature and humidity level. Table 1 shows the experimental conditions in the test rooms. Both the summer and winter dehumidification and humidification tests complied with Japanese Industrial Standard (JIS) conditions. The AD time was varied between 10 and 30 min and the DE time was configured to be half the AD time. AD and DE processes were implemented alternately and several times until the system reached equilibrium.

The air temperature, humidity, and air velocity at the DCHE inlet and outlet were measured and the mass transfer rate at DCHE was calculated using Eq. 1. In this equation, the positive and negative values represent dehumidifying and humidifying respectively. In addition, the average dehumidification/humidification rate within a single cycle of AD/DE processes was calculated taking the time average of the mass transfer rate, as shown in Eqs. 2 and 3.

Table 1: Experimental conditions

Conditions	Indoor side Dry / Wet bulb temp. (°C)	Outdoor side Dry / Wet bulb temp. (°C)
Summer dehumidification	27 / 19	35 / 24
Winter humidification	20 /15	7 / 6

$$MTR = m_a(X_{in} - X_{out}) \times 3600 \quad (1)$$

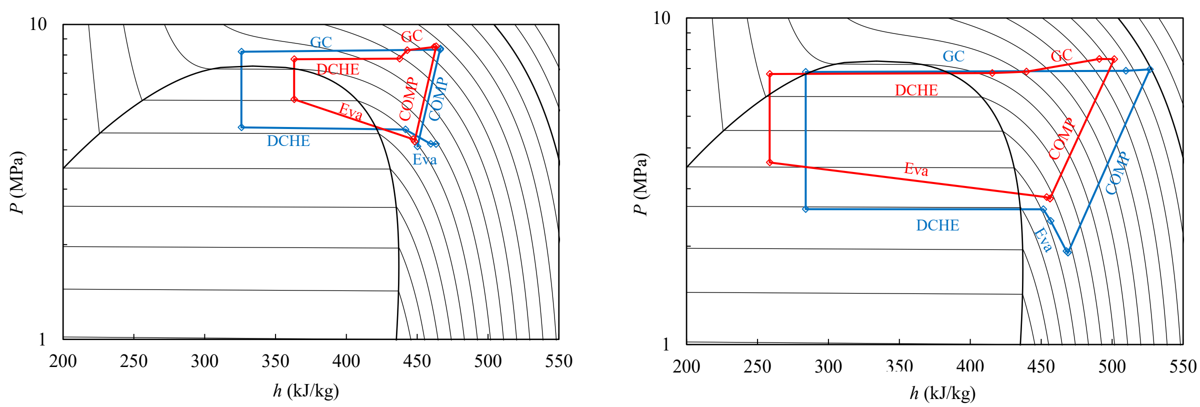
$$\overline{m_{Deh}} = \frac{\int_0^{t_{AD}} MTRdt}{t_{AD} + t_{DE}} \quad (2)$$

$$\overline{m_{Hum}} = \frac{-\int_0^{t_{DE}} MTRdt}{t_{AD} + t_{DE}} \quad (3)$$

3.2 Experimental Results

Fig. 5 shows a typical *p*-*h* diagram for summer (dehumidification) and winter (humidification) conditions, where AD and DE processes were 20 and 10 min, respectively. The horizontal axis shows the specific enthalpy of the refrigerant and the vertical axis shows its pressure. Similarly, the blue and red lines refer to the results of the adsorption and desorption processes respectively. In the adsorption process (shown by the blue line), the compressor compresses the refrigerant, then supplies it to the gas cooler. The heat was released and the specific enthalpy was decreased, whereupon the refrigerant pressure declines while traversing the expansion valve and it is supplied to the DCHE. The DCHE functions as an evaporator at this time to process the adsorption heat. Finally, the refrigerant traverses the evaporator, absorbs the heat, and is returned to the compressor. During the desorption process, conversely, the refrigerant released the heat into the DCHE as well as the gas cooler. The DCHE was functioning as a gas cooler at this time and promoted desorption by heating the desiccant. The temperature and pressure of the refrigerant supplied to the DCHE were controlled by the opening rate of the variable-expansion valves, and the AD/DE processes could be switched.

Comparing the summer and winter dehumidification conditions, it emerged that the results of the winter humidification condition showed a horizontally longer shape. This is because the inlet air temperature at the gas cooler was lower (20 °C) during winter and sufficient heat was released. Conversely, during summer, the air temperature at the gas cooler is up to 35°C, therefore heat could not be released sufficiently and the enthalpy of the refrigerant at the gas cooler outlet was relatively high.



(a) Cooling / dehumidification condition

(b) Heating / humidification condition

AD DE

Figure 5: *p*-*h* diagram

* COMP: Compressor, GC: Gas cooler, DCHE: Desiccant-coated heat exchanger, Eva: Evaporator

Fig. 6 shows the average dehumidification/humidification rates at varying AD/DE switching times. The conditions were varied as below: AD for 10 minutes and DE for 5 minutes, AD for 20 minutes and DE for 10 minutes, and AD for 30 minutes and DE for 15 minutes. Under the summer dehumidification condition, the average dehumidification rate showed a convex upward curve to the AD time; peaking at the AD of 20 minutes; 917 g/h. As for the winter humidification condition, the average humidification rate was 694 g/h at an AD time of 20 minutes. Generally, dehumidification/humidification using DCHE has optimized the AD/DE switching time that maximizes the dehumidification/humidification rate (Vivekh *et al.*, 2018). The same properties were also observed in this research.

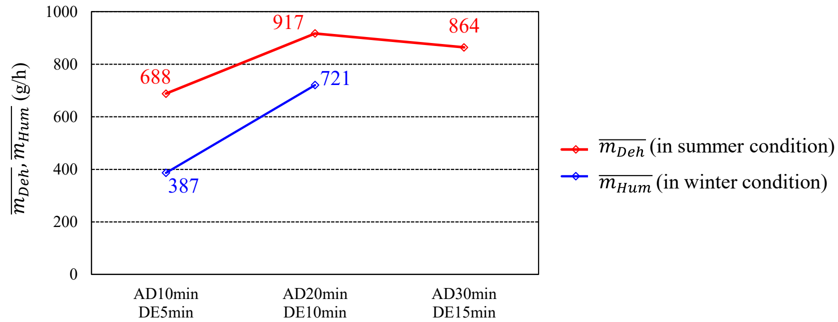


Figure 6: Average dehumidification/humidification rate

4. RESULTS IN FIELD EXPERIMENT

4.1 Methods

The hybrid air-conditioning system was installed in a field-test building and the performances were experimentally investigated in actual environments. The field-test building imitates a two-storied residential house, the second floor of which was used in this research as an air-conditioned area. Fig. 7 shows the air-conditioned area and a schematic diagram of the hybrid air-conditioning installation. The blue area is air-conditioned and covers a floor space of 44 m^2, while the red oblique lines indicate the locations of the desiccant module, the outdoor unit, and the indoor unit. The desiccant module was installed centrally on the second floor and, the outdoor unit at the rear of the building. During this research, we focused on the dehumidifying/humidifying performance of DCHE, which is why the indoor unit was installed in the attic during the experiment, to prevent any impact on the heating and cooling load.

Fig. 8 outlines the installation of the desiccant module, which was located in the dressing room at the center of the second floor. Two ducts connected on the front side carried return air (RA) and outside air (OA) respectively, with supply air (SA) and exhaust (EA) ducts on the rear. During the AD under dehumidification condition and the DE under humidification condition, the RA flowed to the desiccant module, was processed by DCHE, and then supplied to each room. During the DE under dehumidification condition and AD under humidification condition, the OA and the EA airflow passes were connected.

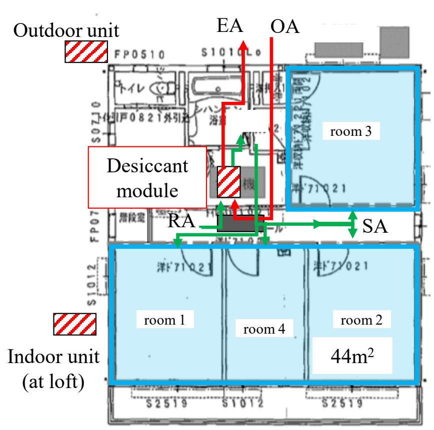


Figure 7: Overview of experimental residential house

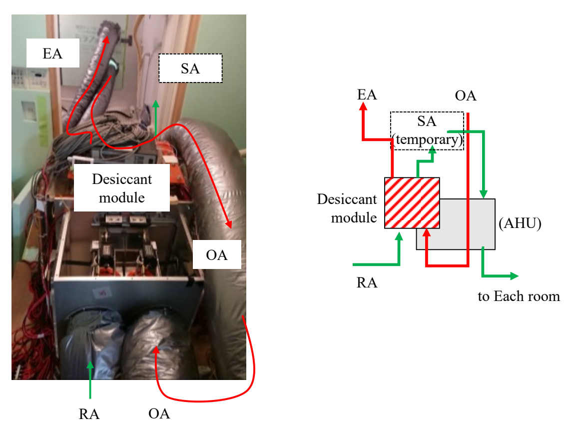


Figure 8: Installation of desiccant module

4.2 Experimental Results

4.2.2 Dehumidification condition: Table 1 shows the measurement time, weather, and ambient air temperature during the dehumidification experiment. The outside temperature was around 21.9°C, which was lower than the summer conditions mentioned in the previous section (outside temperature: 35°C). Accordingly, both the cooling and dehumidification loads were smaller.

Table 2: Ambient air conditions during dehumidification experiment

Time	Weather	Highest Temp. (°C)	Lowest temp. (°C)	Avg. temp.* (°C)
9:30 - 16:30	Sunny	28.7	17.9	21.9

*: Average during dehumidification operation

Fig. 9 shows the inlet and outlet temperatures of the air and refrigerant at the DCHE. Here, two cycles of AD/DE processes from 13:30 to 14:30 are excerpted, with the horizontal axis representing time. The AD process was carried out from 0 to 15 minutes and 30 to 45 minutes, and the DE process from 15 to 30 minutes and 45 to 60 minutes respectively. The switching time (AD: 15min, DE: 15min) was determined by the results of some trial runs before the experiments. In Fig. 9, the refrigerant inlet temperature represented by the green line was about 18°C during the AD process and lower than the inlet air temperature (of around 22°C) represented by the black line. The refrigerant eliminated the adsorption heat. During the DE process, conversely, the maximum inlet refrigerant temperature was about 60°C, the desiccant was heated and desorption was promoted. The outlet temperatures of the air and refrigerant were almost the same: around 21°C and 38°C during the AD and DE processes respectively.

Fig. 10 shows the absolute humidity of the inlet and outlet air of the DCHE, under experimental conditions that were the same as shown in Fig. 9. During the AD process, the absolute humidity levels at the inlet and outlet were about 10 and 9g/kgDA respectively. The results indicated dehumidification performed by adsorption by the DCHE. Conversely, during the DE process, the outlet humidity was high due to the DCHE desorption.

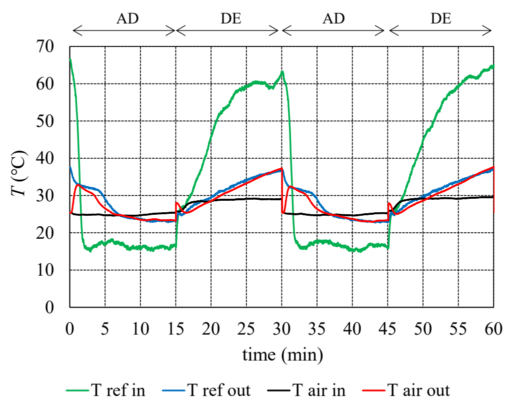


Figure 9: Refrigerant and air temperature at DCHE under dehumidification condition

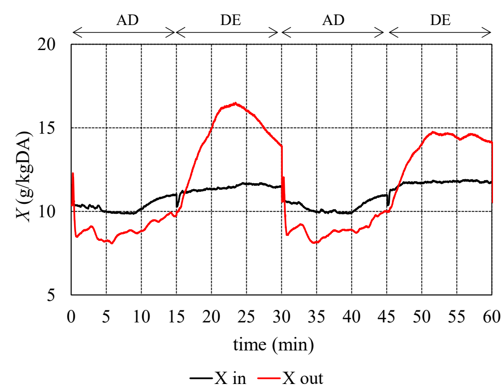


Figure 10: Absolute humidity at DCHE under dehumidification condition

Fig. 11 shows a change in room humidity and temperature under the dehumidification condition. The red line shows humidity during the experimental day, and the black line shows humidity on a different day with similar ambient conditions and no dehumidification operation. Humidity at the black line remained above 60%. As for the red line, the dehumidification operation started at 9:30, and humidity started declining as dehumidification got underway, reaching a level of around 50%. After the dehumidification operation stopped at 16:30, the humidity increased rapidly to a level of around 60% - the same as before the dehumidification operation started. Generally, comfort improves if the humidity is kept below 55% (RIKEN BDR-DAIKIN Collaboration Center, 2020). The dehumidification function of the hybrid air-conditioning system could help make the indoor air more comfortable.

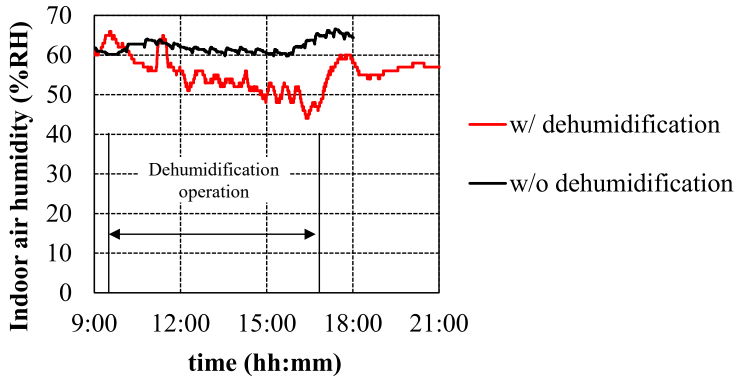


Figure 11: Comparison of change in room humidity and temperature under dehumidification condition

4.2.3 Humidification condition: Table 3 shows the measurement time, weather, and ambient air temperature during the humidification experiment. Compared to the winter condition described in the previous section (outside temperature of 7°C), the heating load was lower due to the higher outdoor air temperature. The outdoor absolute humidity was also lower than the winter condition mentioned in the previous section, approximately 4 g/kgDA.

Table 3: Ambient air conditions during the humidification experiment

Time	Weather	Highest Temp. (°C)	Lowest temp. (°C)	Avg. temp.* (°C)
10:00 – 17:00	Sunny	15.8	6.3	11.1

*: Average during humidification operation

Fig. 12 shows the inlet and outlet temperatures of the air and refrigerant at the DCHE, with two AD/DE process cycles from 13:30 to 14:20 excerpted here. The horizontal axis represents time: 0-15 min and 25-40 min for adsorption, 15-25 min and 40-50 min for desorption respectively. The switching time (AD: 15min, DE: 10min) was determined by the results of some trial runs before the experiments. The inlet refrigerant temperature, as indicated by the green line, was approximately 3°C during the AD process. This temperature was around 16°C lower than the inlet air temperature (of about 19°C) indicated by the black line. This was because of low ambient air humidity, which, in turn, required a lower adsorption temperature, while the outlet air temperature was approximately 4°C. Conversely, the maximum inlet refrigerant temperature during the DE process was approximately 50°C, and the desiccant was heated to promote desorption.

Fig. 13 shows the absolute humidity of the inlet and outlet air of DCHE, with experimental conditions equivalent to those shown in Fig. 12. During the AD process, the inlet absolute humidity was about 4 g/kg DA and the outlet humidity was around 2 to 3 g/kgDA. The results indicated that DCHE adsorbed the water from the outside air. Conversely, however, during the DE process, the humidity at the outlet peaked at about 11 g/kg DA while the inlet humidity was about 8 g/kgDA. Water-free humidification was made feasible by utilizing water from the outside air.

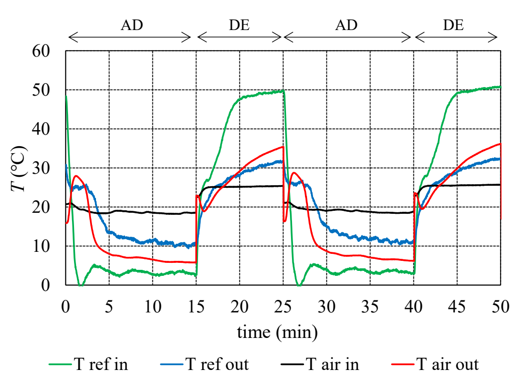


Figure 12: Refrigerant and air temperature at DCHE under dehumidification condition

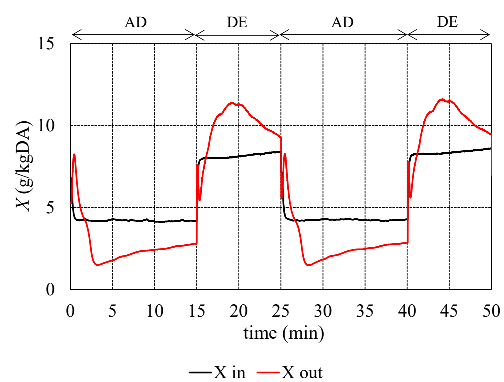


Figure 13: Absolute humidity at DCHE under dehumidification condition

Fig. 14 shows a change in room humidity and temperature under the humidification condition. The red line indicates humidity during the experimental day, while the black line shows humidity on a different day under similar ambient conditions but with no humidification operation. For the black line, the humidity remained low, at around 25%. As for the red line, the dehumidification operation started at 10:00. When the humidification operation got underway, humidity increased to around 50%, then gradually declined after the humidification operation stopped at 17:00. Indoor humidity of 40% or higher is generally recommended for comfort and infection control (Ministry of Health, Labour and Welfare, 2020). It was observed that humidification via the hybrid air-conditioning system improved the indoor air environment.

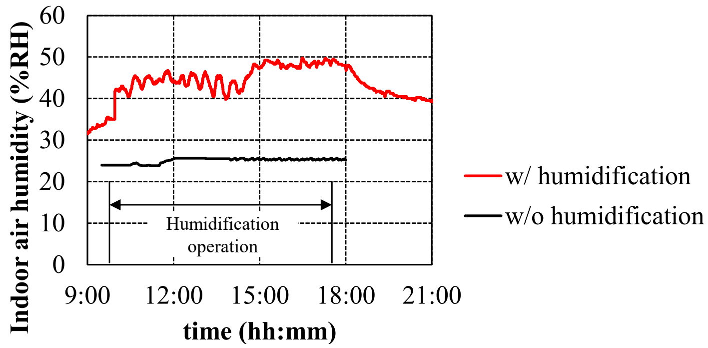


Figure 14: Change in room humidity and temperature under humidification condition

5. CONCLUSION

A prototype hybrid air-conditioning system was created and its performance was experimentally investigated. The system includes an additional desiccant-coated heat exchanger (DCEH) and uses CO_2 as a refrigerant. In this air-conditioning system, the indoor heat exchanger and DCHE handle sensible and latent heat treatment, respectively. This individual control enables the system sensible/latent heat-separation air-conditioning. In this study, field experiments were carried out and the hybrid air-conditioning system was installed in a field-test building resembling a two-storied residential house. In the dehumidification test, the relative humidity in the air-conditioned area declined due to the non-drain dehumidification. As for the humidification test, humidity increased under water-free humidification. The system was capable of maintaining humidity within a comfortable range and improving indoor air quality under actual conditions.

NOMENCLATURE

h	Specific enthalpy	(kJ/kg)
m_a	Air flow rate	(kg/s)
$\overline{m_{Deh}}$	Averaged dehumidification rate	(g/h)
$\overline{m_{Hum}}$	Averaged humidification rate	(g/h)
P	Pressure	(MPa)
T	Temperature	(℃)
t	Time	(s)
X	Absolute humidity	(g/kgDA)

Subscript

AD	Adsorption
DCHE	Desiccant-coated heat exchanger
DE	Desorption
EA	Exhaust air
OA	Outside air
RA	Return air

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