A study on desiccant system regenerated by waste heat from home-use solid oxide fuel cell cogeneration system

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ABSTRACT

Since the spread of covid-19 in 2019, it is necessary to realize an indoor environment that takes measures against viral infections such as covid-19 and influenza virus. One method for realizing such an indoor environment is to control indoor humidity. In a high-humidity environment, mold grows, indoor air quality deteriorates, and physical fatigue increases. On the other hand, in a low-humidity environment, viruses easily suspend and the immune system gets weaker. Therefore, controlling indoor humidity is necessary for human health.

Furthermore, in order to achieve carbon neutrality by 2050, there is a need for significant energy savings in facilities. As energy-saving facilities, cogeneration systems such as those utilizing fuel cells are one of the effective methods. Exhaust heat from fuel cells is commonly used to supply hot water, but a lot of waste heat goes unused in summer and warm regions, because the demand for hot water supply is low. Therefore, by utilizing this unused waste heat to control indoor humidity, it is possible to save energy and improve the total energy efficiency of the fuel cells.

In this way, by researching a desiccant system that utilizes waste heat from home-use solid oxide fuel cell cogeneration system (hereafter Ene-Farm or EF), we aim to contribute to energy conservation and to realize an indoor environment that has a good influence on human health. The results were as follows:

1) Waste heat from the EF (about 450W) is transferred to desiccant system by water, and the amount of available waste heat at this system changes with the water flow rate. As a result of experiment how to maximize the amount of waste heat utilization, we were able to transfer 380W of heat, which is approximately 80% of the waste heat from the EF, to the desiccant system by setting the flow rate to 0.2L/min.

2) In order to maximize the dehumidification amount of the desiccant unit under the condition of 1), an experiment was conducted using the return air volume (RA) and outdoor air volume (OA) as parameters. A maximum dehumidification rate of 350g/h under summer conditions (outdoor:30℃75%, indoor:27℃50%) was obtained when RA was 160m^3/h and OA was 160m^3/h.

3) As a result of simulating the room size that can be controlled to an appropriate relative humidity environment (40% to 60%) with a dehumidification amount 350g/h, it is possible to control the room size of about 30 m^2 in Tokyo and about 20m^2 in Okinawa (the highest humidity environment in Japan).

4) As a result of a demonstration experiment in Okinawa, the indoor absolute humidity environment was 10g/kg' lower than the outdoor absolute humidity environment. Furthermore, we clarified the relationship between outdoor absolute humidity and indoor absolute humidity when this system was introduced.

KEYWORDS

desiccant, humidity control, fuel cell, waste heat utilization, cogeneration system

1 INTRODUCTION

Since the spread of covid-19 in 2019, it is necessary to realize an indoor environment that takes measures against viral infections such as covid-19 and influenza virus. One method for realizing such an indoor environment is to control indoor humidity. High humidity environments during summer promote mold growth, which can worsen air quality and have adverse effects on building materials and human health[1)]. In addition, the high-humidity environment affects sweating and amplifies the feeling of physical fatigue[2)]. On the other hand, in a low-humidity environment such as winter, viruses easily suspend and the immune system gets weaker[3)4)5)]. Therefore, it is necessary to control indoor humidity appropriately throughout the year in order to realize an indoor environment that takes human health into consideration.

Furthermore, COP21 held in Paris in 2015 proposed the goal of becoming carbon neutral by 2050, and COP27 held in 2022 reaffirmed the importance of achieving the 1.5°C target. Under such circumstances, building facilities are required to achieve significant energy savings to become carbon neutral, and waste heat recovery systems such as fuel cell systems (hereafter ENE-FARM or EF) are considered to be effective[6)]. However, EF usually use waste heat for hot water supply, but in summer and in hot and humid regions, the demand for hot water supply is low and unused waste heat is generated[7)]. The unused waste heat could be used for dehumidification in the summer and humidification in the winter. In addition to improving overall efficiency, the use of unused waste heat would also increase the operating hours and high-load operation of EF.

In this way, by researching a system that dehumidifies indoor air using the waste heat from the EF, the goal is to achieve an indoor environment that contributes to energy conservation while also being considerate of human health.

2 DESICCANT SYSTEM UTILIZING ENE-FARM WASTE HEAT

2.1 System Overview

Figure 1 shows the configuration of desiccant system utilizing the EF waste heat. The waste heat from the EF is recovered by the exhaust heat recovery heat exchanger and stored in the hot water storage tank. The hot water stored in the hot water storage tank is pumped from the top of the tank to the desiccant unit and used as pre-heat hot water for regeneration. After the water is used, it is returned to the lower part of the hot water storage tank and again pumped to the waste heat recovery heat exchanger. On the other hand, the desiccant unit is a rectangular rotor honeycomb element with a dehumidification/regeneration area ratio of 1:1, and uses a polymer sorbent that can be regenerated at low temperatures as the moisture absorbing material. On the dehumidification side, indoor air (RA) with high relative humidity, pre-cooled by medium-temperature cold water (20°C) generated by a chiller, is passed through the rotor to sorb moisture, and then the air, whose temperature rises due to sorption heat, is after-cooled to room temperature before being supplied (SA). On the regeneration side, outdoor air (OA) with low relative humidity due to waste heat from the EF is passed through the rotor to desorb moisture, and the rotor is regenerated, and the air containing moisture is exhausted to the outdoors (EA).

Table 1: EF and Desiccant unit specifications

EF specifications		Desiccant unit specifications	
Power generation capacity[W]	700	Desiccant	Polymeric sorbent
Waste heat utilization capacity [W]	430	Air volume of RA[m^3/h] (Upper: Dehumidification experiment	120,140,160,180,200
Waste heat recovery temperature [℃]	65	Lower: Humidification experiment)	80,120,160
Water flow rate from SOFC [L/min]	0.2,0.3	Air volume of OA[m^3/h] (Upper: Dehumidification experiment	140,160,200
		Lower: Humidification experiment)	200

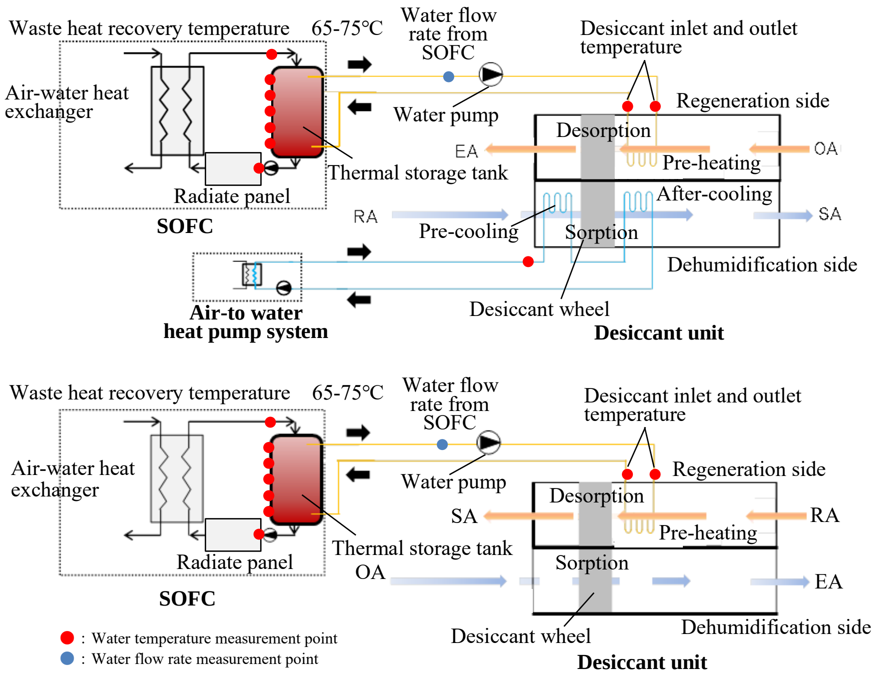

Figure 1: Diagram of desiccant system utilizing ENE-FARM waste heat

(Upper: Dehumidification, Lower: Humidification)

2.2 Optimization of waste heat utilization condition

2.2.1 Experiment Overview

Figure 2 and Table 2 show the 1st floor plan and measurement summary of the demonstration house. The EF has a 28L hot water storage tank and provides approximately 430W of waste heat at a rated power generation of 700W. The conditions for the use of EF waste heat were organized in a two-story wooden experimental housing in Aichi, Japan. The target rooms for measurement were the 1st floor LDK ＋ Japanese-style room space, and the target rooms floor area and rooms volume were 44.5 m^2 and 110.4 m^3, respectively. The measurement period was 6/4/2019-9/23/2019. The parameters of the demonstration are the flow rate of water supplied to the desiccant unit (0.2,0.3L/min).

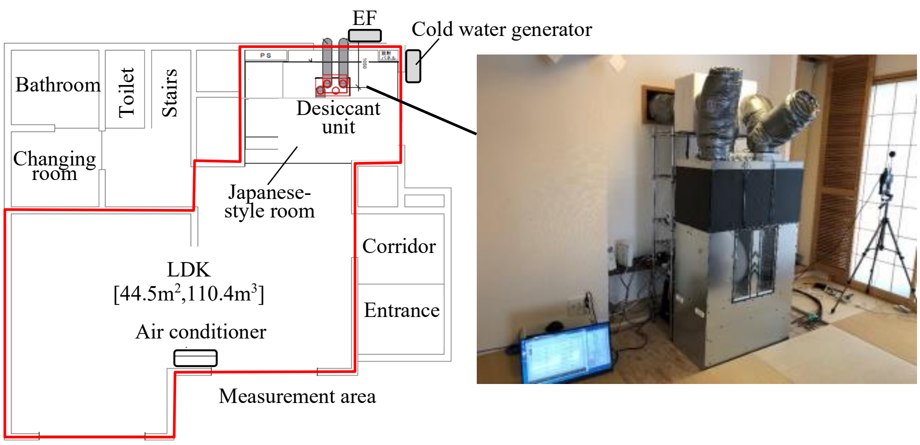

Figure 2: Experimental housing in Aichi, Japan

Table 2: Overview of experimental housing

Experimental housing	
Site	Aichi, Japan
Construction	Wooden framework method
Floor area[m^2]	67.8
Measurement area[m^2]	44.5
Measurement Volume[m^3]	110.4
Q (Heat loss coefficient) [W/(m^2・K)]	1.8
C (Equivalent leakage area) [cm^2/m^2]	2.5
Measurement period	6/4/2019-9/23/2019 (Excluding self-maintenance periods)

2.2.2 Results of experiments

The left panel of Figure 3 shows the outlet temperature of air-water heat exchanger for and the hot water temperature supplied to the desiccant at the flow rates of 0.2 L/min and 0.3 L/min. The outlet temperature of air-water heat exchanger was stable at about 65°C at both flow rates. However, the hot water temperature supplied to the desiccant was stable at 62-63°C, approximately 10°C higher when the flow rate was 0.2 L/min. This is because the 0.2L/min flow rate was generally consistent with the waste heat recovery flow rate, and the high-temperature water that remained at the top of the hot water storage tank could be used in a stable manner. The low flow rate and low return temperature to the hot water storage unit also reduced the amount of heat dissipated from the radiator.

The Right panel in figure 3 shows the amount of waste heat used in the desiccant unit during the mid-season and summer when the water flow rate is 0.2 L/min, which allows stable hot water to be obtained. Of the approximately 430 W of waste heat generated by the EF, approximately 355 W was used by the desiccant unit. This means that about 80% of the heat emitted from the EF was utilized in the desiccant unit in both the mid-season and summer seasons.

From the above, this condition is considered to be the condition that can maximize the use of the waste heat from EF. Therefore, using these conditions, the dehumidification capacity conditions of the desiccant unit were examined in the next chapter.

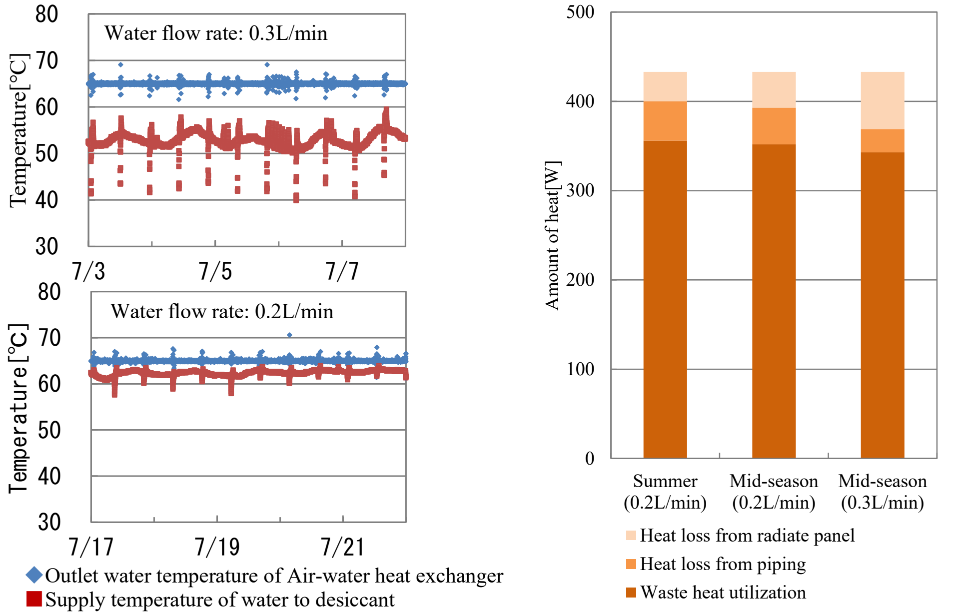

Figure 3: Experimental results graph
(Left panel: Relationship between outlet water temperature of air-water heat exchange and supply temperature of water to desiccant, Right panel: Breakdown of waste heat)

2.3 Experiments to maximize dehumidification and humidification capacity

2.3.1 Experiment Overview

Figure 4 and Table 3 show a plan of the environmental test chamber and an overview of the experiment. This experiment was conducted from 3/9-3/19/2020 in a 2-room environmental laboratory in Ibaraki, Japan. The area and volume of the warm room (WR) and cool room (CR) were 16.2 m^2 and 64.8 m^3 and 24.3 m^2 and 97.2 m^3, respectively. The temperature and humidity setting conditions for each room were 30°C and 75% (outdoor conditions) for WR and 27°C and 50% (indoor conditions) for CR. A desiccant unit was placed on the CR side, and OA and EA ducts were installed on the WR side using sleeves installed in the insulated partition wall. Parameters were determined based on prior numerical analysis and preliminary experiments; RA airflow rates of 120, 140, 160, 180, and 200 m^3/h and OA airflow rates of 140, 160, and 200 m^3/h were used as parameters. The optimum air volume that would result in the maximum dehumidification of this system under the above conditions was studied.

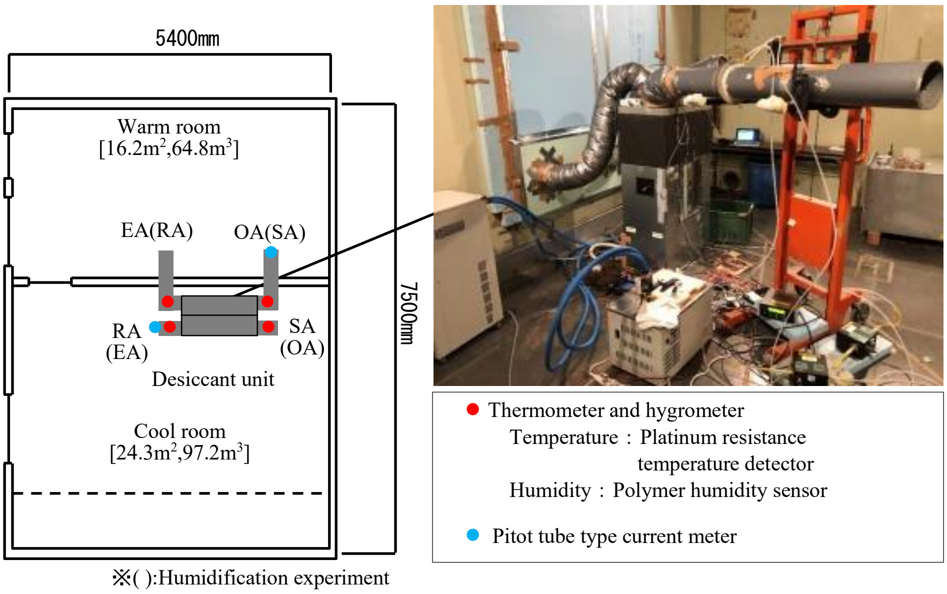

Figure 4: Environment test room

Table 3: Overview of environment test room

Environment test room	
Site	Ibaraki, Japan
Floor area[m^2]	Warm room:16.2 Cool room:24.3
Room capacity[m^3]	Warm room:64.8 Cool room:97.2
Setting temperature[℃] and humidity[%] (Upper: Dehumidification experiment Lower: Humidification experiment)	Warm room:30[℃],75[%],Cool room:27[℃],50[%] Warm room:22[℃],40[%],Cool room:5 [℃],50[%]
Measurement period	3/9/2020-3/19/2020

2.3.2 Results of experiments

The left panel of Figure 5 shows the amount of dehumidification for each RA and OA airflow rate. The peak dehumidification amount was at 160 m^3/h for both air volumes, with a maximum dehumidification rate of 352 g/h. These conditions are the conditions under which the effects of pre-cooling and pre-heating can be greatly obtained. As for the effect of pre-cooling, the air in front of the dehumidifying side wheel could be made low temperature and high humidity. As an effect of preheating, the air in front of the wheel on the regeneration side was made high temperature and low humidity. As a result, the relative humidity difference between the air in front of the wheel on the dehumidification side and the regeneration side became larger, which is thought to have increased the amount of dehumidification.

The Right panel of Figure 5 shows the dehumidification process at maximum dehumidification: RA at 27.5°C, 56.8%, 13.1 g/kg' became high relative humidity to 22.2°C, 76.1% by pre-cooling using cold water (20°C, 2L/min), and after passing through the wheel and after-cooling it became 25.2°C, 55.6%, 11.2 g/kg' and about 1.9 g/kg' of SA was dehumidified. The transition of SA from after pre-cooling is almost on the enthalpy on the air diagram. Furthermore, since it is close to the dehumidification limit, it can be assumed that the sorption and desorption process of the wheel is generally optimized.

On the other hand, the humidification rate tended to increase as the RA air volume decreased, reaching a maximum of 310 g/h at RA air volume of 80 m^3/h and OA air volume of 200 m^3/h. It is assumed that the low RA air volume and slow air velocity in the desiccant unit were the reasons for the large effect of preheating. As a result, the air before sorption could be made less humid and the humidification amount could be increased. In addition, looking at the humidification process, there is a possibility that further increase in humidification can be expected since the transition is not on the enthalpy.

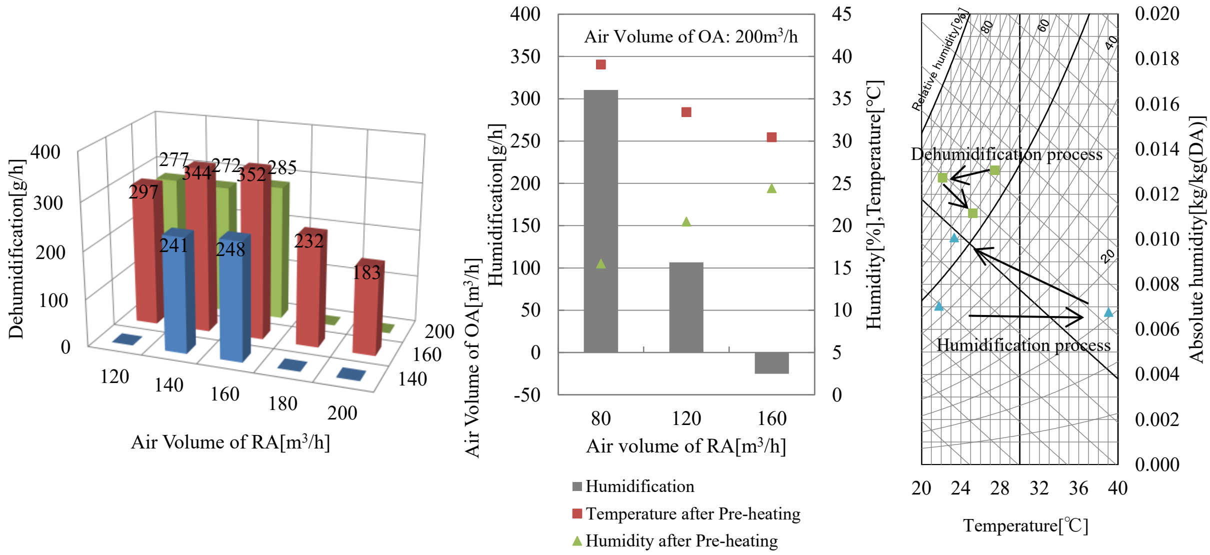

Figure 5: Diagram of the results of the experiment
(Left panel: Dehumidification by air volume, Central panel: Relationship between humidification and humidity, Right panel: Dehumidification and humidification process)

2.4 Study of the effect of improving indoor humidity environment

2.4.1 Simulation Overview

The effect of this system on improving the indoor humidity environment was investigated. Figure 6, Table 4 shows a simulation outline. The system operating conditions were dehumidification operation (dehumidification volume 350 g/h) from the first day the outdoor air temperature exceeded 25°C since June, and humidification operation (humidification volume 300 g/h) from the first day the outdoor air temperature fell below 15°C since November. During the rest of the year, ventilation, air exchange rate, was set at 0.5 times/h. AE-CAD/SimHeat[8)9)] was used as the simulation software, and standard year EA meteorological data 2000 (Tokyo) was used as the meteorological data. The housing model was designed with a total floor area of 124.0 m^2, a room volume of 444.6 m^3, a U_A value of 0.40 W/(m^2K), and a latent heat capacity of 41.9 kJ/(m^3(g/kg'))[10], with the LDK (31.3 m^2, 88.9 m^3) as the target living room. The heating/cooling schedule, human body humidification, and equipment humidification schedule were based on energy conservation standards of japan. However, in order to evaluate the effect of the desiccant system's dehumidification and humidification capabilities, only sensible heat treatment was considered in the air conditioners, not latent heat treatment.

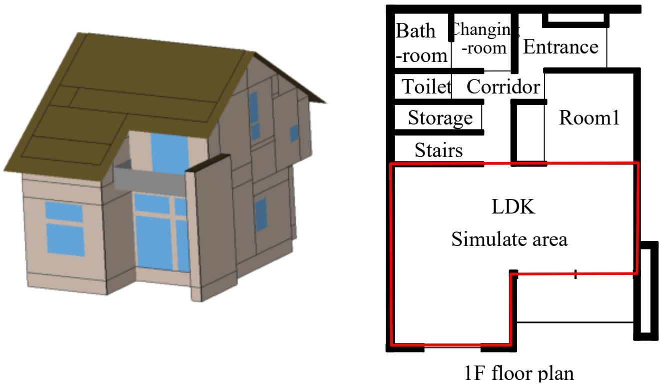

Figure 6: Simulation model

Table 4: Simulation outline

Simulation outline	
Simulation software	AE-CAD/SimHeat
Weather data	Standard EA weather data (Tokyo)
Number of people	4
Simulation room area and volume	LDK(1F):31.3[m^2],88.9[m^3]
U_A value	0.4[W/(m^2・K)]
Room latent heat capacity	41.9[kJ/(m^3(g/kg'))]
Ventilation appliance	0.5[Times/hour] Temperature exchange efficiency: 70[%] Humidity exchange efficiency: 40[%]
Desiccant system	6/15-9/30: Dehumidity (350[g/h]) 11/1-4/15: Humidity (300[g/h]) Other than the above : Ventilation (air exchange rate:0.5[Times/h])

2.4.2 Results of simulation

The left panel of Figure 7 shows the absolute humidity transition with and without this system. During the dehumidification period, the indoor humidity could be dehumidified to less than 12 g/kg' while the outdoor humidity was more than 15 g/kg'. During the humidification period, the indoor was able to be humidified to about 7 g/kg' while the outdoor was dry at about 4 g/kg'. Generally, an indoor relative humidity of 40-60% is recommended. It can be determined that a comfortable indoor humidity environment can be achieved by increasing the time within this range. Therefore, The Right panel of Figure 7 shows the percentage of annual indoor relative humidity occurrence. Without the system, about 30% of the year's relative humidity fell within the 40-60% range, but with the system, about 67% of the year's relative humidity fell within the recommended range. There were time periods during the dehumidification period when the relative humidity fell below 40% and time periods during the humidification period when the relative humidity exceeded 60%. However, this could be resolved by controlling the start-up and shutdown of the system, and considering the control of the system, approximately 88% of the time periods were within the recommended range of 40-60% relative humidity.

From the above, it was found that this system, which performs dehumidification using about 355 W of waste heat of EF, can improve the indoor humidity environment in a living room of about 30 m^2.

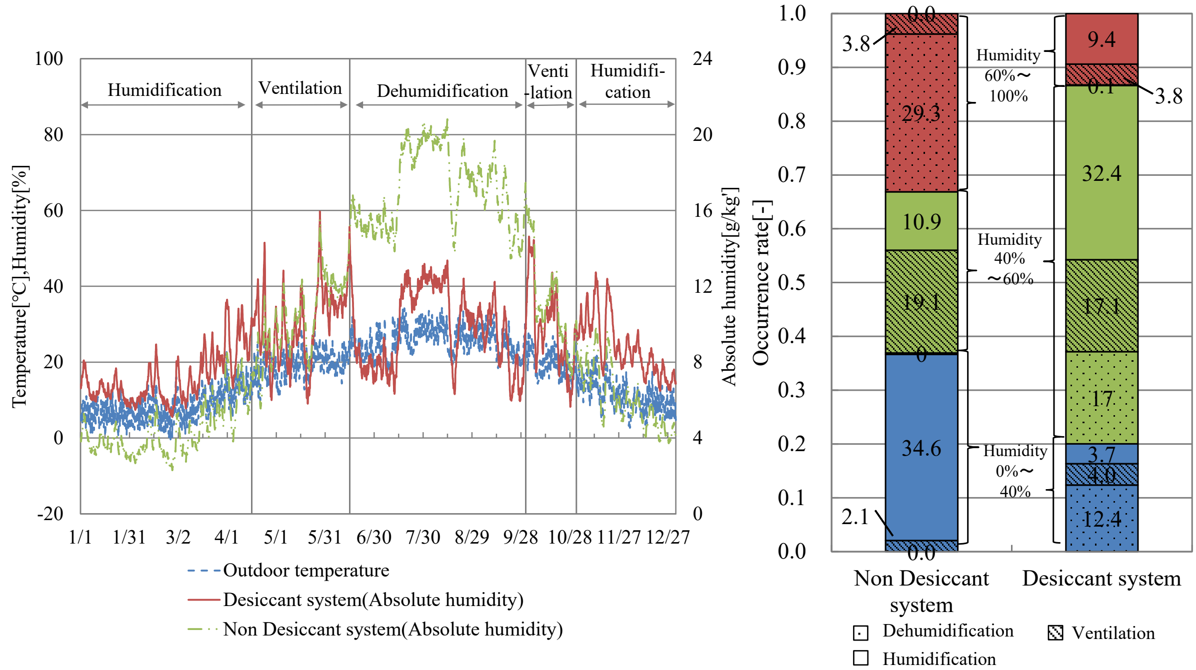

Figure 7: Diagram of the results of the simulation
(Left: Transition of outdoor temperature and indoor absolute humidity, Right: Occurrence rate of humidity)

2.5 Indoor environment measurement in actual environmental conditions

2.5.1 Demonstration Overview

Figure 8 shows an overview of the demonstration. In order to understand the effect of this system on the indoor humidity environment, a demonstration test was conducted in Okinawa, which has the harshest humidity environment in Japan and high demand for dehumidification. This demonstration was conducted in a room of a two-story RC building with an area of 16.5 m^2, assuming the LDK of a typical house. The measurement period was from 6/1/2021 to 8/31/2022, excluding the winter period. In addition, EF is operated as rated continuous operation, and the waste heat utilization conditions and the operating conditions of the desiccant unit are conducted under the conditions described in the previous chapter.

Experimental housing	
Site	Okinawa, Japan
Construction	Reinforced concrete (RC)
Floor area[m^2]	16.5
Volume[m^3]	39.6
C Value[cm^2/m^2]	1.8
Measurement period	6/1/2021-8/31/2022

Figure 8: Overview of the demonstration site

2.5.2 Demonstration Results

Figure 9 shows the indoor temperature, relative humidity, and absolute humidity for one day during the rainy season. By installing this system, the indoor relative humidity can be dehumidified to less than 60% even on days when the outdoor relative humidity exceeds 80%. The indoor absolute humidity was about 10 g/kg', which is about 5 g/kg' lower than the outdoor.

The left figure in Figure 10 shows dehumidification by indoor environment. No significant changes in dehumidification were observed under the summer environment, indicating that this system was able to demonstrate stable dehumidification capacity. Although the amount of dehumidification decreased in low-temperature environments such as the rainy season compared to the summer season, this was not considered a problem because the indoor environment was at the appropriate humidity level.

The right figure in Figure 10 shows the relationship between outdoor and indoor absolute humidity. Under the high humidity environment exceeding 20 g/kg', the indoor environment was able to achieve 5 to 10 g/kg' lower than the outdoor air. It can be said that this system has realized a humidity environment favourable to the building and human body throughout the year.

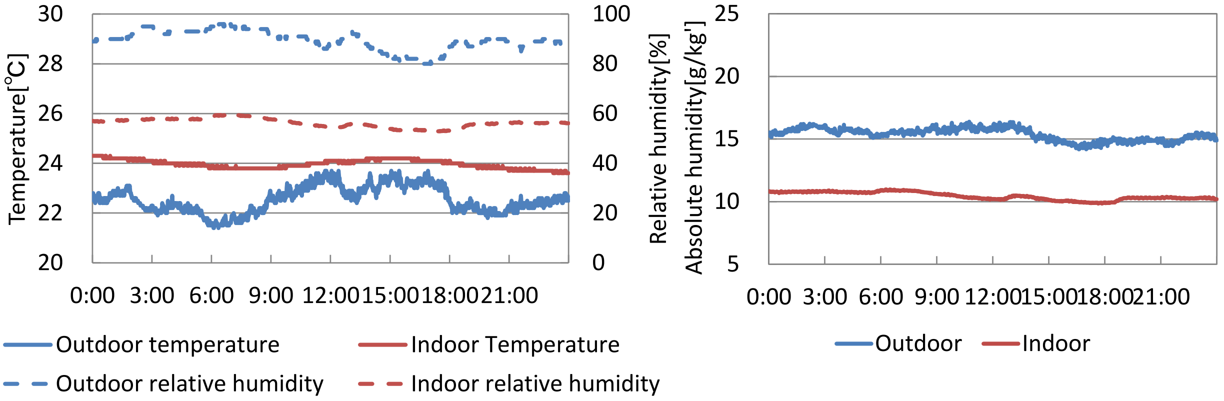

Figure 9: Indoor environmental transition during rainy season

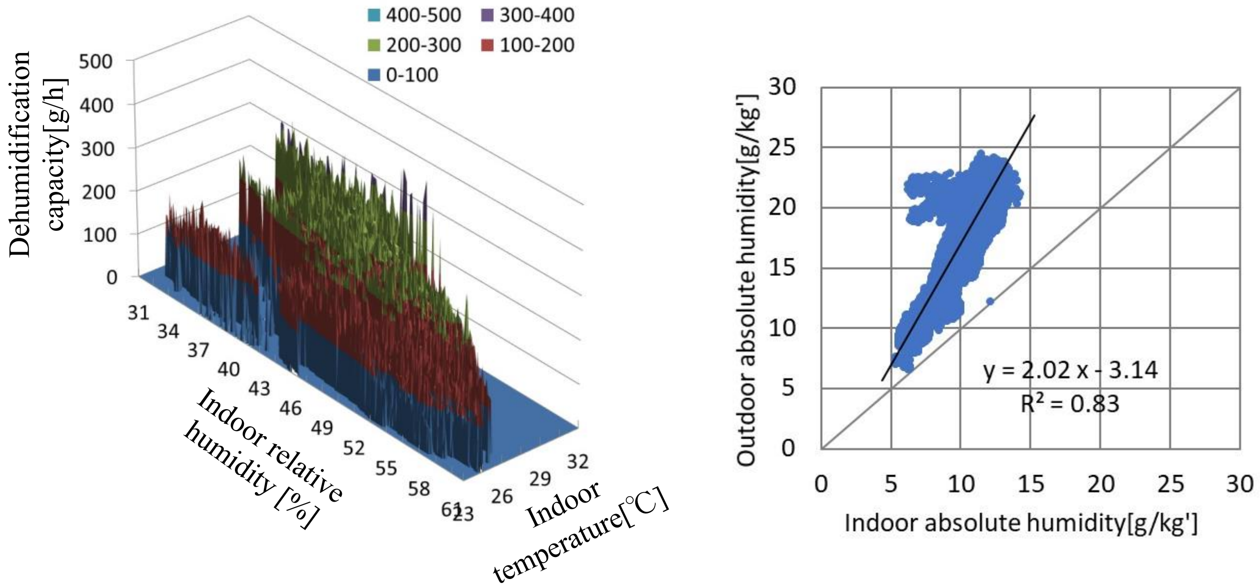

Figure 10: Left figure: Amount of dehumidification for each indoor environment, Right figure: Relationship between indoor and outdoor absolute humidity

3 CONCLUSIONS

A dehumidification system was proposed as a method of utilizing the exhaust heat from the EF, and the performance of the system was evaluated and the indoor environment was assessed through actual measurements. The following are the findings obtained.

1) Waste heat from the EF (about 450W) is transferred to desiccant system by water, and the amount of available waste heat at this system changes with the water flow rate. As a result of experiment how to maximize the amount of waste heat utilization, we were able to transfer 380W of heat, which is approximately 80% of the waste heat from the EF, to the desiccant system by setting the flow rate to 0.2L/min.

2) In order to maximize the dehumidification amount of the desiccant unit under the condition of 1), an experiment was conducted using the return air volume (RA) and outdoor air volume (OA) as parameters. A maximum dehumidification rate of 350g/h under summer conditions (outdoor:30℃75%, indoor:27℃50%) was obtained when RA was 160m^3/h and OA was 160m^3/h.

3) As a result of simulating the room size that can be controlled to an appropriate relative humidity environment (40% to 60%) with a dehumidification amount 350g/h, it is possible to control the room size of about 30m^2 in Tokyo.

4) As a result of a demonstration experiment in Okinawa, the indoor absolute humidity environment was 10g/kg' lower than the outdoor absolute humidity environment. Furthermore, we clarified the relationship between outdoor absolute humidity and indoor absolute humidity when this system was introduced.

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