Study on Environmental Control Methods of the Anterior Room During the Limited Opening to the Public of Burnt Wall Paintings in the Main Hall of the Treasure House at Horyu-ji Temple

Shuichi Kurose[1*], *Daisuke* Ogura[2], and *Hiroyuki* Kitahara[3]

[1]DAIKIN INDUSTRIES, LTD. Technical Engineering Department, Air Conditioning Sales Div, Japan
[2]Department of Architecture and Architectural Engineering, Graduate School of Engineering, Kyoto University, Japan
[3]Total System Laboratory, Japan

Abstract. The Main Hall of Horyuji Temple was damaged by fire in 1949, not only in the building but also in the preserved wall paintings. The wall paintings that survived the fire damage are national important cultural properties and, because of concerns about deterioration, are stored together with the burnt parts in a non-air-conditioned treasure house in the precincts of the temple, which is not open to the public at present as a general rule. In the previous report, a research study was initiated to open the treasure house to the public, and the effects of heat and humidity on the stored items have been studied through annual temperature and humidity measurements and numerical simulations. Based on these findings, an anterior room was constructed in the treasure house and a heat pump desiccant dehumidifier was installed as a dehumidifier to reduce the effects of the outside air and prevent the introduction of moisture into the treasure house. This study reports the control performance of the anterior room and discusses future issues, with the aim of identifying appropriate environmental control measures and operational strategies for the anterior room during periods of limited opening to the public.

1 Research background and objectives

In 1949, the Main Hall of Horyu-ji Temple was damaged by fire. The wall paintings that survived the fire, which are designated as important cultural properties, were moved to a non-air-conditioned, unventilated treasure house. This treasure house is not open to the public as a general rule, with its doors and windows always closed. There are concerns about mold growth on the wall paintings stored in the storage room. The Committee for the Conservation and Utilisation of the Wall Paintings in the Main Hall of Horyu-ji Temple has started research and studies for public access according to a previous report1) , and the behaviour of temperature and humidity variations in the treasure house has been clarified through measurements and numerical simulations to preserve the wall paintings in the treasure house, ensure that changes in temperature and humidity caused by entry are sufficiently minimal. The findings of the numerical simulation have been used to determine the formation mechanism of the temperature and humidity environment of the treasure houses. Based on the findings of these numerical simulations, a limited public exhibition has been carried out, limiting the number of visitors and the opening hours. To prevent mechanical deformation caused by drying shrinkage and moisture expansion of the murals due to airflow or the introduction of air with significantly different temperature and humidity, we avoid ventilation through opening and closing windows. In order to reduce the influence of the outside air and to prevent moisture from entering in the treasure house, and reduce the risk of mold growth, and an anterior room was installed, and a heat pump desiccant humidity control outside air unit (hereinafter referred to as a desiccant dehumidifier), which has been introduced in previous reports2)3) , was installed. The purpose of this study is to clarify the measures to be taken for proper humidity control under natural room temperature in the anterior room at the time of limited opening to the public and the operational behavior during the investigation, including the public access period. This report describes the method of adjusting the anterior room environment and the humidity control findings based on the temperature and humidity measurement findings in the anterior room and around the equipment of the desiccant dehumidifier during the limited exhibition in November 2022.

2 Overview of the treasure house at Horyu-ji Temple

A plan of the treasure house is shown in Figure 1 and a general view of the treasure house is shown in Figure 2. The treasure house for the main mural paintings and the machine room equipped with a desiccant dehumidifier supply dehumidified air to the anterior room through ducts. The anterior room is located at the anterior of the

* Corresponding author: shuuichi.kurose@grp.daikin.co.jp

https://doi.org/10.1051/e3sconf/202668902007

building and visitors enter and exit the building through the door at the anterior of the anterior room. The treasure house is all except the anterior room, where the burnt wall paintings are stored in the central room. During limited open to the public, for a limited period of time, the visitors stay in the anterior room for a certain period of time to prevent the inflow of humid outside air when it rains and to prevent visitors from bringing perspiration and moisture from their clothes into the treasure house. Access to the central room is through the door to the southwest room.

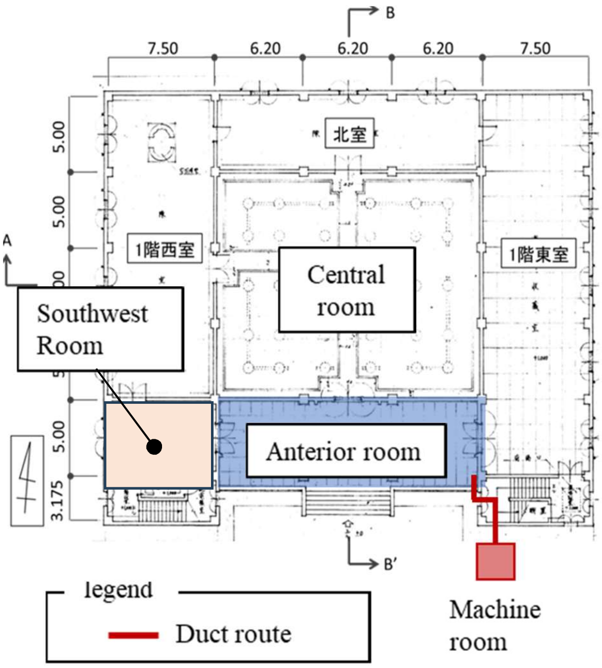


Figure 1. Ground floor plan of the Treasure House at Horyu-ji Temple, showing the layout of the anterior room, central storage area, and adjacent machine room

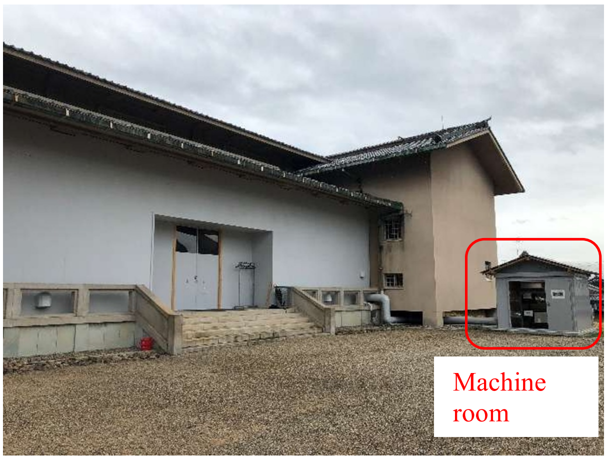


Figure 2. Exterior view of the Treasure House in the Main Hall at Horyu-ji Temple, where burnt wall paintings are stored.

3 About the machine room

A photograph of the inside of the machine room is shown in Figure 3. The machine room contains a desiccant dehumidifier, a booster fan for duct static pressure adjustment and a high-performance filter box. The high-performance filter collects dust and other particles from the outside air to prevent them from being blown into the anterior room, as the desiccant dehumidifier is an outside air treatment machine. In addition, it is clear from previous reports[2)] that the supply air from the desiccant dehumidifier drops below freezing during low outdoor temperatures in winter, so an air conditioner for cold climates was installed to heat and dehumidify the incoming outside air to prevent the temperature of the supply air dropping.

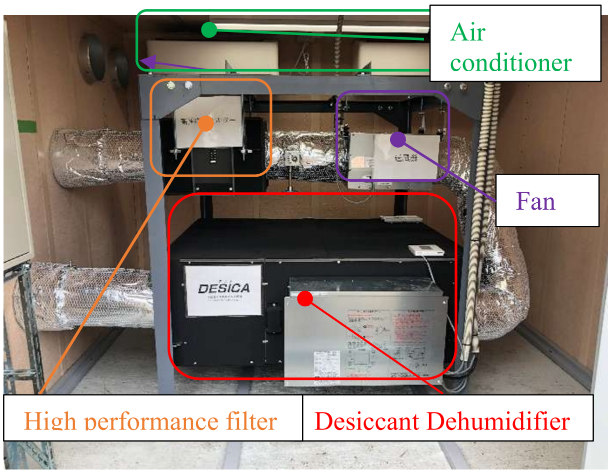


Figure 3. Internal layout of the machine room, including the desiccant dehumidifier, booster fan, air conditioner, and high-performance filter for outside air treatment.

4 About the anterior room

Figures 4 and 5 show the floor plan of the anterior room and a photograph of the interior of the anterior room, respectively. The anterior room serves as a controlled humidity adjustment space and consists of a waiting space where visitors' moisture is removed, and the space where air from the desiccant dehumidifier is blown (hereafter referred to as the buffer). The air supplied from the desiccant dehumidifier is first received in the buffer and then gently supplied to the visitors' waiting space through non-woven fabric. Regarding the humidity adjustment method of the anterior room, outside air is introduced into the machine room, and the target relative humidity for the anterior room is set by the desiccant dehumidifier, using the temperature and humidity measurement data from the control sensors installed in the anterior room and the central room where the Wall Paintings are stored, to ensure there is no difference in absolute humidity between the rooms. The desiccant dehumidifier controls the absolute humidity and supplies dehumidified air through ducts to the anterior room. However, to avoid sudden fluctuations in temperature and humidity, dehumidified air is not directly supplied to the anterior room but is first supplied to the buffer shown in Figure 4. The air, with fluctuations mitigated in this buffer section, is then gently supplied to the anterior room through non-woven fabric. The anterior room was installed for the desiccant dehumidifier setup during periods of limited opening to the public and because it has low airtightness, a positive pressure system was adopted to send dehumidified air without taking in return air.

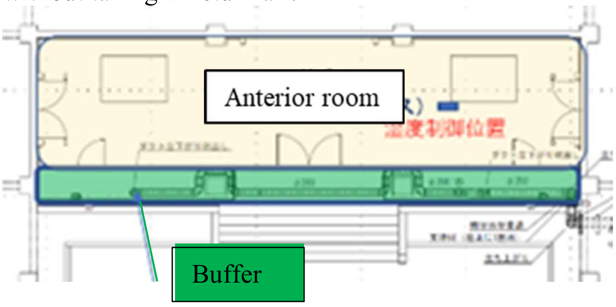


Figure 4. Floor plan of the anterior room, showing the buffer zone and waiting space designed for humidity mitigation during visitor access.

Figure 5. Interior view of the anterior room, including the non-woven fabric outlet for distributing dehumidified air.

5 Installed equipment

Table 1 shows an overview of the installed equipment.The standard equipment has been installed mainly in offices and office buildings and has the functions of dehumidification and humidification in winter when the temperature is low, but this is a refurbished unit that specialises in dehumidification for environmental control of cultural property conservation and has an extended operating range to enable dehumidification in the low outside air temperature range (5°C). The unit does not operate in humidification mode. The structure of the equipment is shown in Figure 6. The unit has two heat exchangers and switches between adsorption and desorption. The heat exchangers are coated with a desiccant element, which saves energy because it can adsorb and dehumidify moisture at a small temperature difference without cooling the air to the dew point temperature. Desorption is also possible at high efficiency and low temperatures without energy loss as the heat exchanger is heated directly by a heat pump.As reported in a previous report2) , the system can supply air by dehumidifying and cooling approximately half the moisture content of the outside air at maximum capacity.

Table 1. Technical specifications of the heat-pump-based desiccant dehumidifier used for anterior room humidity control.

Manufacturer	DAIKIN INDUSTRIES, LTD.
Name	Heat Pump Desiccant Humidity Control Outdoor-Air Unit
	"DESICA" *
Model name	HDMP50DR
Air volume	500㎥/h

*DESICA is a Daikin registered trademark in Japan.

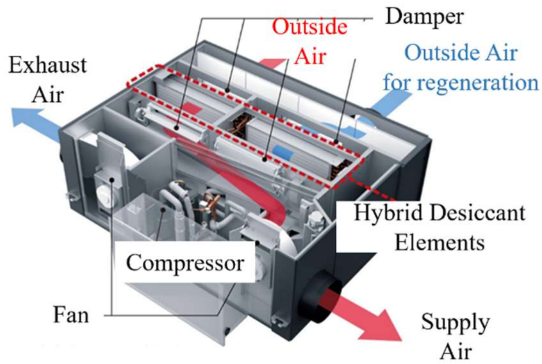


Figure 6. Internal structure of the desiccant dehumidifier, showing heat exchangers and the adsorption/desorption process. (Source: DAIKIN INDUSTRIES, LTD)

6 Measuring method

Temperature and humidity measurements were carried out as follows to verify changes in the environment around the desiccant dehumidifier equipment in the machine room and in the anterior room. Temperature and humidity were measured using Sensirion SHT35 and SHT75 temperature and humidity sensors. Measurements were taken at one-minute intervals in the anterior room and at ten-second intervals in the buffer zone and around equipment. The measured temperature and humidity information is recorded on a PC. The temperature and humidity sensors were installed in the anterior room as shown in Figure 7. at locations where they could be installed in the anterior room east and west of the anterior room (1-4) buffer east (1-7) and buffer west (1-6). Each measuring point FL+100, FL+900, FL+1700, FL+2500, FL+3,300, FL+4,100.

A total of 126 points were measured, including the anterior room and buffer. A cross-sectional view of the buffer is shown in Figure 8. Desiccant dehumidifiers supply dehumidified air directly down through a Ø150 duct in a buffer from a height of FL+2,500 (two locations, east and west). The lower end of the non-woven fabric is at FL+1,850.

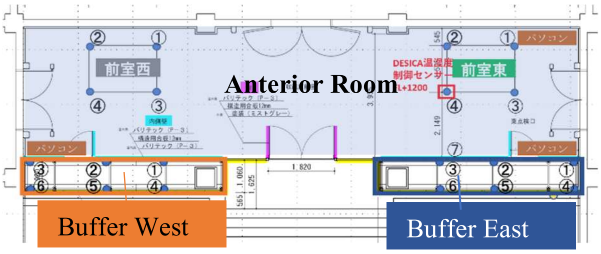


Figure 7. Locations of temperature and humidity sensors installed in the anterior room and buffer zones at multiple heights (FL+100 to FL+4,100)

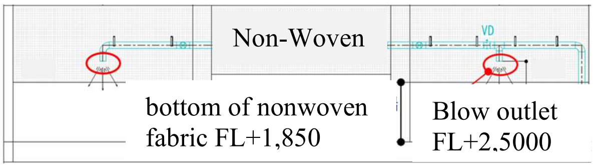


Figure 8. Cross-sectional view of the buffer space, showing the vertical positioning of the air supply outlet and the non-woven fabric distribution layer.

7 Method of investigation

7.1 Methods of limited opening to the public

The Conservation Environment WG of the Committee for the Conservation and Utilisation of the Horyuji Main Wall Paintings discussed the number of visitors and the duration of their stay in advance, based on the premise of natural ventilation through gaps, to control high humidity and humidity fluctuations and to ensure air quality to prevent new coronavirus infection among the visitors. A new anterior room was constructed and a desiccant dehumidifier was installed to suppress fluctuations in the relative humidity in the treasure house because of the inflow of heat and moisture and the inflow of outside air caused by the large number of people entering the room. As shown in Table 2, five people entered the treasure house at one time and 50 people entered the treasure house on a daily basis. The exhibition was held in November, the middle of the year when the moisture content in the air was relatively low.

Table 2. Visitor flow management and environmental control strategy during the limited public exhibition period in November 2022.

Public Period	2-30 November. Closed on 12th, 13th, 15th and 20th	Number of people in the public (Final)	992 persons, average 40 persons/day
Public Methods	10am - 4pm.(break between 1pm and 2pm) Entry and exit at 30-minute intervals 5 persons/times 50 persons/day	Public Action	Southwest Room → West Room → Central Room

7.2 Operation and management of equipment

The operational control of the desiccant dehumidifier during the public access period is presented. The desiccant dehumidifiers were not operated 24 hours a day, but were operated from approximately 9.30 am before the start of the daily open house to 4.00 pm, the end of the open house period (the operation was manual, so the time varied each day).As described in Chapter 4, the target relative humidity was set based on the temperature and humidity in the anterior room to be controlled and in the central room where the burnt wall paintings were stored.

8 Measurement findings and discussion in limited opening to the public

The findings of measurements taken under the operational control methods described in the previous section during limited opening to the public are presented and discussed.

8.1 Temperature and humidity changes in the anterior room

8.1.1 Changes in relative humidity during the open period

Figure 9 shows the changes in relative humidity, temperature and absolute humidity in the anterior room from 2 Nov to 30 Nov of the open period. The temperature change in the anterior room was represented by the control points of the desiccant dehumidifier, FL+1,700 and FL+100, which is close to the floor level. The target relative humidity was calculated from the temperature and humidity data of the central room and the anterior room at around 9.30 am before the opening to the public, and to avoid differences in absolute humidity between rooms, the target relative humidity in the anterior room between 10 am and 4 pm was set at 52.5% until 11 November and changed to 55% from 12 November. The figure shows that the relative humidity of the outside air is higher than or similar to that of the anterior room. The temperature of the outside air is lower than that of the anterior room; from 2 to 5 Nov, the relative humidity is controlled close to 52.5%; from 6 to 11 Nov, the relative humidity is lower than 52.5% and remains in the 40% range; 12 and 13 Nov were closed days, so the desiccant dehumidifier was not in operation, and the relative humidity changed naturally; from 14 to 21 Nov, the relative humidity remains in the 40% range; and from 14 to 21 Nov, the relative humidity is lower than the 52.5% range. The relative humidity remained in the 40% range from 14 Nov to 21 Nov, and from 22 Nov onwards generally remained at 55%, the set humidity at that time, except on 28 Nov. Relative humidity was in the 40% range at times. On days when the absolute humidity of the outside air was low, the relative humidity in the anterior room was lower than the target value, and when the absolute humidity of the outside air and the anterior room was equal or the absolute humidity of the outside air was high, the relative humidity was close to the target value. The relative humidity in the central room where the murals are preserved remained stable at around 60% throughout the exhibition period. Absolute humidity did not rise significantly in the anterior room even during periods when the absolute humidity of the outside air was high: November 2–4, 12–14, 20–24, and 28–30.

https://doi.org/10.1051/e3sconf/202668902007

Consequently, the absolute humidity in the central room also remained stable without significant changes. On other days, the outside air's absolute humidity was lower than that in the central and anterior room, and the humidity in the central room followed suit, being slightly lower, but no significant changes in relative humidity were observed. This is likely because supplying dehumidified air to the anterior room creates positive pressure, preventing increases in absolute humidity caused by the influx of high humidity outside air from visitors entering and exiting, or by moisture adhering to surfaces. In addition, the number of visitors allowed to enter the repository during the limited exhibition was strictly controlled to minimize heat and moisture generation from occupants, which also contributed to maintaining the stable humidity conditions.

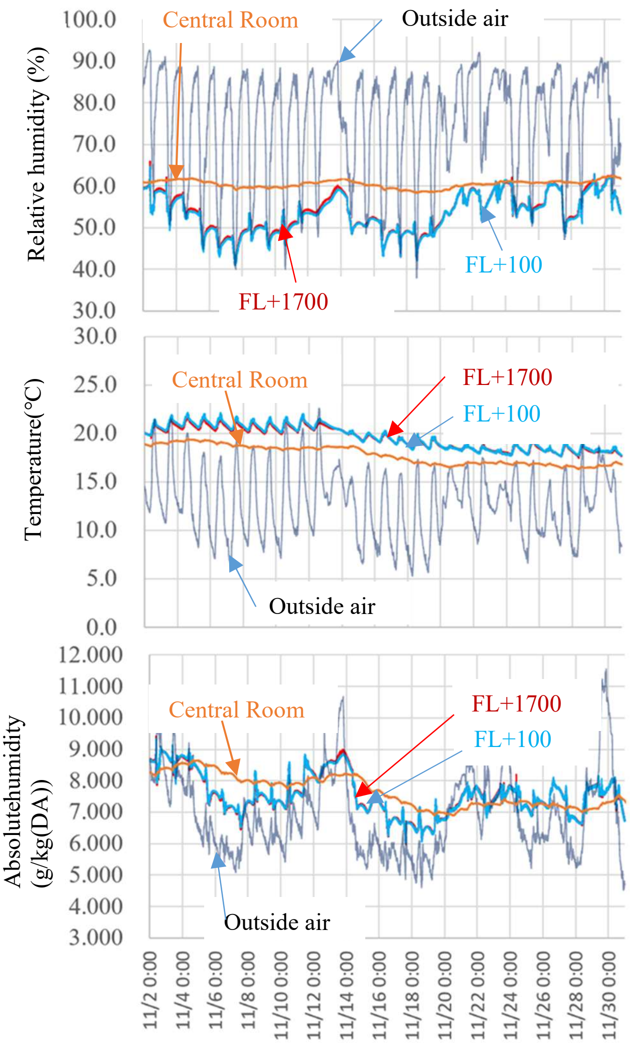


Figure 9. Time-series changes in temperature, relative humidity, and absolute humidity in the anterior room during the limited opening to the public (November 2–30, 2022).

8.1.2 Considerations on relative humidity changes. Figure 10 and Figure 11 show the changes in relative humidity, temperature, and absolute humidity from November 21 to November 24 and November 27 to 30, respectively. This includes consecutive days during the period of limited opening to allow a more detailed study of the environment in the anterior room, and 29 Nov, when there was a sudden change in absolute humidity during the day. The yellow-coloured areas in the figure indicate the limited open hours (10:00-16:00), during which the desiccant dehumidifier is in operation. The lower part of the figure shows the weather conditions during the daily open hours. The figure shows that on 21 and 22 (cloudy), the absolute humidity in the outside air was already high before the opening to the public, and the relative humidity in the anterior room fell after 10am and reached the set level of 55% because of the operation of the desiccant dehumidifier, but on 21, it rose to 57.5%. On 22nd, the relative humidity dropped to 52%, but this was due to a sudden drop in the absolute humidity of the outside air after 10am and the inflow of outside air because of the opening of the door, which also caused the absolute humidity in the anterior room to drop and the temperature to rise. It is assumed that the desiccant dehumidifier operated at different capacities until it reached the target relative humidity of 55%, and even after that, as the outside air was humid. Although the relative humidity was lower than the target, it is considered to have been controlled on the safe side. On the 23rd and 29th, both days were rainy, and the absolute humidity of the outside air rose rapidly with the start of the limited opening to the public, and the relative humidity was as high as approximately 88%.The relative humidity in the anterior room at the start of the limited opening was about 60%, and although it dropped to 57.5% with the operation of the desiccant dehumidifier, periodic fluctuations of 1% to 2% were observed. This is thought to be because of the inflow of outside air from the opening of the entrance door of the anterior room, which is used to change visitors every 30 minutes, and to moisture adhering to the visitors. After the changeover, the door to the anterior room is closed. Dehumidified air from the desiccant dehumidifier is supplied to the anterior room to create positive pressure, so there is almost no inflow through the gaps and the anterior room is controlled without high humidity.

The relative humidity in the anterior room was approximately 60% when the desiccant dehumidifier started operating on the 24th, 27th and 28th, but reached 55% after operation. The relative humidity in the anterior room increased and stabilised at about 58% as visitors entered and left the room. The desiccant dehumidifier is thought to have been in ventilation operation without humidity control because of the low absolute humidity of the outside air, and on 27th, the desiccant dehumidifier was in operation all day with ventilation because the absolute humidity of the outside air was lower than in the anterior room and the load was also lower. On the 28th, unlike the 24th and 27th, the temperature and the absolute humidity of the outside air rose sharply with the start of the limited opening. In addition, the outside air temperature and the temperature in the anterior room were almost equal, so the behaviour was almost the same as that of the outside air, but in the afternoon the room temperature was also higher,

and the relative humidity decreased. During opening hours, the relative humidity in the central room increased by approximately 0.002 to 0.003 kg/kg (DA) due to people entering and exiting, but it was confirmed that the relative humidity remained stable with no significant change.

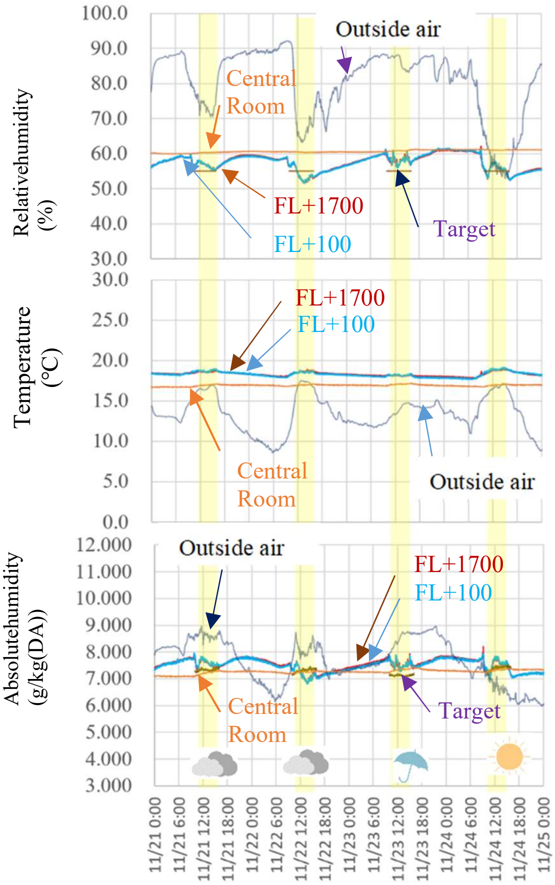


Figure 10. Daily variation of relative humidity, temperature, and absolute humidity in the anterior room (November 21–24), including the influence of visitor movement and weather conditions.

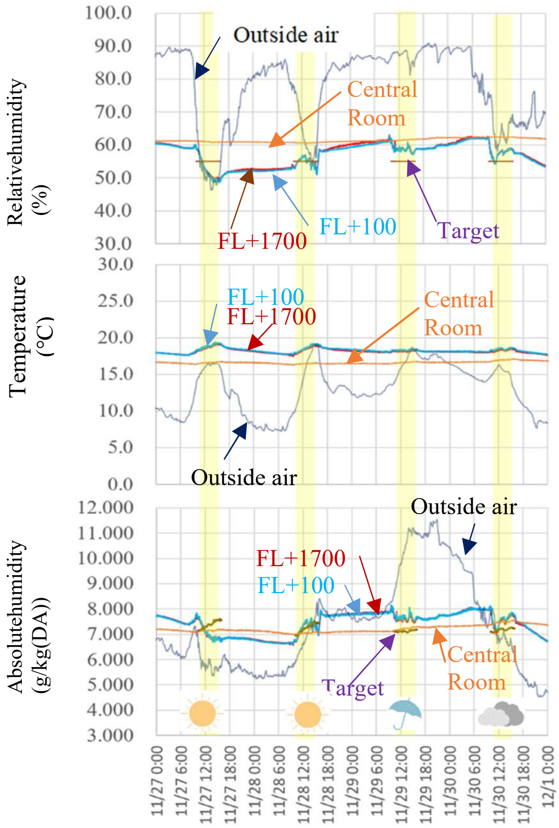
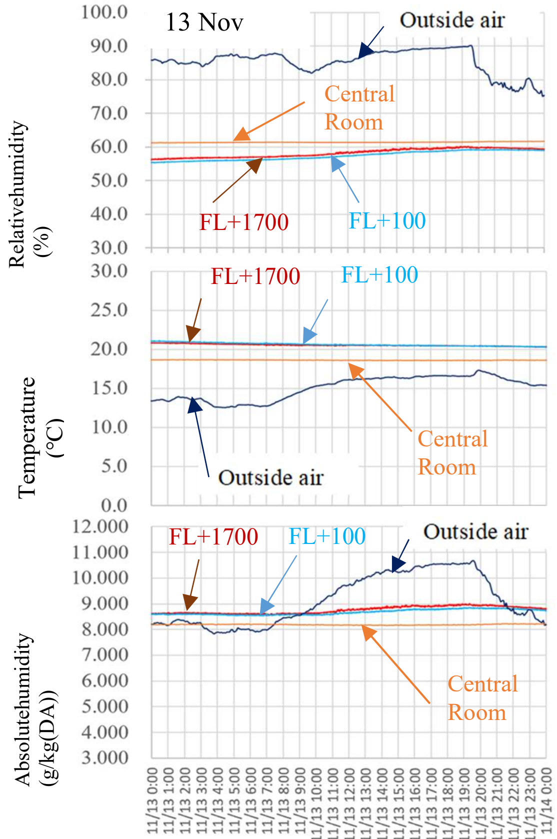


Figure 11. Environmental data during the limited opening to the public on rainy and clear days (November 27–30), highlighting humidity control performance.

(Weather symbols are quoted from DAIKIN INDUSTRIES, LTD website.)

8.2 Daily relative humidity, temperature and absolute humidity changes

Figure 12 shows the daily changes in relative humidity, temperature and absolute humidity on 13 November (Top figure), a closed day during the limited opening to the public when no people entered or left the building and the desiccant dehumidifier was not used, and on 29 November (Bottom figure), an open day and a rainy day when the desiccant dehumidifier in the anterior room was in dehumidification operation. The yellow-coloured area indicates the open hours; on 13 Nov, the relative humidity changed by 3-5%, but the fluctuations were small. The central room has no entry or exit, and the door remains closed, so both temperature and humidity, as well as absolute humidity, remain constant. On 29 November, it was raining, but the relative and absolute humidity decreased because of the operation of the desiccant dehumidifier. As mentioned above, the relative humidity is controlled at an almost constant level, although there are small fluctuations at 30-minute intervals when visitors enter and leave the room. Despite the sudden increase in absolute humidity of the outside air, the central room successfully suppressed the rise in the anterior room. Consequently, the absolute humidity also remained virtually unchanged, stabilizing at around 60% relative humidity. After the public viewing period ended, with no air movement, both temperature and humidity, as well as absolute humidity, showed no change.



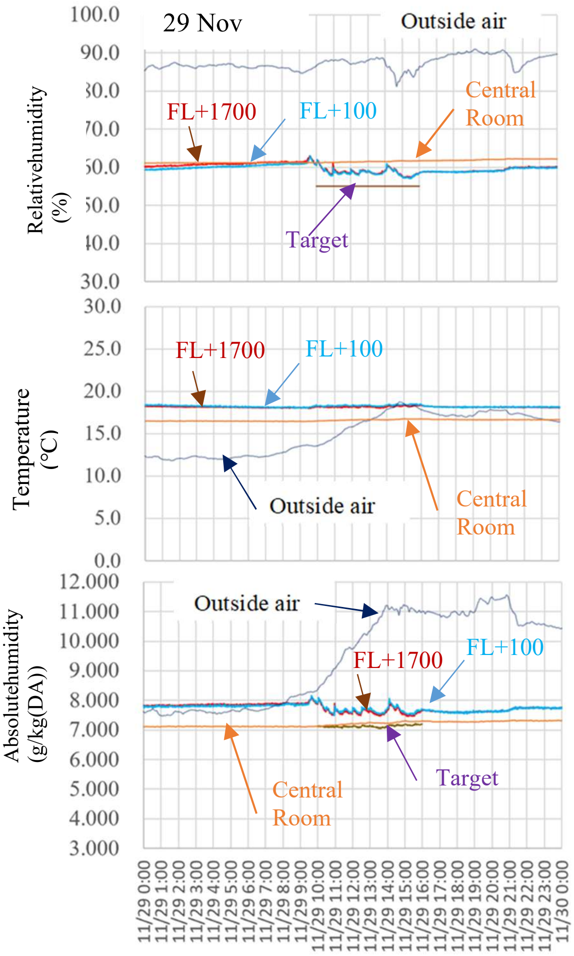


Figure 12. Comparison of temperature and humidity fluctuations on a non-operating day (13 Nov) and an operating day with rain (29 Nov).

8.3 Relative humidity in the buffer zone

Figure 13 shows the relative humidity variation in the buffer supplied with air dehumidified by the desiccant dehumidifier on a representative day, 29 November, which was a rainy day. From the figure, fine fluctuations were observed at FL+100 and FL+900.This is because of fluctuations in the supply air relative humidity when switching the heat exchanger of the desiccant dehumidifier. The fluctuations are thought to occur below the air supply outlet in the buffer from the desiccant dehumidifier (blowing directly down from FL+2,500 as shown in Fig. 8). The airflow at FL+3,300, which is located higher than the outlet, is not affected by the fluctuations of the airflow. It was confirmed that the buffer mitigates the highly fluctuating air supply and allows air to be fed from the non-woven fabric into the anterior room.

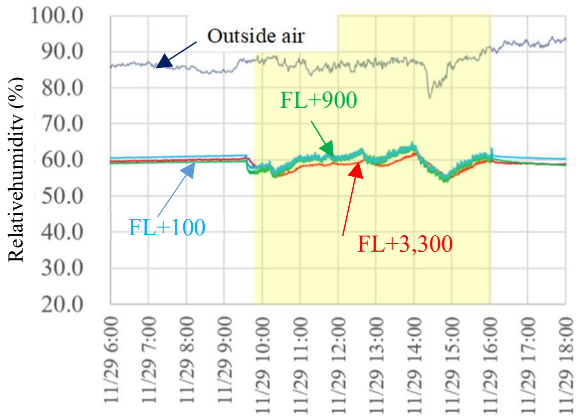


Figure 13. Relative humidity changes at different heights in the buffer zone (FL+100 to FL+3,300), indicating fluctuations in supply air during exchanger switching.

9 Summary and future tasks

Based on temperature and humidity measurements, we examined the environmental conditions in the anterior room during the limited public opening of the treasure house of the Main Hall at Horyu-ji Temple, and the following findings were identified. By introducing a desiccant dehumidifier into the anterior room, we found that the anterior room remained stable without becoming highly humid even when the absolute humidity of the outside air was high. Furthermore, the relative humidity inside the anterior room varied by about 1–2% during the entry and exit of visitors, but it was possible to reduce the relative humidity. It was confirmed that the relative humidity in the central room, where the wall paintings are stored under the specified limited opening to the public conditions, remained stable with no significant changes. By blowing dehumidified air through the buffer, the anterior room was maintained at a positive pressure , which minimized the influence of outside air and demonstrated that the buffer was effective in preventing fluctuations. In the future, consideration will be given to: (1) the desiccant dehumidifier's ability to respond to changes in load, such as a decrease in humidity when the load is small, and sudden changes in outside air, together with optimization of the relative humidity setpoint control , and (2) for annual dehumidification, especially in winter when the outside air temperature is generally below 7 °C, the preheating of outdoor air supplied to the desiccant dehumidifier using a cold-climate air conditioner will be examined..

Future renovations of this treasure house are planned to prepare for public access. In this context, the use of this desiccant dehumidifier system is being considered as a humidity control method. Based on the knowledge gained here, further studies on temperature and humidity regulation inside the treasure house will be conducted.

Acknowledgments

Acknowledgement is made to the following organizations and individuals:

The cooperation of Horyu-ji Temple, The Asahi Shimbun Company and the members of the Conservation Environment WG, the secretariat of the Committee for the Conservation and Utilisation of the Wall Paintings in the Main Hall of Horyuji Temple, was gratefully acknowledged.

This research was partly funded by Grant-in-Aid for Scientific Research (A) (Issue no: 24H00349, PI: Daisuke Ogura).

References

1) Imaoka et al. " Study on conservation and exhibition of burnt wall paintings in Main hall, in treasure house at Horyu-ji Temple -Study of environmental measurements in treasure house during the limited opening to the public in 2021-" 2022 Kinki Branch Research Presentation Meeting of the Architectural Institute of Japan. (In Japanese)

2) Kitahara, Kurose et al. "Investigation of a storage room dehumidification system 1st Report: Dehumidification performance test at low outside temperatures" Proceedings of the Japan Society of Air-Conditioning and Sanitary Engineering [2021.9.15-17 (Fukushima)] P249-P252 (In Japanese)

3) Kurose, Kitahara et al. "Case studies of countermeasures to the problem of high humidity in storage rooms: Second report, field tests - delivery and measurement", Proceedings of the Japan Society of Air-Conditioning and Sanitary Engineering Conference [2021.9.15-17(Fukushima)] P253-P256 (In Japanese)