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Active Environmental Control Strategies for Brick Historical Buildings, Combining Heritage Conservation and Thermal Comfort

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Abstract. For historical buildings, it is a challenge to utilize HVAC system to improve the thermal comfort within a reasonable range without increasing the risk of deterioration. This research selected a traditional temple building located in Hubei Province, China, aiming to clarify the impact of different operation modes of heating systems on the preservation status of the building, and to further propose reasonable active environmental control strategies. A two-dimensional hygrothermal model of the temple building was established and used to evaluate the influence of different heating parameters, operation schedules, and ventilation strategies on heritage conservation and thermal comfort with the application of floor heating. The main conclusions are as follows: for Honghua Temple, low-level heating at 16 °C with conventional ventilation or heating at 18 °C with enhanced ventilation is the preferred solution; enhanced ventilation mode can reduce the risk of mold growth while satisfying the convenience of using the Buddha worship space; for intermittent heating in winter, preheating the system is necessary, and maintaining a low heating level at night is more conducive compared with shutting down the system directly; the impact of evaporation increasing caused by heating should be weighed in active environmental control.

1. Introduction

Architectural heritage protection is an important application field of building physics. There are a large number of historical buildings in contemporary society. These buildings face two major issues: deterioration under the external climate fluctuations; their original thermal performance incapable of meeting the needs of modern thermal comfort. In this case, especially for historical buildings where people need to stay for a long time, active environmental control using equipment such as air conditioning, floor heating, and ventilation has become a possible solution.

Since the building still needs to be put into use, many historical buildings around the world have introduced air conditioning and other environmental control systems in the reconstruction and renovation projects. UK National Trust developed an environmental control strategy based on “humidistatically controlled heating” for the care of collections on open display and maintained relative humidity (RH) in 40-65 % by heating alone [1]. In a mountain church situated in the village of Rocca Pietore in the Alps, after the installation of the conventional hot air heating system, the church also introduced electrically heated pews and carpets to ensure thermal comfort [2]. In the case of the Art



Gallery in the Academy of Fine Arts, Vienna, a ventilation system with dehumidification and cooling functions was introduced. The pure radiant heater was also added to the wall, so as to ensure indoor warmth in winter [3].

However, due to the use of environmental control equipment, active control has certain invasiveness, which brings instability and raises the risk of deterioration. Scholars have also launched multi-dimensional research on related issues. Camuffo et al. have discussed some church cases based on the EU funded Friendly-Heating Project and analyzed the benefits and limitations of different heating forms, pointing out that the needs for cultural heritage and energy conservation are divergent, and the extent of the compromise should depend on the vulnerability and value of specific heritage [4]. Due to the lack of thermal quality of the external wall in combination with a wrong convective heating system, mold was found on the back of the painting and the drapery on the wall in the Vienna Museum of Fine Arts. Kaerferhaus et al. used a tempering system to heat the wall and turned off convectors and humidifiers to solve the problem [3]. Bencs et al. analyzed the Rocca Pietore Church to compare the hot air heating system and low-temperature radiation system from the perspective of the distribution change of gaseous air pollutants [2]. Muñoz-González et al. evaluated the environmental conditions of the Church of San Francisco de Asís in the Mediterranean region before and after using HAVC system [5].

Different from the passive control measures, the active control has flexible combination possibilities. The actual effect of using different schedules, system settings, and ventilation strategies is lack of quantitative data support. In fact, brick is a typical material in historical buildings. Due to the structural characteristics of large pore size and small mineral particles, brick materials are more prone to deterioration, such as efflorescence, mold growth, and so on. Therefore, specific environmental control research for brick buildings is also necessary.

In this study, Honghua Temple in Huangshi City, Hubei Province, China is selected as the main research object. Combined with environmental monitoring and a two-dimensional hygrothermal model, this research explores how to use active environmental control to provide suitable preservation conditions for brick historical buildings in the winter heating period and also to make the buildings better serve its users. This research provides quantitative data support and possible application directions for the implementation of active control strategies in historical buildings.

2. Methods

2.1. Research object

The Honghua Temple building is composed of two function halls called the Great Buddha's Hall and the Hall of Patriarch. Figure 1-2 shows the appearance of the building and its surrounding environment. The building is located in Dongfang Mountain Forest Park. The annual average temperature on the mountain is about 16 °C, which is 3~4 °C lower than that on the plain area nearby. The building has a traditional Chinese sloping roof with concrete and brick structure. The envelop enclosure uses traditional blue bricks and the roof is covered with grey tiles.



Figure 1. Architectural appearance of the Honghua Temple.



Figure 2. Surrounding environment of the Honghua Temple.

Honghua Temple is a place for Buddhists' morning classes and daily worship. In 2019, it started the renovation project planning. The new project introduces a floor heating system in the middle space of

the building (Buddha worship space) to improve comfort. To protect the building from being affected by improper heating behavior, environmental monitoring and simulation were carried out.

2.2. Environmental monitoring

Before the model development of the historical building environment, comprehensive field measurement and monitoring was implemented. 7 monitoring points were set up on the site (Figure 3). The interior can be divided into three areas. At points 001~004, the air temperature and humidity of the front room, middle room, back room and outdoor were measured by electronic temperature and humidity recorders (type: HOBO MX2301; precision: $\pm 0.2^\circ\text{C}$ and $\pm 2.5\%$; measurement range: $-40\sim +70^\circ\text{C}$ and $0\sim 100\%$). At points 005~007, the surface temperatures of the walls, ground and Buddha statue of the middle room, were measured by T-type thermocouples and recorder (type: TESTO 176-T4; precision: $\pm 0.3^\circ\text{C}$; measurement range: $-200\sim +400^\circ\text{C}$). The monitoring was started on January 3, 2020, and the air temperature, humidity and surface temperature were recorded every 30 minutes.

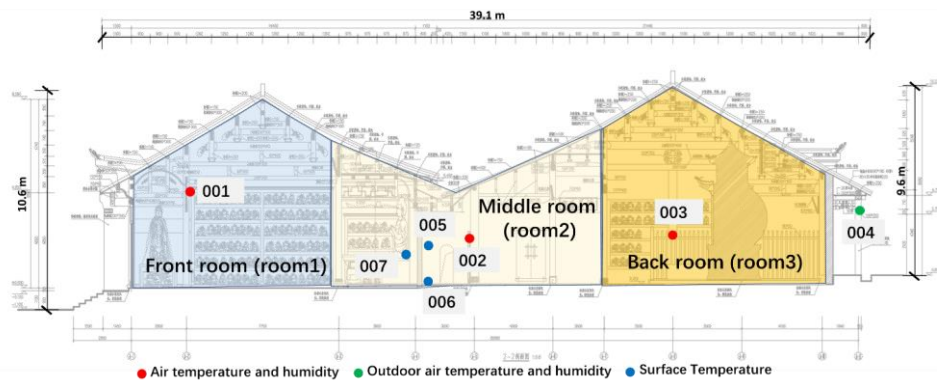


Figure 3. Layout of environmental monitoring points.

2.3. Simulation model

2.3.1. Basic building model

Firstly, the basic model of Honghua Temple is established. The longitudinal section located at the central axis was selected and partitioned (Figure 4a). The heat and moisture exchange at all air-solid interfaces will be simulated using meteorological data. Figure 4b shows the two-dimensional calculation area ($46.9\text{m} \times 27.7\text{m}$) and grid division (419 (horizontal) $\times 279$ (vertical)). The core area adopts dense grid ($0.1\text{m} \times 0.05\text{m}$), and the north and south walls adopt denser grid ($0.05\text{m} \times 0.05\text{m}$). Furthermore, the interior of the building is divided into three areas: the front room (Room1), the middle room (Room2), and the back room (Room3). The foundation and wall are made of traditional Chinese blue bricks, and the roof is made of wood and grey tiles. Because of the rainproof effect of the grey tiles covering outside and the oil layer covering the inner surface of the sheathing, the roof material in the model is assumed to be impermeable. Additionally, based on the geologic report, the groundwater level is set at 1 m.

A heat and moisture simultaneous transfer model proposed by Matsumoto [6] was adopted in this research. The time step is set as 30s and the main equations used are as follows (the water chemical potential μ in Equation (1) is used to express the moisture state; Equation (2) and Equation (3) are the heat balance equation and moisture balance equation):

$$\mu = R_v T \ln(h) \quad (1)$$

$$c\rho \cdot \frac{\partial T}{\partial t} = \nabla[(\lambda + \lambda'_{Tg})\nabla T + r\lambda'_{\mu s}\nabla\mu] \quad (2)$$

$$\rho_w \left(\frac{\partial \Psi}{\partial \mu} \right) \left(\frac{\partial \mu}{\partial t} \right) = \nabla[\lambda'_{\mu}(\nabla\mu - gn) + \lambda'_T \nabla T] \quad (3)$$

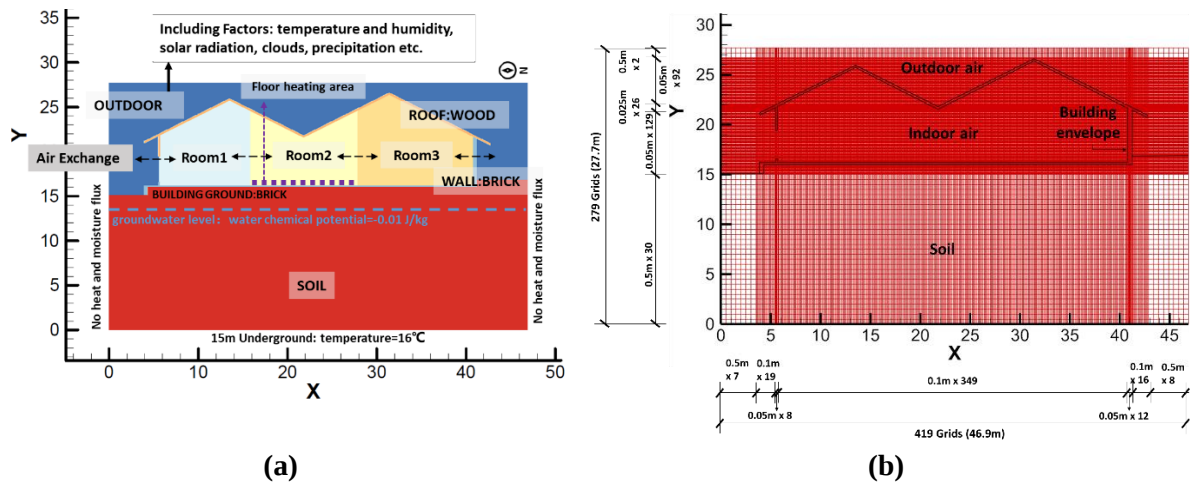


Figure 4. Schematic diagram of heat and moisture transfer model of Honghua Temple: (a) model partitions and boundary conditions, (b) calculated region and meshing.

2.3.2. Floor heating model

To predict the suitability of heating behavior in Honghua Temple, a floor heating system is added in Room2 of the model (Figure 4a). The heating system consists of finishing layer (hardwood), heating panel and compound insulation layer (50 mm XPS with impermeable heat-reflecting film). Furthermore, several kinds of possible active control schemes were analyzed. Table 1 shows the control variables in the simulation. The possibility of enhanced ventilation and intermittent heating is considered for the space particularity of Room2 (Buddha worship space). By adjusting these variables, the parameters related to the preservation of historical buildings (water content, evaporation, etc.) and the parameters related to the thermal comfort of users (indoor temperature and humidity) can be adjusted too.

Table 1. Description of control variables in floor heating simulation.

Variable type	Variable range & mode description	
Temperature Setpoint ^a	14 °C, 16 °C, 18 °C, 20 °C, 22 °C, 24 °C	
Ventilation	Conventional Mode	Enhanced Mode
	ACH ^b :	ACH:
	R1 ^c to Outdoor is 0.8 h ⁻¹ ; R2 to R1 is 0.25 h ⁻¹ ; R2 to R1 is 0.25 h ⁻¹ ; R3 to Outdoor is 0.6 h ⁻¹	R1 to Outdoor is 0.8 h ⁻¹ ; R2 to R1 is 2.8 h ⁻¹ ; R2 to R1 is 0.25 h ⁻¹ ; R3 to Outdoor is 0.6 h ⁻¹
Operation Mode	Continuous Heating	Intermittent Heating
	System remains operational throughout the day with a constant T _p value	Mode A: T _p maintains 24 °C during the daytime (5:00-17:00) and system shutdown at night; Mode B: T _p maintains 24 °C during the daytime (5:00-17:00) and maintains a low heating level of 18 °C at night

^a Setpoint refers to the floor surface temperature T_p.

^b AHC=Air changes per hour; the Enhanced mode increases the ventilation between R1 and R2.

^c R1=Room1, R2=Room2, R3=Room3.

3. Results

3.1. Environmental monitoring results

Figure 5 shows the monitoring results of Honghua Temple during the winter from 2020.01 to 2020.02 (without heating). January is the coldest month in 2020. Figures 5a-5b shows the environmental fluctuation range during January, with the outdoor temperature at -1~12°C, the indoor temperature at 0~8°C, the outdoor RH at 40~100%, and the indoor RH at 60~100%.

Based on the monitoring results, it can be judged that the building has a low comfort level and low air tightness in winter (the fluctuation range of indoor climate is close to that of outdoor). Room1 has a larger ventilation level. From January to February, indoor RH was higher than 70% for more than 84% time. During the field investigation, traces of mold growth were also found in some indoor wall surfaces [7]. Therefore, the existing preservation environment is not ideal, and the building has a practical need to introduce some environmental control. Figure 5c shows no obvious risk of condensation without heating. Considering the potential changes caused by heating, these indicators will be further compared.

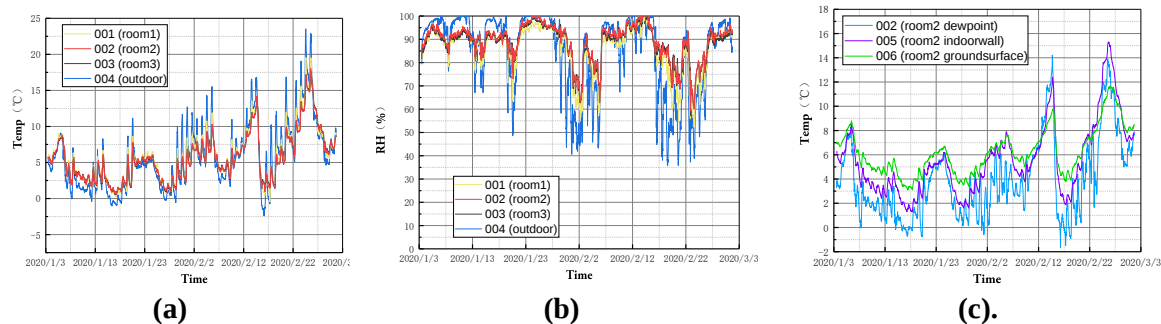


Figure 5. Environmental monitoring results of Honghua Temple (2020.01~2020.02): (a) air temperature, (b) air RH, (c) dewpoint temperature and surface temperature.

3.2. Validation of proposed model

January 19, which is the day closest to the monthly average temperature and humidity of the coldest month, is selected as the winter typical day for validation of the proposed model. The simulated results compare fairly well with the monitored results (Figure 6a). Small deviation after 2 pm maybe because the AHC does not account for variation in the real situation but uses a fixed value. It can be judged that the model can offer reasonable feedback to the thermal and humid environment of Honghua Temple. To meet energy conservation needs, all doors shall be properly shielded during the heating period (Different ventilation settings were used in floor heating model). The AHC settings for door opening condition are: R1 to Outdoor is 10.5 h^{-1} ; R2 to R1 is 5.5 h^{-1} ; R2 to R1 is 0.86 h^{-1} ; R3 to Outdoor is 2.86 h^{-1} . The door closing condition can refer to the conventional ventilation mode in Table 1). Figure 6b shows the comparison.

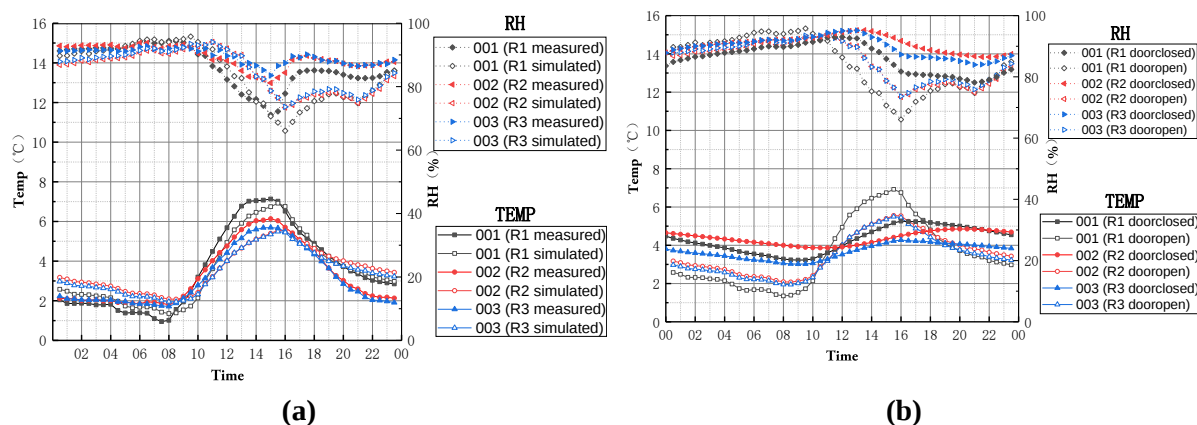


Figure 6. Validation of proposed model (2020.01.19- winter typical day): (a) comparison of simulated and measured temperatures and RH when the doors are open, (b) comparison of simulated temperatures and RH when doors closed & opened.

3.3. Simulation results of active environmental control

3.3.1. Simulation results of continuous heating

For the continuous heating mode, the conventional and enhanced ventilation modes are studied. Six temperature setpoints (T_p) of floor heating, 14°C , 16°C , 18°C , 20°C , 22°C , and 24°C , are simulated.

Figures 7a-7b show the variations of daily average indoor temperature and humidity in heated space (Room2) and non-heated space (Room1, Room3) under two ventilation modes. It can be seen that, in the conventional mode, the temperature of Room2 rises significantly, and basically below the setpoint by 0.5°C, the RH is in the range of 26~46.2%. The temperature of Room1 and Room3 is still low, and the RH is maintained at a high level; In the enhanced ventilation mode, the temperature of Room2 is basically below the setpoint by 1°C. the temperature of Room1 is 4~8°C higher than 6°C in the conventional mode. The RH of Room1 and Room2 both reduce to below 70%. It is worth noting that the RH of Room2 is only higher than 40% at low heating level (14~18°C). When the temperature setpoints become higher, the indoor environment will be in an excessively dry state that is not conducive to heritage preservation.

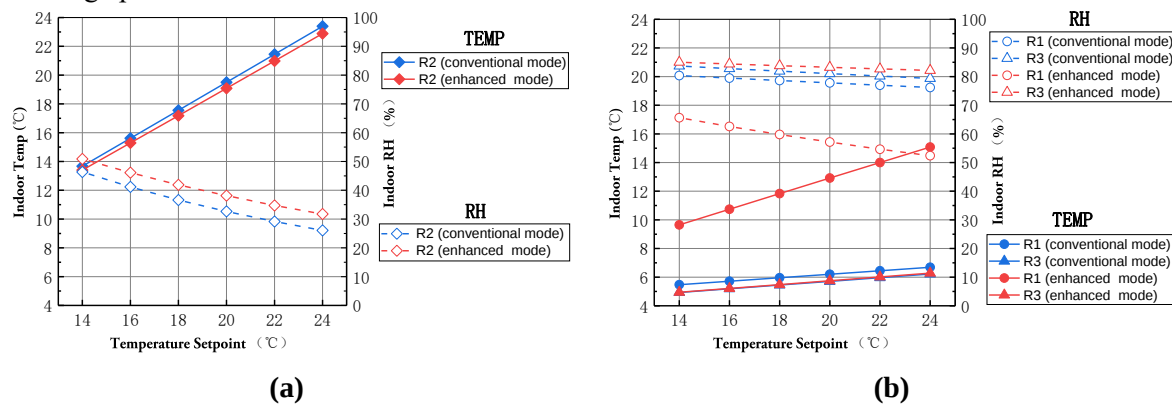


Figure 7. Daily average temperature and RH simulation results of different temperature setpoints under continuous heating (2020.01.19- winter typical day): (a) heated space (Room2), (b) non-heated space (Room1&Room3).

3.3.2. Simulation results of intermittent heating

Figure 8 shows the simulation results of two intermittent heating modes, MODE A and MODE B (both in conventional ventilation mode). In MODE A, T_p will keep 24°C during the daytime and turned off during the night; In MODE B, the system will keep at a low heating level of 18°C during the night. Because launching the system or elevating setpoints will lead to quick temperature rise in a short time, rapid temperature and humidity fluctuation occur around 5: 00 for both modes. When the system shuts down or switches to a low heating level at night, the heating panel will cool down naturally and gradually, so the transition of environmental change is gentler. The low heating level adopted by MODE B can reduce the temperature fluctuation level by 5°C compared with MODE A.

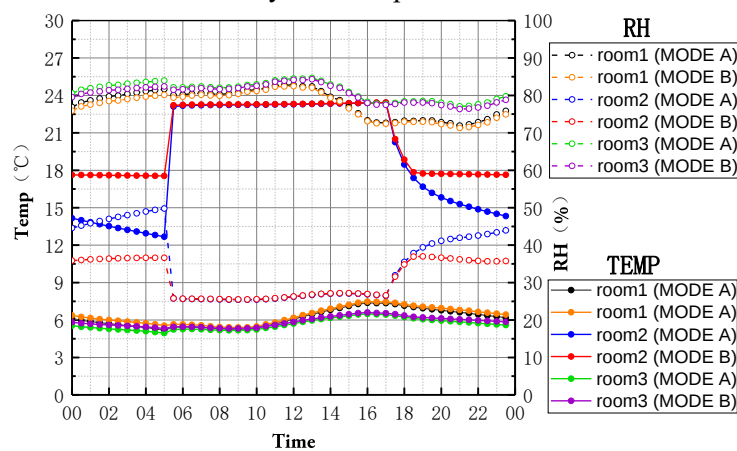


Figure 8. Simulation results of daily temperature and RH change under intermittent heating (2020.01.19- winter typical day).

4. Discussion

4.1. Impact on the protection of historical buildings

For historic buildings preservation, a high humidity environment brings the risk of mold growth, and a dry environment condition with RH less than 40% is also not ideal. The indoor environment simulation results shown in Figure 7-8 show that low-level heating can provide an RH range of 41.2~50.8% for heated space (T_p is set to 14~16°C in conventional ventilation mode and 14~18°C in enhanced ventilation mode). Furthermore, the water content of a material is a critical factor for its preservation. Figure 9a shows the average water content of the ground surface feature points (located in the center of the room) of Room1 and Room3 in different setpoints. It can be seen that the average water content of Room1 ground surface decreases with the increase of the setpoints under the enhanced ventilation mode. According to the simulation, these heating schemes do not bring obvious condensation risk. What is more noteworthy is the evaporation level of the materials. The salt inside the brick will migrate to the brick surface with evaporation, which may lead to efflorescence. In the simulation, the influence of different heating schemes on the north exterior wall of Room3 is not significant, with the daily average evaporation level basically maintained at 0.15~0.2 kg/m². Figure 9b shows the daily average evaporation from floor brick surfaces in Room1 and Room3. Due to the enhanced air exchange with the heated space, the evaporation from the floor brick in Room2 increases from 0.16 kg/m² (conventional ventilation) to 0.33~0.64 kg/m², and the evaporation increases by 0.067 kg/m² for every 2°C increase of the setpoints. Therefore, the impact of evaporation increasing caused by heating should be considered with caution in active environmental control.

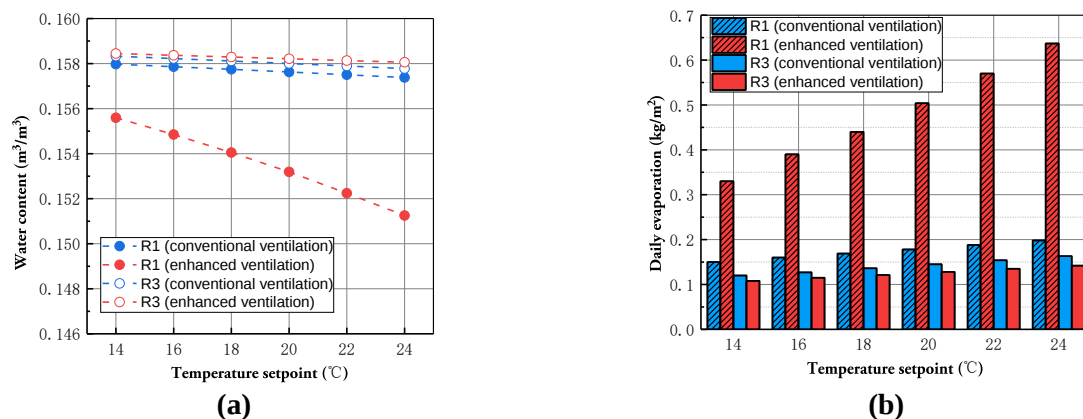


Figure 9. Comparison of moisture fluctuation in materials under different control schemes (2020.01.19- winter typical day): (a) average water content of R1 and R3 floor surface, (b) daily evaporation of R1 and R3 floor surface.

4.2. Evaluation of user comfort

There are various methods to evaluate the comfort with active environmental control in historical buildings. Some researchers calculated PMV and PDD before and after using HVAC system, while others investigated users' satisfaction with the heating system [8]. However, considering that RH has only a slight effect on human thermal sensation [9], This research will only discuss the thermal comfort briefly according to the limit value given by ANSI / ASHRAE standard 55-2013.

The lower limit of acceptable operational temperature in ASHRAE is 19.6 °C and the upper limit is 28.2 °C. 7 °C was taken as the critical temperature for people to feel significantly cold. The results show that the average air temperature of Room2 is as low as 4 °C without heating; In continuous heating, the indoor temperature of Room2 is 13.6~23.3°C, and it can meet the thermal comfort well when the setpoint is above 20°C; with enhanced ventilation, Room2 needs a heating level of 22~24 °C to reach the lower limit. But the temperature of Room1 is increased from 6°C to 9.6~15°C. Given these points, the temperature setpoint of floor heating above 20°C can better meet the comfort need, but compared with the situation without heating, even the most conservative heating scheme ($T_p=14^\circ\text{C}$) can significantly reduce the cold feeling of users.

4.3. The balance of active environmental control strategies

It is a delicate task to provide a satisfactory indoor environment in historical buildings. Comfort needs tend to increase the temperature and reduce RH, thus there is an inevitable conflict with the preservation of historical buildings. However, the simulation results show that the change caused by heating is not always harmful. For Honghua Temple, heating at 16°C with conventional ventilation or heating at 18°C with enhanced ventilation can achieve a relatively ideal indoor environment with RH above 40%. Although achieving balance is challenging, if properly applied, active environmental control still can become a reasonable solution to the protection of precious cultural heritage.

This study discusses the suitability of various active control strategies for brick buildings only in the winter heating period. And it should be noted that this study has not carried out an in-depth analysis on the phenomenon of air stratification and energy consumption. Future studies on energy consumption of different schemes and the impact of different climate changes (rain, snow, etc.) on environmental control are planned to continue to seek possibilities of balancing protection needs and human comfort.

5. Conclusion

The main conclusions are as follows:

- (1) For Honghua Temple, low-level heating at 16 °C with conventional ventilation or heating at 18°C with enhanced ventilation can make the heated space achieve a relatively ideal preservation environment with RH between 40~70% while improving the thermal comfort.
- (2) The control strategy of enhancing ventilation can significantly improve the indoor humidity environment and reduce the risk of mold growth while satisfying the convenience of using the Buddha worship space. But it will lead to higher energy consumption.
- (3) For intermittent heating in winter, in order to provide adequate environmental buffering phase, preheating the system before formal heating is necessary. Maintaining a low heating level at night can reduce the fluctuation level compared with shutting down the system directly.
- (4) In Honghua Temple, the enhanced air exchange with the heated space can make the evaporation from floor bricks in non-heated space increases by 0.067 kg/m² for every 2°C increase of the setpoints, thus the impact of evaporation increasing caused by heating should be considered with caution in active environmental control.

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