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Influence of Energy-saving Renovation Plan on the Hygrothermal Distribution Inside Kyo-machiya Soil Walls Considering their Moisture Buffering Effect

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Abstract. Kyo-machiya are traditional townhouses in Kyoto that represent an important aspect of cultural heritage preservation. Because of the poor thermal insulation performance, they require energy-saving renovations. However, their unique soil walls possess a moisture-buffering effect that can be strongly influenced by the applied renovation plan and are expected to remain functional even after renovation. Conventional renovation methods apply an inside vapor barrier to the interior insulation to prevent condensation between the insulation and wall; however, applying this barrier may hinder the buffering effect and deteriorate the unique interior appearance of the soil wall. Therefore, we conducted a case study on the hygrothermal environment of a typical Kyo-machiya structure in winter when the moisture generated by indoor activities was adsorbed by soil walls. We used the finite difference method to divide the various renovated envelope systems into thin layers and calculated the temperature and humidity distributions. Based on these results, we propose the use of exterior insulation for renovations, owing to its excellent thermal performance. However, if the space between the adjacent buildings is insufficient, interior insulation can be applied without a vapor barrier.

1. Research background

Kyo-machiya (Figure 1) are traditional townhouses in Kyoto that represent a significant part of Kyoto-style streets. They are not only used as residential homes but also as a part of the regional cultural heritage. The preservation of Kyoto City streets as prominent tourist destinations relies on the maintenance of their integrity, with Kyo-machiya serving as the primary architectural features (Figure 2). However, ensuring the longevity of these structures for future generations presents a challenge, given the deterioration they have endured over the past seven decades [1].

With the westernization trend in Japan, vernacular houses, including Kyo-machiya, were renovated, and rooms were combined or remodeled to increase floor area [2]. As originally constructed, houses in relatively warm areas in Japan, including Kyo-machiya, provide a high natural air change rate and were designed to reduce indoor temperatures during summer. Hosham et al. clarified that indoor temperature can be 2 ℃ lower than the corresponding outdoor temperature in summer [3]. However, their extensive air leakage owing to their unique structure, as well as their poor thermal insulation resulting from their traditional appearance and materials, can lead to discomfort and high heating energy consumption during winter [4], as shown in a study conducted by Ooka in the Hokuriku district, confirming cold and discomfort in winter [5]. Therefore, a unique and appropriate energy-saving renovation technique must be developed. A study conducted by Iba discussed the hygrothermal environment in a newly constructed Kyo-machiya, in which the condensation risk related to the thermal insulation retrofit was emphasized as the next step [6]. Although a study conducted by Yokobayashi examined the buffering effect of soil walls, they were not evaluated at a building scale [7]. In this study, we evaluated Kyo-machiya using numerical modeling to clarify the impact of different renovation plans on the thermal and buffering performances of its unique soil walls.

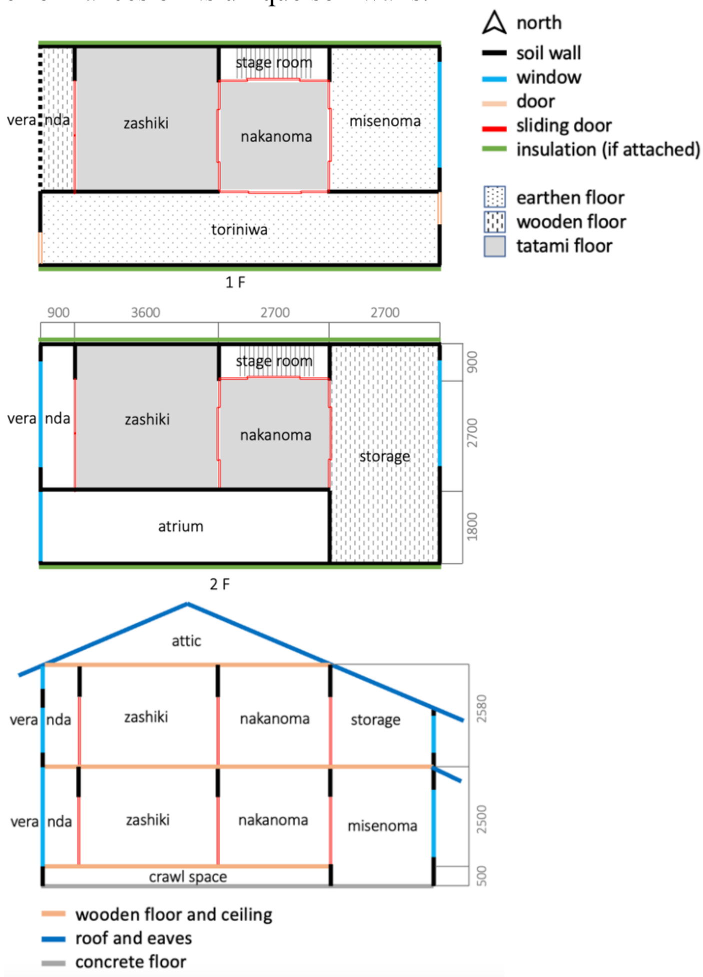

Figure 1. Layout of a model of a Kyo-machiya (unit: mm).

Figure 2. Example of Kyoto-style streets.

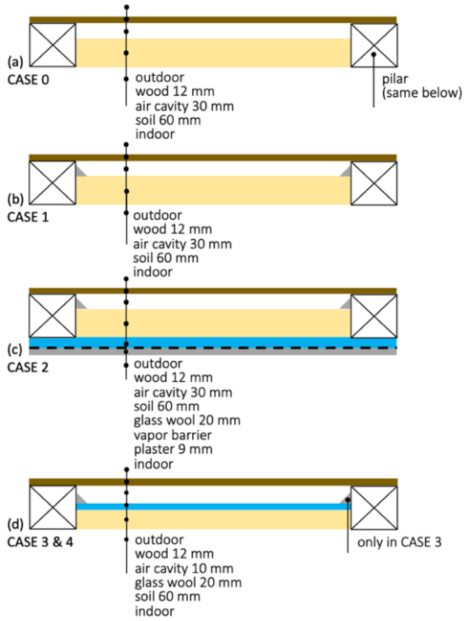

Figure 3. Renovation cases.

2. Methodology

2.1. Basic equations

The model employed for the case studies was constructed in the Julia Programming Language using the forward difference method to express the governing equations for heat and moisture transfer through the building envelope as follows [8,9]:

$$(c\rho + c_w\rho_w\psi)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left\{\lambda\frac{\partial T}{\partial x} + r\left(\lambda'_{\mu g}\frac{\partial \mu}{\partial x} + \lambda'_{Tg}\frac{\partial T}{\partial x}\right)\right\} \quad (1)$$

$$\rho_w\psi\frac{\partial \psi}{\partial \mu}\frac{\partial \mu}{\partial t} = \frac{\partial}{\partial x}\left(\lambda'_{\mu g}\frac{\partial \mu}{\partial x} + \lambda'_{Tg}\frac{\partial T}{\partial x}\right) \quad (2)$$

where c, ρ, and λ refer to the material's specific heat, J·(kg·K)$^{-1}$, density, kg·m^{-3}, and thermal conductivity, W·(m·K)$^{-1}$, respectively; ψ refers to the moisture content of the material, m^3·m^{-3}; μ refers to chemical potential of free water, J·kg^{-1}; $\lambda'_{\mu g}$ and λ'_{Tg} respectively represent the moisture conductivities determined by the chemical potential difference, kg·(s·m·(J·kg^{-1}))$^{-1}$, and temperature difference, kg·(s·m·K)$^{-1}$; and the subscripts w and g refer to water and vapor, respectively. This model was used to conduct one-dimensional heat and moisture transfer simulations in the direction of wall component thickness. The heat and moisture fluxes on the envelope surfaces were calculated using the Robin boundary conditions.

A multizone airflow network model was developed to estimate the airflow through the gaps between rooms and air leakage from window sashes. The mass flow rate through horizontal gaps can be expressed as [8]

$$G = \rho_{air} q (\Delta p)^{\frac{1}{n}} \tag{3}$$

and that through the vertical gaps as

$$G = \frac{\rho_{air} q}{h_{top} - h_{btm}} \int_{h_{btm}}^{h_{top}} (\Delta p)^{\frac{1}{n}} dh \tag{4}$$

where G refers to the mass flow rate of air, kg·s^{-1}; q is the unit airflow rate, m^3·s^{-1}·Pa$^{-1/n}$, depending on the gap area (which depends on the width and length) and the air leakage characteristic value n.

2.2. Calculation conditions and different renovation patterns

Intermittent heating was assumed to be provided only to the nakanoma and zashiki on the first floor (Figure 1). The calculation was performed from October to January using the December and January results as outputs. Standard Expanded AMeDAS Weather Data based on the years 2011–2020 (provided by the Meteorological Data System Co., Ltd.) were used as outdoor boundary conditions. The heating temperature and schedule were set based on a field survey conducted from 2015 to 2019 in a real Kyo-machiya, whose layout and envelope composition were similar to those of the model used in this study [10]. The preferred heating temperature was set as 20 °C, the heating time for the nakanoma (working space) was set to 6:00–9:00 during weekdays with no heating on weekends, and the heating time for the zashiki (bedroom) was set to 17:00–22:00 during weekdays and 6:00–22:00 during weekends. Nakanoma and zashiki were equipped with 1000 and 1500 W heaters, respectively. The initial temperature and humidity conditions of all envelope materials were set as 7 °C and 80%, respectively.

Table 1. Material properties.

Material	Thickness (mm)	Density (kg·m^{-3})	Specific heat (J·(kg·K)$^{-1}$)	Vapor permeability (kg·(m·s·Pa)$^{-1}$)	Thermal conductivity (W·(m·K)$^{-1}$)	Comment
Soil wall	60	1300	880	1.38×10^{-11}	0.5	
Wood	15	400	1300	1.10×10^{-12}	0.10	First level floor and exterior layer of north and south soil walls
Plywood	12	550	1300	1.11×10^{-13}	0.15	Second level floor and roof-base
Glass	3	/	/	0	0.78	Only resistance was considered
Fusuma	20	/	/	3.07×10^{-12}	0.068	Wood frame covered with paper; Only resistance was considered
Tatami	55	230	2300	2.00×10^{-12}	0.11	Only used in the nakanoma and zashiki
Ground (earth)	/	1900	1400	/	1.0	
Concrete	150	2200	840	2.98×10^{-12}	1.6	Floor of the misenoma and toriniwa
Roof tile	16	2000	760	/	0.96	A waterproof layer is provided under the tile
Glass wool	20	/	/	1.70×10^{-10}	0.032	Only resistance was considered

The material properties assumed for the Kyo-machiya construction and renovation are listed in Table 1, and the five renovation cases evaluated in this study are described in Figure 3 and Table 2. Case 0 refers to the baseline model used to express poor thermal performance, Cases 1 and 4 were used to evaluate the importance of enhancing airtightness, and Cases 2 and 3 were used to evaluate the influence of different insulation locations on the hygrothermal distribution in the soil wall. In all cases, partial insulation was only applied to the north and south exterior walls, and no insulation was provided on the roof or floor. This represents the most feasible renovation scenario, considering the unique structure of Kyo-machiya.

Table 2. Evaluated cases.

Case name	Insulation condition	Airflow rate
Case 0 (baseline)	None	100%
Case 1	None	10%
Case 2	Interior insulation after vapor barrier	10%
Case 3	Exterior insulation	10%
Case 4	Exterior insulation	100%

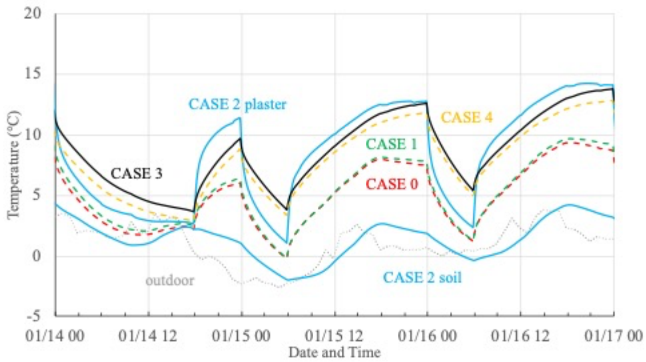

Figure 4. Surface temperature on the northern soil wall of the zashiki.

3. Results

3.1. Interior surface temperature

Figure 4 shows the surface temperature changes in the northern soil wall of zashiki for each case during the coldest period (1/14–1/16). In Case 2, the temperature is shown for the surface between the insulation and soil wall and for the interior surface of the plaster layer; in all other cases, it is shown for the surface in contact with the indoor air. The temperature in Case 4 was similar to that in Case 3, although the former exhibited a lower peak value and a slightly slower rate of increase over time. Cases 0 and 1 exhibited similar trends; the difference between the two cases indicated that the enhanced airtightness slightly increased the peak temperature and its rate of increase. Case 2 exhibited the lowest soil wall temperature, and its change trend closely followed the outdoor air temperature. However, the corresponding interior temperature (plaster surface) exhibited the highest peak value and fastest rate of increase, although it also exhibited the fastest rate of decrease. The Case 3 results indicated that use of exterior insulation could keep the entire wall warm, whereas the Case 2 results indicated that the use of interior insulation left the wall at extremely low temperatures that even dropped below 0 °C. Thus, even if no condensation occurs on the interior surface of the soil wall (according to the results presented in Section 3.2), penetrated rainwater can freeze and damage its exterior surface.

3.2. Interior surface relative humidity

Figure 5 shows the change in surface relative humidity on the northern soil wall of the zashiki for each case. Similar to the surface temperatures in Figure 4, Case 2 shows the relative humidity of the surface between the insulation and soil wall, and of the interior surface of the plaster layer; in all other cases, it is shown for the surface in contact with indoor air. In all the cases, the relative humidity remained below 80%, indicating that no condensation occurred. For the Case 2 soil wall surface, the relative humidity remained constant because the soil wall was isolated by a vapor barrier.

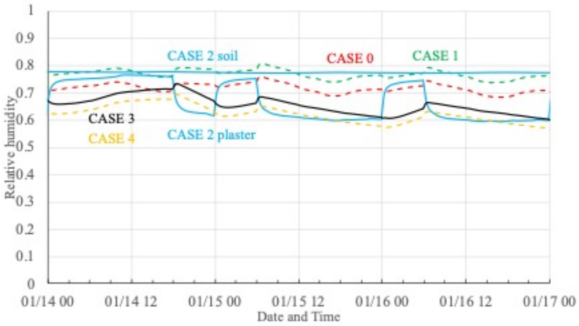

Figure 5. Relative humidity on the northern soil wall of the zashiki.

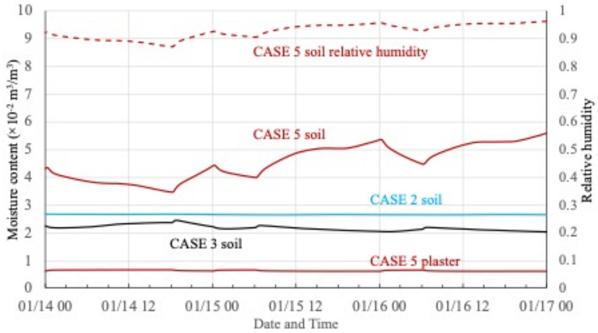

Figure 6. Moisture content and relative humidity on the northern soil wall of the zashiki with and without the vapor barrier.

4. Discussion

As Figure 5 indicates, the use of a vapor barrier would prevent the soil wall from adsorbing and releasing moisture; therefore, we evaluated an additional case, Case 5, in which the vapor barrier used in Case 2 was removed. Figure 6 shows the resulting moisture content and relative humidity on the northern soil wall of zashiki. The figure demonstrates that without a vapor barrier, the moisture content on the interior surface of the soil wall changed dramatically, indicating that the soil adsorbed and released moisture. However, when the relative humidity was lower than 100%, no condensation occurred.

5. Conclusions

The Kyo-machiya renovation plan significantly influenced the soil buffering effect. The following conclusions can be drawn based on the results of the simulations conducted in this study:

1. Insulation must be combined with enhanced airtightness to improve renovation effectiveness.
2. Partial insulation is inadequate for reaching the target temperature.
3. Exterior insulation is the preferred option; however, when not feasible, interior insulation can be effective. In both cases, a vapor barrier was unnecessary because of the ability of the soil wall to adsorb moisture. Considering the difficulty of applying a vapor barrier, this could provide useful information in practice.

However, as no humidifier was considered in these simulations, the full risk of condensation without a vapor barrier remains to be evaluated. In addition, although the relative humidity of the soil wall remained below 100% after the vapor barrier was removed, condensation still may occur between the wall and wooden beams. Therefore, a two-dimensional calculation should be conducted in future research to confirm moisture dispersion on the soil wall surface.

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