Energy-saving Renovation of Kyo-machiya Considering the Moisture Buffering Effect of Soil Walls

Pei LIU1*, and Chiemi IBA1

1Graduate School of Engineering, Kyoto University, 6158540, Japan

Abstract. Kyo-machiya, a type of traditional townhouse in Kyoto, is considered as cultural heritage that needs to be preserved. However, the high air leakage due to its unique structure and poor thermal insulation because of its traditional appearance may lead to high heating energy consumption. Therefore, an appropriate energy-saving renovation technique is proposed. However, the lack of quantitative analysis hinders the establishment of effective renovation guidelines focused on the energy-saving and healthy indoor environments of Kyo-machiya. Previously proposed retrofits were conducted using conventional methods with limited effectiveness. The soil wall in Kyo-machiya has an impact on indoor environments and is considered as a significant feature, and its appearance is crucial for the residents. Also, the soil wall has a moisture-buffering effect. Therefore, the adoption of interior insulation should be considered with caution. In addition, high air leakage is not fully resolved via the conventional methods. In this study, we used a numerical model of a typical traditional Kyo-machiya to evaluate different renovation designs, including interior and exterior insulation, vapour/moisture proof solutions, and effectiveness of enhancing air-tightness. Finally, we proposed a renovation plan based on the conventional methods, considering the balance between energy-saving and hygrothermal risk.

1 Introduction

Kyo-machiya (Fig.1) is a type of traditional townhouse in Kyoto and a significant element of the integrity of Kyoto style streets. They are not only used as residential houses, but also considered as cultural heritage. The integrity of Kyoto City streets is significant for tourism, and Kyo-machiya plays an important role in it as a principal component. However, passing it to future generations might become challenging owing to its degradation since they originated in as early as the Heian period and continued to develop through the Edo period and even into the Meiji period [1]. This means that even the youngest Kyo-machiya possesses a history of 70 years.

The original Kyo-machiya have a high natural air change rate in order to reduce the indoor temperature during summer. Local heating appliances, such as kotatsu or heating blankets, are used in winter and can only heat the lower limbs and leave the room temperature low. However, some studies have indicated that low room temperature is not good for occupants’ health [2].

Some renovations have been conducted to transform these historical buildings into hotels or other commercial buildings. However, the high air leakage due to its unique structure and poor thermal insulation because of its traditional appearance may lead to high heating energy consumption. By the typical energy-saving renovation plans in Japan, many studies have focused on insulation enhancement [3, 4]. However, air infiltration load responsible for the entire heating energy demand was estimated at 33% in American office buildings [5], 10.5–27.4%, 10.27% in Spanish and Korean multi-unit residential buildings, respectively [6, 7], and 11-15% in British housing stock [8]. The infiltration rate of residential buildings is 0.05 – 0.59 ACH in Beijing [9], 0.24 – 1.28 ACH in Korea, and rises to 0.7 – 1.84 ACH for Kyo-machiya [10, 11]. In traditional residential buildings, in particular, in houses with high air leakage such as Kyo-machiya, enhancing airtightness could be a cost-effective measure. Therefore, an exclusive appropriate energy-saving renovation technique should be proposed. However, this type of house has unique features such as a deep rectangular shape and soil walls (including exterior and partition walls) with buffering effect which cannot be neglected [12]. The two opposite walls and gables

Fig. 1. Front view of Kyo-machiya

* Corresponding author: be.liupei@archi.kyoto-u.ac.jp
represented by the long side of the rectangle are sometimes covered with wood boards. These should be considered when making a renovation plan. In addition, the lack of quantitative analysis hinders the establishment of effective renovation guidelines focused on the energy-saving and healthy indoor environments of Kyo-machiya.

Therefore, in this study, we conducted several case studies via a numerical model in order to clarify the impact of feasible renovation techniques, including the improvement of airtightness and thermal insulation, on the indoor temperature, humidity, and heating load.

2 Methodology

2.1 Model description

The model (Fig.2 and Table 1) has two layers, with an attic and a crawl space appended. The two opposite exterior walls (in this model they are located in north and south) have larger areas, and are covered by a wooden board outside and an air cavity sandwiched between the soil layer and the board (Fig. 4). The other two exterior walls in east and west and partition walls are composed of a single layer of soil. Owing to shrinkage after drying of the soil and unevenness of the wood structure, gaps exist on all edges of each wall, resulting in high air leakage between the indoor rooms and outdoor air, and hence, need to be factored in the calculations.

2.2 Basic equations

2.2.1 Heat and moisture transfers through component materials

The moisture sorption isotherms of each material are shown in Fig. 3. The heat and moisture transfer equations are as follows [13]:

---

Table 1. Material property

<table>
<thead>
<tr>
<th>Material/type</th>
<th>Thickness mm</th>
<th>Density kg/m³</th>
<th>Specific heat J/(kg·K)</th>
<th>Vapour permeability kg/(m·s·Pa)</th>
<th>Thermal conductivity W/(m·K)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil wall</td>
<td>60</td>
<td>1300</td>
<td>880</td>
<td>1.38×10⁻¹¹</td>
<td>1.0</td>
<td>1F floor and exterior layer of north and south soil walls</td>
</tr>
<tr>
<td>Wood</td>
<td>15</td>
<td>400</td>
<td>1300</td>
<td>1.10×10⁻¹²</td>
<td>0.10</td>
<td>2F floor and roof</td>
</tr>
<tr>
<td>Plywood</td>
<td>12</td>
<td>550</td>
<td>1300</td>
<td>1.11×10⁻¹³</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>3</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>Fusuma</td>
<td>20</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>3.07×10⁻¹⁵</td>
<td>0.068 wood frame covered with paper</td>
</tr>
<tr>
<td>Tatami</td>
<td>55</td>
<td>230</td>
<td>2300</td>
<td>2.00×10⁻¹⁶</td>
<td>0.11</td>
<td>only used in nakanoma and zashiki</td>
</tr>
<tr>
<td>Ground (earth)</td>
<td>/</td>
<td>1900</td>
<td>1400</td>
<td>/</td>
<td>/</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>150</td>
<td>2200</td>
<td>840</td>
<td>2.98×10⁻¹ⁱ</td>
<td>1.6</td>
<td>floor of misenoma and torinowa</td>
</tr>
<tr>
<td>Tile</td>
<td>16</td>
<td>2000</td>
<td>760</td>
<td>/</td>
<td>0.96</td>
<td>under the tile is waterproof layer</td>
</tr>
<tr>
<td>Glass wool</td>
<td>20</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>1.70×10⁻¹⁰</td>
<td>0.032</td>
</tr>
</tbody>
</table>

---

Fig. 2. Layout of the model dwelling (unit: mm)

Fig. 3. Moisture isotherms of materials
\begin{equation}
(c_p + c_{wp} \rho_{w}) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( l \frac{\partial T}{\partial x} + r \left( \lambda_{\mu g} \frac{\partial q}{\partial x} + \lambda_{Tg} \frac{\partial T}{\partial x} \right) \right)
\tag{1}
\end{equation}
\begin{equation}
\rho_{w} \frac{\partial q}{\partial t} = \frac{\partial}{\partial x} \left( \lambda_{\mu g} \frac{\partial q}{\partial x} + \lambda_{Tg} \frac{\partial T}{\partial x} \right)
\tag{2}
\end{equation}

where \( \psi \) refers to moisture content of material, \( \text{m}^3/\text{m}^2 \); \( \mu \) refers to chemical potential of free water, \( \text{J}/\text{kg} \); \( \lambda_{\mu g} \) and \( \lambda_{Tg} \) are moisture conductivity by chemical potential difference, \( \text{kg/s m}/(\text{J/kg}) \), and temperature difference, \( \text{kg/s m}/\text{K} \).

In this model, 1-dimensional heat and moisture transfer simulations in the direction of the component thickness were conducted. The heat and moisture fluxes on the surface of envelope are expressed as follows:
\begin{equation}
\begin{aligned}
\frac{\partial T}{\partial x} - r \left( \lambda_{\mu g} \frac{\partial q}{\partial x} + \lambda_{Tg} \frac{\partial T}{\partial x} \right) \\
= (h_r + h_c)(T_a - T_{\text{out}}) + rh'(p_{\text{va}} - p_{\text{vs}}) \\
- \left( \lambda_{\mu g} \frac{\partial q}{\partial x} + \lambda_{Tg} \frac{\partial T}{\partial x} \right) = h'(p_{\text{va}} - p_{\text{vs}})
\end{aligned}
\tag{3}
\end{equation}

where \( h_r \) and \( h_c \) are the radiative and convective heat transfer coefficients, respectively, \( \text{W/m}^2\text{K} \), \( p_{\text{va}} \) is vapour pressure; and subscript \( a \) and \( s \) are the room air and envelope surface, respectively.

### 2.2.2 Multizone airflow network

A multizone airflow network model [14] was developed to estimate airflow through gaps and window sashes. The mass flow rate through the horizontal gaps can be expressed as follows:
\begin{equation}
G = \frac{\rho_{\text{air}} q(Dp)^{\frac{1}{n}}}{\pi}
\end{equation}

and for vertical gaps:
\begin{equation}
G = \frac{\rho_{\text{air}} q}{h_{\text{top}}} \frac{1}{h_{\text{bottom}}} (Dp)^{\frac{1}{n}} dh
\end{equation}

where \( q \) is the unit airflow rate, \( \text{m}^3/\text{s}/\text{Pa}^{\frac{1}{n}} \), depending on the gap area (which depends on width and length) and the air leakage characteristic value \( n \).

Temperature and humidity of each zone were estimated thus:
\begin{equation}
\begin{aligned}
c_{\text{air}} \rho_{\text{air}} h_r \frac{\partial T_{ar}}{\partial t} &= \sum_{i=1}^{N_r} (h_r + h_c) S_i (T_{ai} - T_{ar}) \\
+ \sum_{j=1}^{M_r} c_{\text{air}} (G_{r} T_{aj} + G_{r} T_{ar}) + Q_{\text{genr}}
\end{aligned}
\tag{7}
\end{equation}
\begin{equation}
\rho_{\text{air}} V_{r} \frac{\partial X_{ar}}{\partial t} = \sum_{i=1}^{N_r} h' S_i (p_{\text{va},i} - p_{\text{va},r})
\tag{8}
\end{equation}

where \( N_r \) is the number of envelopes in contact zone \( r \); and \( M_r \) is the number of airflow paths leading to zone \( r \). Twelve zones and 147 airflow paths existed in total in this model.

### 2.3 Calculation conditions

The envelopes were divided into non-equal-width layers perpendicular to the flux directions. To reduce the time cost, we made the layers denser on both sides and sparser in the middle, considering that moisture adsorption and emission mainly occur on the perimeter layers. For example, the 60-mm soil wall is divided into 23 layers, with the outermost layer’s thickness of 0.5 mm and the innermost layer of 7 mm. For the layers exposed to solar radiation (such as roof or veranda floor), the outermost layer was made thicker to avoid divergence in the calculation due to the small heat capacity. Similar conditions occurred when the insulation materials were considered. The specific heat capacity \( c_p \) is 20.16 kJ/(m$^3$/K) for dry glass wool and 1144 kJ/(m$^3$/K) for contacted dry soil. Thus, in the current phase, the capacity of glass wool was not considered. The forward difference method was used, and the timestep was set to be 0.5 s.

As the outdoor boundary conditions, standard Expanded AMeDAS Weather Data based on 2011–2020 data (provided by Meteorological Data System Co., Ltd.) were used for the calculation. Based on a previous lifestyle survey conducted by the authors [15], the heating temperature was set to be 20°C as the preferred value. The heating time was set to 5:00-9:00 and 16:00-22:00 (5:00-22:00 on weekends) for nakanoma as the working space, and to 6:00-9:00 and 22:00-2:00 (next day) for zashiki as bedroom. Nakanoma is equipped with a heater with the maximum power of 2000 W and

<table>
<thead>
<tr>
<th>Case name</th>
<th>Insulation</th>
<th>Airflow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE 0</td>
<td>×</td>
<td>100%</td>
</tr>
<tr>
<td>CASE 1</td>
<td>×</td>
<td>10%</td>
</tr>
<tr>
<td>CASE 2</td>
<td>Interior insulation after vapour barrier</td>
<td>10%</td>
</tr>
<tr>
<td>CASE 3</td>
<td>Exterior insulation</td>
<td>10%</td>
</tr>
<tr>
<td>CASE 4</td>
<td>Same as CASE 3</td>
<td>100%</td>
</tr>
</tbody>
</table>

Fig. 4. Renovation types

Table 2. Calculated cases

<table>
<thead>
<tr>
<th>Case name</th>
<th>Insulation</th>
<th>Airflow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE 0</td>
<td>×</td>
<td>100%</td>
</tr>
<tr>
<td>CASE 1</td>
<td>×</td>
<td>10%</td>
</tr>
<tr>
<td>CASE 2</td>
<td>Interior insulation after vapour barrier</td>
<td>10%</td>
</tr>
<tr>
<td>CASE 3</td>
<td>Exterior insulation</td>
<td>10%</td>
</tr>
<tr>
<td>CASE 4</td>
<td>Same as CASE 3</td>
<td>100%</td>
</tr>
</tbody>
</table>
3000 W for zashiki (the load that also refers to heater’s power increases gradually from 0 after being turned on, instead of instantaneously providing power in need, and because of the limitation of room air heat capacity, excessive heat input causes divergence). The calculation runs from October to January, with the December and January results as the output. The five calculated cases are shown in Table 2 and Fig. 4. Among them, CASE 0 refers to the baseline model to express poor thermal performance, CASES 1 and 4 emphasize the importance of enhancing airtightness, and CASES 2 and 3 discuss the impact of interior insulation (only applied on two walls, as Fig. 2) on the buffering effect.

2.4 Estimation of gap parameters

In this hypothetical model, it is important to make the parameters representative of Kyo-machiya’s features. However, even for an actual case, validation is a difficult task because of the uncertainties associated with constructors’ skills and as the accuracy of the input parameters cannot be guaranteed. However, if the key parameters influencing the hygrothermal performance can be reasonably defined, we can demonstrate that the model is reasonable and representative enough. In this model, the air leakage characteristic value \( n \) was set to be 1.548, which was larger than the values in general houses [16], representing high air leakage. The unit air flow rate \( q \) is influenced by the gap width, set to 0.5 mm (Table 3). The results are consistent with on-site data measured in an actual Kyo-machiya that shares a similar layout and the same envelope composition (no insulation and high air leakage) [15].

### Table 3. Summary of airflow paths

<table>
<thead>
<tr>
<th>Path</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top and bottom (horizontal) sides of sliding door, window and door</td>
<td>0.5</td>
</tr>
<tr>
<td>Left and right (vertical) sides of sliding door, window and door</td>
<td>0.5</td>
</tr>
<tr>
<td>Middle seam of sliding door</td>
<td>3</td>
</tr>
<tr>
<td>Horizontal and vertical wall crack</td>
<td>0.5 (renovated)</td>
</tr>
<tr>
<td></td>
<td>0.05 (renovated)</td>
</tr>
</tbody>
</table>

3 Results

3.1 Temperature of each case

Fig. 5 shows the temperature of the two heated rooms, which was recorded every 10 minutes during the coldest weekend (1/18 – 1/20). In both rooms, enhancing the airtightness can increase the rate of temperature increase but cannot prevent heat from escaping after the heater is turned off. During the period when the heater was turned off, the temperature was 2-3 °C lower in CASES 0 and 1 than in the other insulated cases. In larger room zashiki the tendency was more obvious as the minimum value was 2-4 °C lower. In CASES 0 and 1, when the initial temperature before heating was lower, the time cost of reaching 20 °C rose.

The interior insulation CASE 2 had a higher rate of temperature change than did the exterior insulation CASES 3 and 4, especially in zashiki, whose envelope was partially insulated. After the heater was turned off,

![Fig. 5. Air temperature of nakanoma (a) and zashiki (b)](image)

![Fig. 6. Temperature of interior layer of soil wall](image)
usage. Fig. 6 also shows that in CASE 2, the surface temperature could drop to near 0 °C, which may cause condensation or frost damage (will be discussed in 4.2).

In all cases the room temperature dropped by 6-7 °C within 10 minutes after the heater was turned off. The temperatures in the other rooms remained at the same level as the outdoors, indicating that only two opposite walls insulated was not sufficient for Kyo-machiya to meet the modern standards.

3.2 Heating load of each case

<table>
<thead>
<tr>
<th>Case name</th>
<th>Heating load of nakanoma (GJ)</th>
<th>Heating load of zashiki (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE 0</td>
<td>4.0941</td>
<td>4.0845</td>
</tr>
<tr>
<td>CASE 1 (airtightness)</td>
<td>3.8085</td>
<td>3.9832</td>
</tr>
<tr>
<td>CASE 2 (interior + VB)</td>
<td>3.5805</td>
<td>3.3191</td>
</tr>
<tr>
<td>CASE 3 (exterior)</td>
<td>3.5422</td>
<td>3.5867</td>
</tr>
<tr>
<td>CASE 4 (exterior - leakag)</td>
<td>3.7796</td>
<td>3.6871</td>
</tr>
</tbody>
</table>

The instantaneous heating load was also recorded every 10 minutes. Table 4 listed the integrated heating load of two months, and Fig. 7 shows the heating loads of two heated rooms for each case during the same period. Fig. 7 shows that, for both rooms, airtightness and insulation can reduce the heating load when the temperature reaches stable.

Table 4. Integrated heating load (January and February)

Fig. 7. Heating load of nakanoma (a) and zashiki (b)

Fig. 8. Relative and absolute humidity of nakanoma (a)(c) and zashiki (b)(d)

A comparison of CASES 0, 1 and 4 indicates that nakanoma was more easily affected by ventilation than was zashiki. This was foreseeable because nakanoma
was not directly connected with the exterior walls, and heat loss via conduction did not fall because the temperature differences between nakanoma and the other adjacent rooms changed slightly. While as for the case of zashiki, the conduction-induced heat loss from one envelope fell significantly. Thus, besides was affected by ventilation, the heating load of zashiki also depended on the insulation performance.

A comparison of CASES 2 and 3 shows that the interior insulation can reduce the heating load of zashiki. According to 3.1 only the plaster board (interior layer) was heated, and the soil wall with a large heat capacity, remained at a low temperature.

3.3 Relative humidity of each case

Fig. 8 shows the indoor relative humidity and absolute humidity for each case during the same period. As for RH in nakanoma, all the cases dropped to 40 % when heated. RH had the highest and the lowest values in CASE 2 and 4, respectively when heated, approximately 6% lower in CASE 4 than 2. RH in zashiki dropped below 40% when heated. The case with the most stable RH was difficult to determine due to the short heating duration in zashiki. However, after the heater was turned off, RH in the interior insulation CASE 2 rose the fastest among all the cases. The exterior insulation CASES 3 and 4, which exhibited the full advantage of the buffering effect of the soil, had the most stable RH.

As for absolute humidity, CASE 2 had the highest value during and after heating in nakanoma and the slowest drop rate. In zashiki, CASE 2 had the fastest increase rate and the highest value during heating. After the heater was turned off, CASE 4 reached its lowest value. In addition, absolute humidity in CASES 3 and 4 was more stable, with its change taking a longer time.

4 Discussion

4.1 Heat loss due to infiltration

Fig. 9 shows the heat exchange via ventilation in the 1st floor zashiki in CASES 0 and 1 (Plus curve refers to heat flowing into zashiki while minus curve refers to heat flowing out of zashiki. Heat exchange with nakanoma has two curves because the gaps are separated by neutral height). The figures shows that most infiltration occurs through the gap between the sliding door connecting the veranda. Filling this gap could significantly reduce air leakage.

4.2 Feasibility of moisture open design

Fig. 10 shows RH and moisture content of the interior surface of the soli wall (only in CASE 2, between the soil and VB). The fluctuation of the moisture content indicates the buffering effect of the soil, except for CASE 2, in which the moisture content remained constant. In addition, since VB is not preferable by constructors due to its difficulty of application to the wall, we added an additional CASE 5 which removed VB in CASE 2.
Fig. 11 shows that RH and moisture content of the innermost layer of the soil in CASE 5 compared with those in CASE 2. Since RH did not exceed 100% even without VB, condensation may not occur. The moisture content was higher in CASE 5 than 2 and fluctuated, indicating a buffering effect. The moisture content changed a lot, and this result matches the soil curve in Fig. 3: buffering effect becomes stronger when RH is high, which also means soil wall can contain moisture generated in daily life.

5 Conclusion

In this study, we conducted a scenario analysis involving several case studies to create guidelines for energy-saving renovation of Kyo-machiya. By simulations, we obtained the following useful conclusions: 1) the enhancement of airtightness has a great impact on renovation and cannot be neglected; 2) the interior insulation saves more energy, with a compromise in the thermal performance; 3) removing VB to let the buffering effect of the soil to adjust humidity is feasible, however, RH may keep exceeding 80% for several hours.

The traditional renovation focuses only on the insulation of the two large walls and the thermal performance is not optimistic. The intermittent heating life style can cause low room temperature, which is detrimental to the occupants’ health. Therefore, in future research, it is important to evaluate additional insulation parts such as the floor, window and roof and try to maintain the room temperature at a stable level even after the heater is turned off. Although exterior insulation shows lower risk of condensation, it may not be feasible because of the narrow space between two adjacent Kyo-machiya. In that case, although results have shown that soil wall can contain normal moisture generation without condensing, knowing the peak value of moisture generation before it condenses is still important.

References

1. Kyoto City Planning Bureau, Pamphlet about the future of Kyo-machiya, 2019, 6 (2019)