

Article

Traditional Town Houses in Kyoto, Japan: Present and Future

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Abstract: Climate change is an important issue that affects energy consumption, causes health problems, such as heat stroke, and requires urgent countermeasures. Serious health problems, including cardiac arrest, often occur in winter in traditional residences in Japan. Cooling-heating energy is required to maintain a healthy thermal environment. Although energy efficiency standards for buildings have been introduced worldwide to reduce energy consumption and various passive energy-saving methods are being investigated, traditional residences still face difficulties in conducting renovations because of various restrictions, such as the conservation of historical or aesthetic values. In this study, these issues and their appropriate countermeasures were investigated for a traditional townhouse in Kyoto, Japan, “Kyo-machiya” (including its new form “Heisei-no-Kyo-machiya”). The potential of reducing heating and cooling loads was examined by conducting numerical analysis considering residents’ lifestyles. Field surveys of the indoor environment were conducted in both summer and winter. It was revealed that by optimizing the times and positions of opening and closing the windows and indoor partitions, the indoor air flow could be adjusted from both thermal comfort (cooling in summer) and discomfort (cold drafts in winter) perspectives, leading to improving the indoor environment without using energy.

Keywords: Kyo-machiya; indoor environmental control; environment adjusting space; natural ventilation; cold draft

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1. Introduction

Climate change is a crucial issue that requires urgent countermeasures. Overheating in dwellings in summer, especially in urban areas, has a considerable influence on our daily lives and health and can result in heat strokes on hot and sunny days, as examined by Hamdy [1], Santamouris [2], and Taylor [3]. Thus, it is imperative to address these problems by creating a suitable indoor environment, not only through the passive design of buildings but also by cooling. The cooling of buildings results in increasing energy consumption [4] and worsening of the urban environment caused by waste heat from air-conditioning (AC) systems [5]. However, health problems, such as cardiac arrest, often occur in winter, especially in dwellings with poor thermal insulation [6,7]. In Japan, one of the causes of these health problems is the habit of bathing in hot water in cold bathrooms. To prevent these, raising the temperature of the bathroom and dressing room using heating devices [8] is effective but requires more energy.

Therefore, improving energy saving in dwellings and creating a healthy indoor environment is required. Energy efficiency standards have been implemented worldwide and satisfying them is regarded as the minimum requirement. Various laws, directives, and standards have been established, such as the Energy Performance of Buildings Directive (EPBD) [9,10]. The main goal of this directive is to increase the renovation rate and to make less energy-efficient buildings more sustainable. However, issues have been identified in existing buildings, including cost-effective methodology, evaluator-independent consistency, and appropriate evaluation methods [11]. Currently, energy efficiency policies and regulations have been created and enforced in countries with various climates, such as

Arab countries [12], the Gulf Cooperation Council [13], Morocco [14], and South-Asian countries [15].

Energy efficiency standards for residential buildings (hereafter: energy efficiency standards) were first enacted in Japan in 1980 as one of the main countermeasures against the 1973 oil crisis. Building performance was regulated with a specific focus on thermal insulation, airtightness, and solar control. The standard was improved under the “New energy efficiency standards” in 1992 and further strengthened under the “Next generation energy efficiency standards” (hereafter: next-generation standards) in 1999 [16] in response to the Kyoto Protocol. The annual maximum allowable space conditioning (heating-cooling) loads for houses claimed in each standard are listed in Table 1. These values are for moderate climate regions, including Kyoto City, where heating degree-days based on 18 °C are in the range of 1500–2500. Even now, almost the same level of building insulation performance has been adopted as the next-generation standard. The total energy consumed in a building depends not only on its thermal performance, but also on the energy used for utilities, such as heating, cooling, lighting, and supplying hot water and the energy produced by solar panels. Therefore, appropriate energy savings are possible by considering the building as a whole system. Based on this, an integrated energy-saving concept was introduced in 2013, in which the evaluation of energy-saving performances was changed based on primary energy consumption [17]. Furthermore, in response to the Paris Agreement (2015), the “Act on Improvement of Energy Consumption Performance of Buildings” was amended in 2019.

Table 1. Annual maximum allowable space conditioning (heating-cooling) loads for houses in moderate climate regions in Japan.

Standard	1980 Standard	1992 Standard	1999 Standard
Heating-cooling load	1030	800	460

Unit: MJ/m²/year.

As Japan has four seasons, summer cooling and winter heating are generally required. Thus, energy-saving measures and building design must consider these seasonal requirements, which differ from those in other countries. Climographs of the major cities of several countries are shown in Figure 1 [18]. High relative humidity throughout the year is a notable feature of Kyoto, which causes a muggy environment in summer.

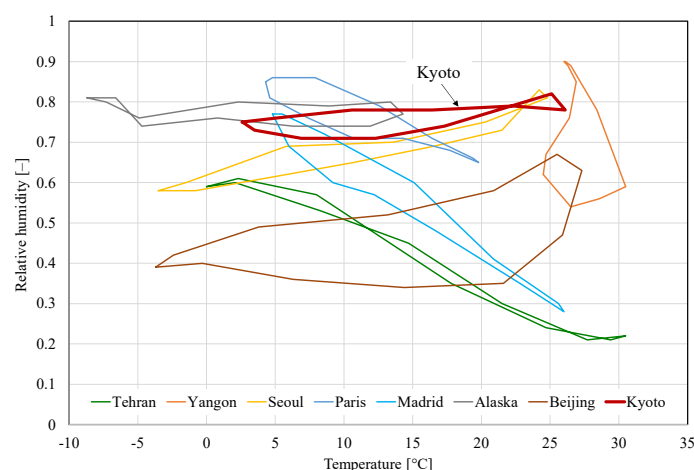


Figure 1. Comparison of climatic conditions in Japan and other countries [18].

As the western parts of Japan have extreme summers and mild winters, the people there historically emphasized measures to withstand the summer heat while neglecting the winter cold. Consequently, it has become common sense that residential buildings should be designed to be open, and the openings should be kept open to ensure sufficient natural

ventilation. This seems to have become permanent in the lifestyle of Japanese people, cemented by the fact that most Japanese residential buildings are made of wood with poor airtightness. This not only influences energy consumption, but also residents' health.

The target of our project is Kyo-machiya, which is a wooden detached house or a townhouse-type residential building built before 1950 by “traditional wooden post and beam construction” or “traditional construction”. It was defined by the ordinance of Kyoto City in 2017 [19] and has all or several of the following features (Figure 2): Tori-niwa (a thin and long earth floor running from the entrance, which faces the road, to the courtyard), Tsubo-niwa or Oku-niwa (a small courtyard), Tori-bisashi (eaves installed along the roadside), and Koshi (types of windows, such as Mushiko-mado or Kyo-goushi). The upper part of the Tori-niwa is an atrium called the Hibukuro, whose original purpose was to discharge smoke and soot generated by the burning of wood during cooking.

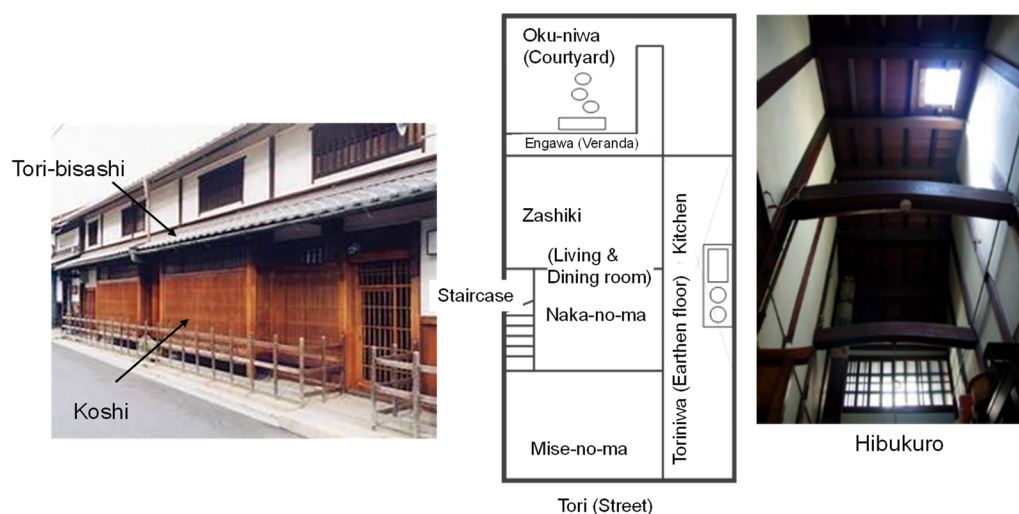


Figure 2. Typical appearance and floor plan of a Kyo-machiya (townhouse-type).

There are numerous difficulties in applying the usual energy-saving strategies, including insulation and airtightness, to a Kyo-machiya. Similar problems have been discussed in several previous studies. Caro et al. [20,21] described the difficulty of improving building elements and the complexity of applying current energy efficiency standards to heritage buildings. With respect to the facade of Kyo-machiya, external insulation cannot be applied without changing the traditional external appearance (a white plaster wall), and there are limited fire-preventative materials that can be used for external finishing. Similarly, regarding the inner surfaces of the soil walls, inner insulation cannot be applied while maintaining traditional elements, particularly since the residents place great importance on the feeling of the soil wall. Internal insulation is generally adopted in historical masonry buildings in Europe to preserve their appearance. Particularly in cold regions, it may increase the risk of condensation inside the outer wall, mold growth, and frost damage, among other factors. Therefore, such risks have been assessed by experiments and computational simulations [22–24]. Furthermore, it is concerning that heat can easily be transported through humid walls, leading to increased energy consumption [25]. When applying internal insulation to Kyo-machiya, these issues should be examined beforehand.

The poor airtightness of the soil wall is a serious issue because cracking between the soil and wood columns/beams, caused by shrinkage of the soil in the long term, is unavoidable with conventional construction methods. Because the original style of the inner spaces is an open design, there is poor airtightness between the inside and outside (openings, veranda, corridor, passage to toilet, etc.). Thus, specially designed and constructed fittings are required to make wooden structures airtight. However, when improving airtightness, it is necessary to consider alternative methods for maintaining good indoor air quality, such as the installation of ventilation equipment [26].

There are several issues concerning Kyo-machiya, especially as traditional residences are demolished and replaced with high-rise flats. For example, the preservation and inheritance of Kyo-machiya has become important because of their relevance as homes, cultural heritage, and tourist attractions. Additionally, the conservation of forests surrounding Kyoto City is also an area of concern. To address these issues, Kyoto City held a civic meeting in 2008: “Kyoto, a city taking care of wood culture.” The civic meeting adopted “Heisei-no-Kyo-machiya” as one of the main themes to be discussed. “Heisei-no-Kyo-machiya” is a new residence model, designed based on tradition and associated knowledge of the Kyo-machiya, while also integrating the most advanced environmental technology. Figure 3 shows the concept of a “Heisei-no-Kyo-machiya”, whose cross-sectional features are almost the same as those of a conventional Kyo-machiya: effective wind trail, partial use of earthen floor, and small attached courtyards. The largest difference between them is the thermal insulation performance and airtightness. Based on the report of the civic meeting released in 2010, Kyoto City has taken measures [27] to advance the construction of “Heisei-no-Kyo-machiya”.

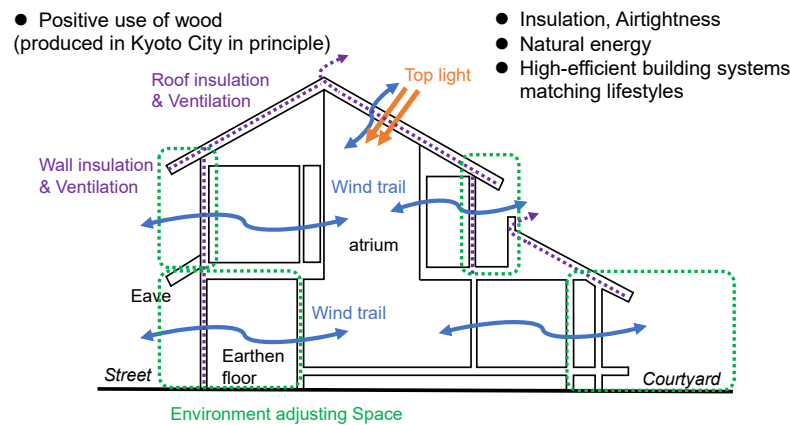


Figure 3. Concept of the “Heisei-no-Kyo-machiya” (depicted by authors based on a website [27]).

In a “Kyo-machiya”, the relationship between the inside and outside is crucial to maintain which of the connecting spaces, including the “Tori-niwa” and “Engawa” (veranda), are adjusted in the indoor environment. Through this relationship, a fruitful living culture is cultivated depending on the season. The “Heisei-no-Kyo-machiya” concept aims to improve the design of this intermediate region that connects the inside and outside, creating an “environment adjustment (buffer) space” (Figure 4). In this way, “Heisei-no-Kyo-machiya” retains the relationship between an individual and his/her environment, and that between a residence and the surrounding area, with an “environment adjusting space” intervening between them.



Figure 4. Examples of environment adjustment (buffer) spaces.

As presented in the “Heisei-no-Kyo-machiya” concept, heating and cooling energy savings in residential buildings are primarily achieved through passive techniques, such as thermal insulation and airtightness. Although solar radiation (heat) should be avoided in

summer, it is beneficial and should be used indoors in winter. Similarly, natural ventilation is generally an effective cooling technique in summer that does not consume energy, but suitable means of avoiding cold drafts and air leakage are required in winter. To achieve energy savings, various passive (sometimes combined with active) methods have been proposed and investigated under different climatic conditions worldwide.

Although the German passive house standard has been adopted in other countries, in anticipation of the risk of overheating caused by climate change in the future [28], glazing ratios and external shading devices [29], and additional cooling by natural ventilation [30], have been focused on. The effects of individual passive technologies on summer heat, including roof insulation in tropical regions [31], the use of building thermal inertia [32], and a combination of building heat capacity and night ventilation [33,34], have been evaluated. One study showed that indoor thermal comfort can be improved by the intake of outdoor air at appropriate times [35], and another study showed that hybrid ventilation that combines mechanical and natural ventilation leads to better energy efficiency and indoor air quality (IAQ) than the window-opening behavior of residents [36]. On the other hand, an atrium space, which is strongly desired in many newly built residential buildings, is effective in promoting natural ventilation, resulting in unpleasant cold drafts in winter in residences without sufficient insulation of the external walls [37].

When using passive natural ventilation, it is also necessary to understand the residents' window-opening behaviors. Using a multi-level logistic regression model, Shi et al. [38] explained the relationship between the probability of opening a window and environmental factors. Jiang et al. [39] showed that even during the winter heating period, there was a tendency to open windows for fresh air, and Verbruggen et al. [40] revealed that the behavior was also affected by daily habits.

The behavior of residents regarding energy consumption in their houses is garnering attention [41], and efforts are being made to consider them while developing future energy conservation plans [42–44]. Krarti [45] demonstrated that energy can be saved by changing the set temperature of air conditioning according to the usage pattern of the given room in the house. Ascione et al. [46] showed that the wrong behavior of residents can significantly increase the energy demand. Although national and international indoor environmental quality standards specify indoor environmental conditions that are considered acceptable to most residents [47], there are large differences in thermal comfort and resident preferences among individuals [48]. Establishing energy-saving methods without considering the preference of occupants also leads to a decrease in the satisfaction of residents [49,50]. Different age groups, such as the elderly and non-elderly [51], have also been identified to have different preferences and behaviors, leading to different environmental requirements for acting or sleeping [52,53]. Furthermore, it is well known that occupants' thermal sensation changes according to the climate of the residential area [54,55] and the house structure [56].

Regarding the improvement of thermal environment in traditional houses, several studies have been conducted on unique dwellings in each country and region. Traditional homes in the Duyarbakir region of Turkey provided protection to the residents from the sun and the hot dusty winds with compact, low-rise structures and small courtyards [57]. Ryu et al. [58] quantitatively analyzed the characteristics of the wind flowing through a semi-open space with a wooden floor located between the front and back yards of traditional Korean residences. In Nepal, creating a sun space at the entrance of traditional Humla homes was recommended as a means of reducing the use of firewood in winter and improving thermal comfort [59]. In Pol House, a traditional residence in the Indian city of Ahmedabad, some techniques such as improving the thermal insulation of walls and roofs, seasonal shades for windows and courtyards, and using mechanical fans were examined from the perspective of energy saving and thermal comfort [60]. In Lhasa, Tibet, the mechanism for creating an indoor thermal environment for traditional homes was investigated [61]. In Japan, there have been many studies on the historical value and transition of Kyo-machiya, including the relationship between townhouses and streets in

the city [62], and the changes in vegetation cover of gardens at Kyo-machiya [63]. In addition, multifaceted investigations, such as seismic reinforcement experiments on traditional houses [64], or sliding fire-prevention shutters that match the exterior design [65], have been carried out. In 1990, Ishida et al. [66] measured the indoor temperature and humidity and the pressure difference between rooms in a Kyo-machiya and analyzed the mechanisms of the thermal environment in the summer. They reported that the cool condition was maintained on the first floor because of the air being cooled by the evaporation of water in a small courtyard and the heat being effectively exhausted through the atrium (Hibukuro), even if the house had no insulation. In 1991, based on the survey results on the trend of the floor plan change of Kyo-machiya, Matsubara et al. [67] reported that the number of mechanical appliances had increased in the renovated houses to improve residents' thermal comfort in summer, which led to more energy consumption and temperature rises in urban areas. Ooka [68] investigated the thermal environment of traditional houses with soil walls, earthen floors, and thatched roofs in a colder region of Japan and revealed that the residents withstood the winter cold directly with a brazier or fire pit.

The authors have examined the possibility of heating and cooling with a heat pump that uses water from a well that normally exists in Kyo-machiya as a heat source [69,70]. However, few studies have been done on the thermal environment improvement of Kyo-machiya, which mainly uses passive techniques, and its effect on the saving energy.

Considering these previous studies, the aims of this paper with respect to the traditional dwelling Kyo-machiya are as follows: (1) to examine how much the heating-cooling load can be reduced considering the residents' lifestyle, (2) to suggest a technique to prevent cold draft in the atrium space in winter, (3) to estimate the cooling effect of night ventilation in summer by utilizing the heat capacity of the soil wall, and (4) to investigate the effective methods of natural ventilation for summer cooling by opening/closing the indoor partition doors. Based on these results, the potential to reduce energy consumption while maintaining comfort in traditional dwellings is discussed.

2. Methods

2.1. Model Residence

The "Heisei-no-Kyo-machiya" model residence was used for this investigation. Its appearance and plan are shown in Figure 5. The specifications of the building envelope are listed in Table 2. In this residence, all the external walls were 50 mm thick and made of soil. External 40 mm wooden insulation was applied to the east/west walls (no windows) and the roofs on a trial basis. Note that the insulation performance does not meet next-generation energy efficiency standards. Although traditional "Kyo-machiya" are generally terraced houses, this model residence is a stand-alone type built in an open space around the center of Kyoto City.



Figure 5. Outer and inner appearances of the "Heisei-no-Kyo-machiya" model.

Table 2. Specifications of the building envelope.

Part	Specification
North, south external wall	Soil wall 50 mm
East, west external wall	Soil wall 50 mm + Wooden insulation ¹ 40 mm + Cedar board 10 mm
Partition wall	Soil wall 50 mm
Roof	Roof tile 20 mm + Wooden insulation ¹ 40 mm + Cedar board 30 mm
Floor (first floor)	Tatami 55 mm + Wooden insulation ¹ 20 mm + Cedar board 30 mm
Windows	Single glass
Foundation wall	Cedar board 10 mm
Earthen floor	Sandy soil

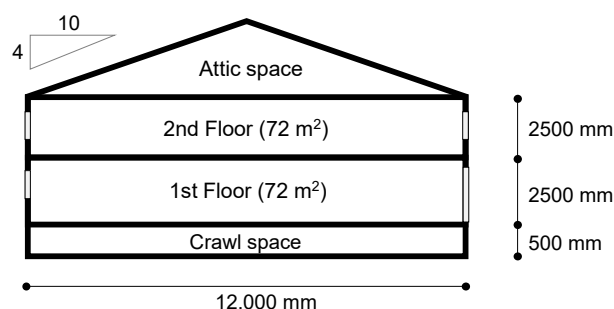
¹ Thermal conductivity of wooden insulation was 0.038 [W/mK].

2.2. Investigated Issues

Calculations and/or experiments were conducted on the model residence from four perspectives: reduction in energy consumption throughout the year, cold draft prevention in winter, utilization of heat capacity in summer, and effective natural ventilation in summer.

2.2.1. Estimated Energy Consumption and Countermeasures

We examined whether energy consumption could be reduced depending on the manner of living, even in a house whose insulation performance did not meet the energy efficiency standard. The model residence was simplified as the calculation model shown in Figure 6. An unsteady heat conduction calculation of the building envelopes was performed and the room air temperature was estimated by considering the heat transfer from the surrounding walls/floors/roofs and ventilation. The calculation program was written using Fortran 90 and the solution was confirmed not to be divergent.

**Figure 6.** Analyzed Kyo-machiya model.

The outdoor temperature and amount of solar radiation in a standard year in Kyoto determined from the Expanded Automated Meteorological Data Acquisition System (AMeDAS) Weather Data [71] were used as inputs. Based on next-generation standards (in 1999), when the daily mean outdoor temperature was lower than 15 °C, the rooms were heated at a setpoint temperature of 18 °C, and otherwise cooled at a setpoint of 27 °C. During the daytime (6:00–18:00) in the cooling period, natural ventilation was performed if the outdoor temperature was lower than the indoor temperature.

The air exchange rate was set to 10 [1/h] during naturally ventilation and 0.5 [1/h] during no ventilation. It is assumed that the residents principally inhabit the first floor, whereas the second floor comprises a storage space and a space used only to lodge temporary visitors for a few days.

First, to specify the thermal performance of the model house compared to the conventional Kyomachiya, annual heating-cooling load when there is no insulation on the

east/west walls and roof was calculated. Next, the following parameters were changed, assuming the resident's way of living: (1) heated/cooled spaces, (2) heating hours, and (3) heating/cooling setpoints. Note that per the current energy efficiency standards, processes including air conditioning, lighting, and energy consumption by home appliances are evaluated by primary energy consumption considering equipment efficiency. Here, only the heating-cooling load is discussed, referring to the standard value of the next-generation standard (1999), in which the insulation performance does not change. This is because the influence of the residents' way of living on the heating-cooling load is the focus, regardless of the type of air-conditioning appliance.

2.2.2. Cold and Draft in Winter: Issues Related to the Atrium

The temperature and airflow distributions in the staircase of a model residence (Figure 7) were measured in winter to analyze the characteristics of cold draft occurring in the atrium. When the Zashiki on the first floor was air-conditioned at 25 °C, the door (Fusuma) connected to the staircase was kept open. The effect of opening or closing the door on the second floor was also examined.

The temperature was measured using small thermo-hygrometers (T&D Corp., RTR-503) at 1 min intervals. The wind speed and direction were checked intermittently using an omnidirectional hot-wire anemometer (KANOMAX Model 6543-21) and small streamers, respectively.

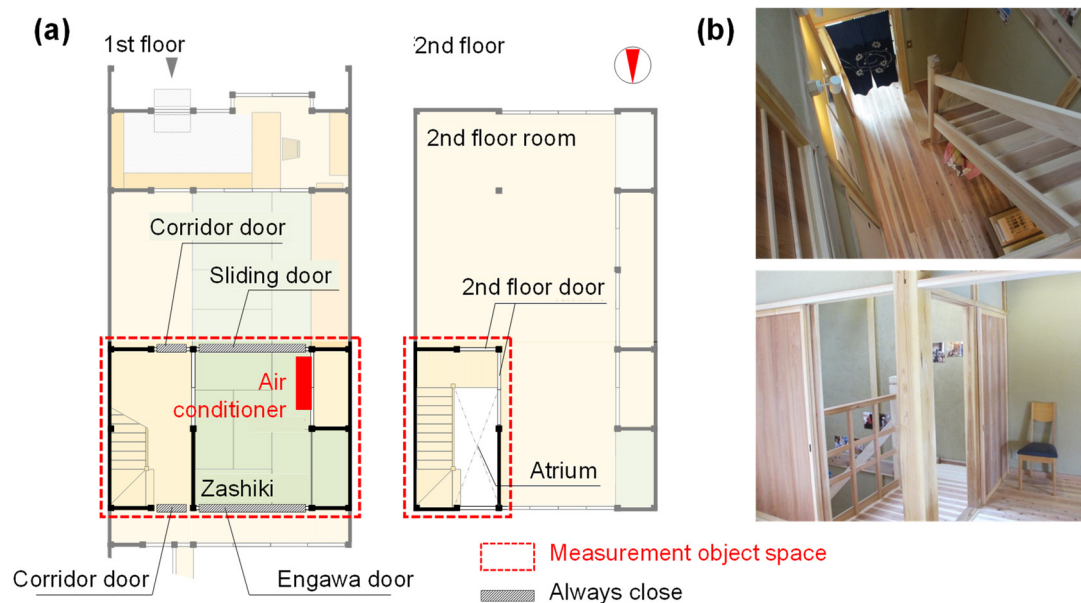


Figure 7. Model residence: (a) plan and (b) overview of measured staircase.

2.2.3. Thermal (Cooling) Storage of the Building Structure by Natural Night Ventilation

The cooling effect of the thermal storage of the building structure was examined to analyze the natural night ventilation in summer. The measurements were performed in the same model residence. On the first day, the doors were opened during the day and closed during the night (normal operation), whereas the opposite was done on the second day (night ventilation operation). Figure 8 shows the measurement procedure, including the durations of keeping the doors opened and closed. For measurement, a thermo-hygrometer (T&D Corp., RTR-503) was set at the center of each floor, recording at 10 min intervals.

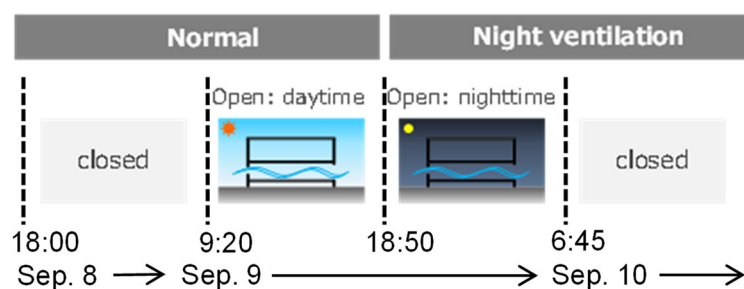


Figure 8. Procedure of measurements and opening/closing of doors.

To investigate the effect of ventilation cooling in more detail and more effective uses of thermal storage of soil wall, simple calculations were conducted. The calculation model was almost the same as that described in Section 2.2.1 (Figure 6). The examination period was 3 days from September 8, 2014, which is the same as the measurement, and the run-up calculation was performed from 1 month before that. The outside air temperature and solar radiation measured in the back court of the model residence was used as input data. The calculation cases are listed in Table 3. Case 1 is the same condition as the measurement in which the doors were opened during the day and closed during the night on the first day, and the opposite was done on the second day. Case 2 is when the night ventilation is not conducted on the second day (same operation as on the first day), and Case 3 is when the thickness of the insulation attached to the east and west walls is increased from 40 mm to 100 mm, in addition to Case 1, aiming to evaluate the influence of insulation. Note that there was the possibility of increasing the insulation thickness on the east/west walls with exterior materials (cedar board), without any change in appearance.

Table 3. Calculation conditions: Insulation.

		Night Ventilation	Insulation: East and West
Case 1	Same condition as the measurement	Yes From 18:50 on September 9 To 6:45 on September 10	Wooden insulation 40 mm
Case 2	No night ventilation	No Windows closed during night	Wooden insulation 40 mm
Case 3	Increased Insulation of side walls	Yes From 18:50 on September 9 To 6:45 on September 10	Wooden insulation 100 mm

2.2.4. Influence of Partition Doors on Ventilation Cooling

Because the position and closure of the partition doors affect the indoor air flow, they also strongly influence the effectiveness of natural ventilation cooling during daytime in late summer and autumn. Although the usual strategy is to open all doors, the air may flow into an unoccupied space, thereby wasting natural energy. Therefore, their influence was examined using computational fluid dynamics (CFD) analysis as described below.

Simulations were performed for the model residence. The software Flow Designer 12 [72] was used for the calculations. The computational domain was 100 m (x) × 100 m (y) × 30 m (z), as shown in Figure 9a, and the number of grids was 90 (x) × 134 (y) × 68 (z). The size of the target residence is shown in Figure 9b. The outdoor wind velocity and direction were set at 2.14 m/s and north-northwest, respectively, which are frequently observed in Kyoto in late summer. In this calculation, the temperature is assumed to be constant at 20 °C.

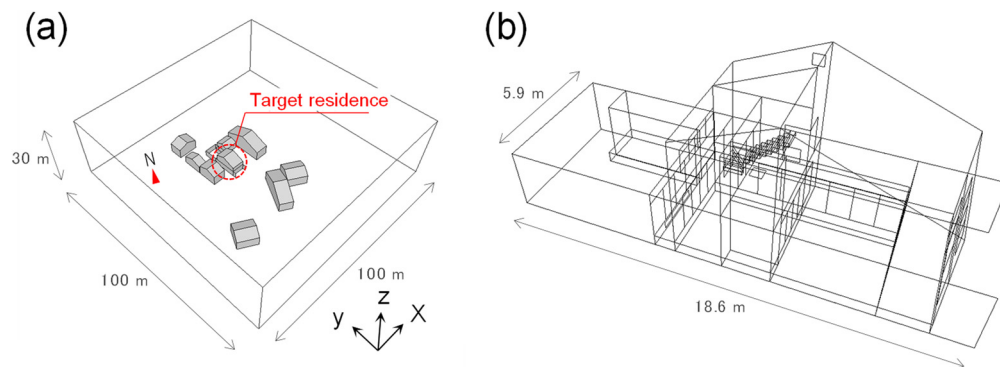


Figure 9. (a) Computational domain and (b) the wire frame model of the target residence.

Here, the effects of opening/closing the Fusuma (Japanese-style partition door) were examined according to Patterns 1–3 (Figure 10). In Pattern 3, the cases with stronger outside wind (3.0 m/s, 3.5 m/s) were also examined.

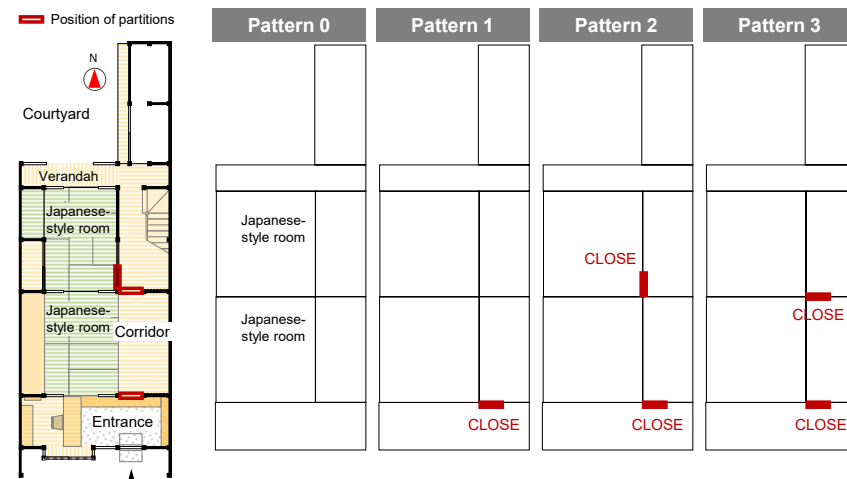


Figure 10. Closure of doors (Fusuma) in the model residence.

3. Results

3.1. Estimated Energy Consumption and Countermeasures

Based on the evaluation procedure of the next-generation energy efficiency standards, heating-cooling loads in the case of the current model residence and of no insulation were calculated. The results are shown in Figure 11a. Because it was assumed that the whole house was heated/cooled as required, the annual heating-cooling load was obtained per total floor area (first and second floors). The current model houses do not meet the standard value (460 MJ/m²), to say nothing of the case of no heat insulation. Next, assuming the actual lifestyle as described in Section 2.2.1, we focused on the following points: (1) heated/cooled spaces, (2) heating hours, and (3) heating/cooling setpoints. Note that the calculation conditions are different from those of the energy efficiency standard used to examine the potential for energy saving.

Figure 11b shows the calculation results of the annual heating and cooling loads for the different heated/cooled areas in the residence. In this figure, right bar presents the annual heating-cooling load divided by only the first floor area (72 m²) because only the first floor was assumed to be a living space, whereas the left bar shows the load divided by the total floor area (144 m²). Although the heating/cooling load seems to have increased when the heated/cooled spaces were limited from both the first and second floors (specified by the standard) to only the first floor, the load for whole residence was reduced by 38%, from 77,616 MJ to 48,024 M. Figure 11c shows the results for different heating hours. By changing

the heating hours from 24 h (following the standard) to 6:00–24:00 (waking hours) or to 6:00–12:00 and 18:00–24:00, the heating/cooling load decreased by 18 and 26%, respectively. The effect of no heating during the night was substantial when the outdoor temperature was low. Figure 11d shows the results for the heating/cooling setpoint temperatures. By changing the setpoint temperature from heating 18 °C/cooling 27 °C to heating 17 °C/cooling 28 °C, the annual load decreased by 17%, and the annual heating/cooling load was 438 MJ/m², which satisfied the standards.

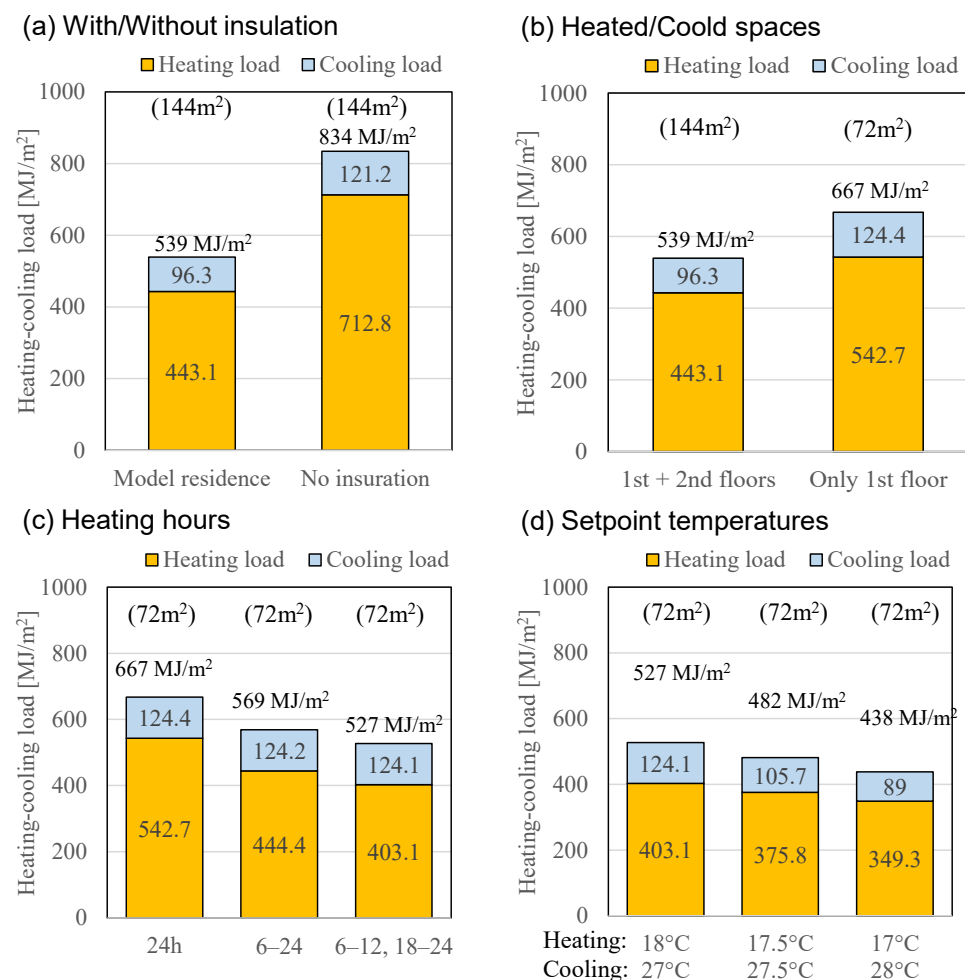


Figure 11. Calculated results of annual heating/cooling load.

3.2. Cold Draft in Winter: Issues Related to the Atrium

Using a simple streamer, it was found that hot air flowed into the staircase through the door, rose to the second floor, and then flowed down along the staircase as cold air. The measurement results are shown in Figure 12.

When the door on the second floor was open, the 29 °C hot air flowed out from the Zashiki on the first floor at 0.3–0.4 m/s through the upper part of the door, and rose to the second floor at a flowrate of 0.5 m/s. From the second floor, 19 °C cool air flowed down the stairs at 0.2–0.35 m/s, and then returned to the Zashiki at 21 °C through the lower part of the door on the first floor.

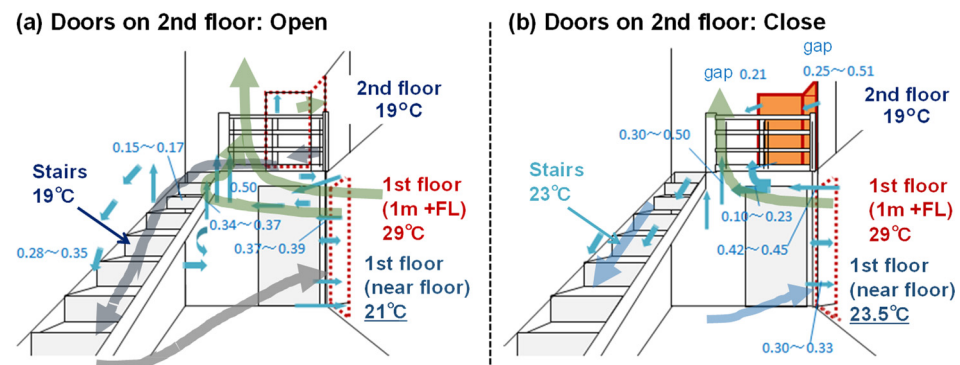


Figure 12. Air velocity and temperature in the staircase; (a) opened and (b) closed cases.

In contrast, when the door on the second floor was closed, the downward air velocity decreased, returning to the Zashiki at 0.3–0.33 m/s and 23.5 °C, and the draft in the Zashiki was weakened.

3.3. Thermal (Cooling) Storage of the Building Structure by Natural Night Ventilation

The room temperature at the center of the first floor during the measurement is shown in Figure 13, along with the outdoor temperature and solar radiation. With night ventilation operation, the room temperature during the night decreased by 2.5 °C compared to that with normal operation because of the night ventilation, and as a result, the increase in the room temperature on the following day was suppressed by 1.7 °C.

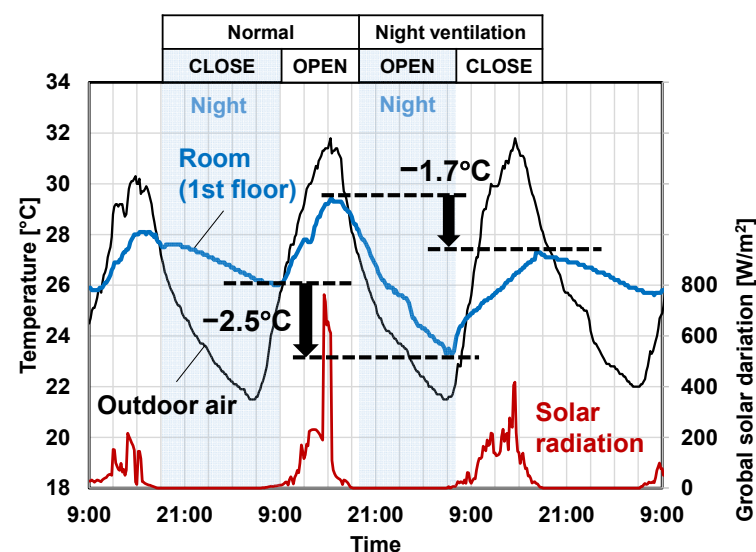


Figure 13. Measured results of the night natural ventilation experiment.

Figure 14a shows the calculated room temperature on the first floor in Case 1 along with the measured results. Although the calculated temperature drop during night is slightly less and slower than the measured results, the temperature rise during the day is in good agreement with the measured value. Figure 14b shows the calculated room temperature of each case. When no night ventilation was conducted (Case 2), the room temperature decreased by only 2 °C because of heat emission from the soil walls that had stored heat during the day, in contrast to Case 1 in which the temperature dropped by about 5 °C. The amount of night cooling of the soil wall was considerably small, and the high room temperature was maintained during the day. In Case 3 with thicker insulation, the room temperature changed almost same as in Case 1.

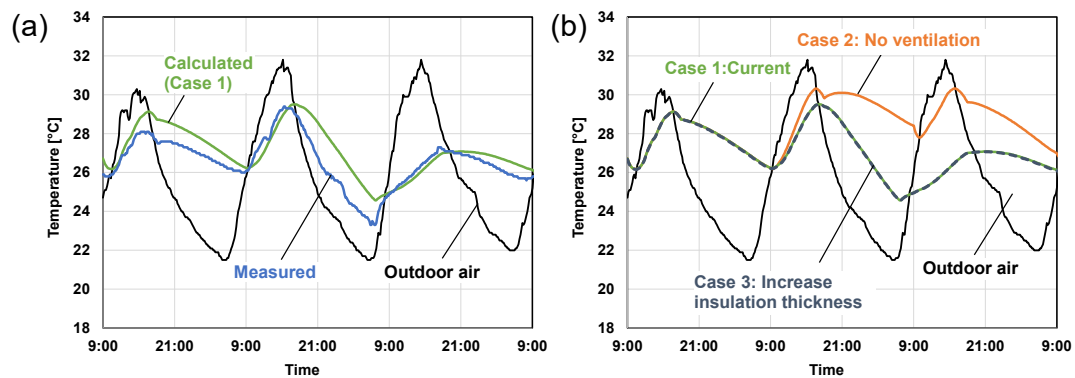


Figure 14. (a) Measured and calculated (Case 1) indoor temperature on the first floor, and (b) calculated indoor temperature in each case.

3.4. Influence of Partition Doors on Ventilation Cooling

The wind speed distributions corresponding to Patterns 0–3 are shown in Figure 15. In Patterns 0 and 1, the outdoor air flowing through the north windows diffused into the Japanese-style rooms and weakened, making it ineffective for ventilation cooling in these rooms. By closing two partition doors along the corridor in Patterns 2 and 3, the airflow route can be clearly specified, and sufficient air velocity can be obtained in the Washitsu (Japanese-style rooms). The contours of wind velocity for cases with different outdoor wind velocities in Pattern 3 are shown in Figure 16. The air velocity in the corridor did not change significantly even when the outdoor wind velocity increased.

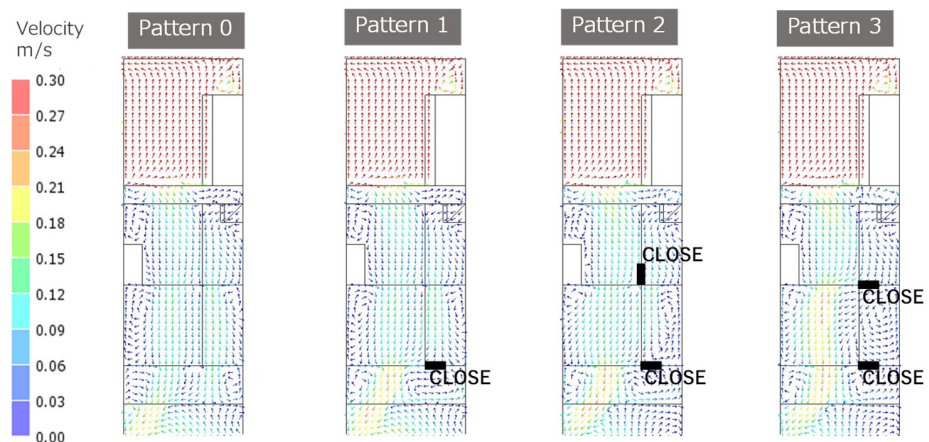


Figure 15. Simulated results of airflow patterns and velocities.

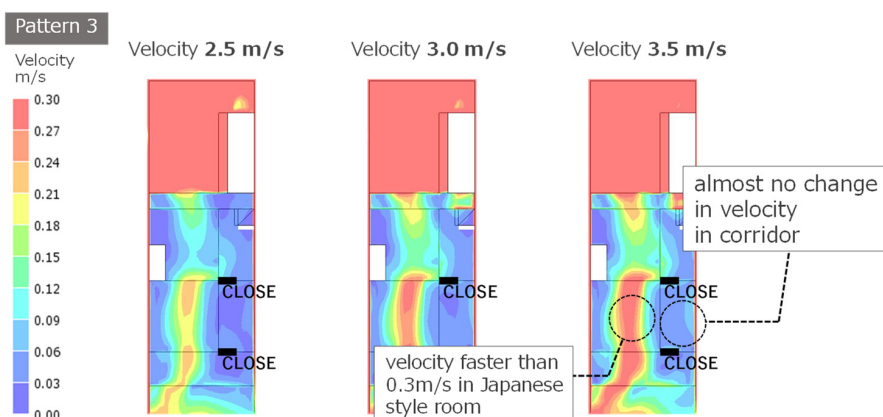


Figure 16. Simulated results of airflow velocities under different outdoor wind velocities.

4. Discussion

4.1. Energy Efficiency Standards

The simulation conditions described in Section 2.1 do not satisfy the specifications of the energy efficiency standards. However, because of the present situation (an aging society), the lack of use of the second floor may be regarded as an energy-saving strategy in line with the reality of the present “Kyo-machiya” lifestyle. The changed heating/cooling hours and setpoints are common to all areas in Japan, except for the northern parts, and seem reasonable. Adaptation to the living environment may be involved.

The rationale for the specific cooling hours and setpoint temperatures in summer is partly discussed in Sections 3.2 and 3.3 from the viewpoint of natural night ventilation (purge) and ventilation cooling (lowering of the perceived temperature by increased indoor air velocity). As discussed in Section 3.1, the perceived temperature and insulation performance were increased in winter by reducing cold drafts and infiltration.

Although the reduction in the heating load has a large influence on satisfying the standards, as shown in Section 2, possible measures to do so are very limited in “Kyo-machiya”. However, in a terrace-type “Kyo-machiya”, the boundary walls with neighboring houses can be ideally regarded as adiabatic if symmetry can be assumed, resulting in no heat loss. The situation of the model house with insulation on both side walls is quite similar to this situation. In addition, the Engawa (a veranda connected to the courtyard), a thermal buffering zone, can play an important role as an insulation layer by controlling the opening/closing of the doors on both sides of it, although this measure is not basically allowed to evaluate the heat load under the present standards.

Despite facing some problems, such as lower indoor temperatures and contact with the cold floors caused by decreased heating hours and setpoints, many people who live in Kyo-machiya are likely to accept this situation. As previous surveys [73,74] have shown, this is because they currently live in such environments.

4.2. Control of Draft in Winter

Historically, heaters, such as the Kotatsu (a low-table frame with an internal heater covered by a heavy blanket) or Hibachi (a container made of ceramics, metal, wood, etc., in which charcoal burns on ash), have been used against the cold during winter. However, these local heaters can only warm the human body and cannot maintain high temperatures across the entire house, which is preferable from a health perspective. If only local heaters are used and low room temperature prevails, cold draft can create a colder thermal sensation. This influence is significant in modern housing with an atrium. Because a colder thermal sensation encourages an increase in heat energy, reducing cold drafts is also important from an energy-saving point of view.

From the measurements in Section 3.2, it can be understood that the atrium and staircase influence the temperature and airflow in other rooms, and the results are significantly affected by opening or closing the door on the second floor. Thus, the separation of the atrium from the neighboring spaces is important, although the insulation of the external walls is more important.

Figure 17 shows examples of movable doors and windows installed in the staircase and atrium to prevent cold draft considering the results in Section 3.2. The measured values (not shown here) of temperature and air flow showed that the draft could be suppressed by suitably closing the sliding doors and windows.

There is no window connected to the room on the second floor on the upper part of the Hibukuro in the Tori-niwa (Figure 2) and considering the role of the Hibukuro in discharging smoke, it is beneficial for suppressing the draft in winter. Furthermore, the Hibukuro and Tori-niwa can be isolated by closing the doors connected to the Zashiki on the first floor. Although there is a staircase in the Naka-no-ma (refer to Figure 2) connected to the second floor, it also has a door that can be closed, allowing airflow to be controlled. Thus, the Hibukuro can be completely isolated from the neighboring spaces.



Figure 17. Fittings isolating the atrium.

Reducing the cold draft leads to an improvement of thermal sensation of residents, which may decrease the heating set temperature. As presented in Figure 11d, lowering the heating set temperature by 0.5 °C reduces the heating load by about 7%, and lowering it by 1 °C, reduces the load by more than 13%.

4.3. Control of Natural Ventilation Cooling and Thermal Storage during the Night

It is important to evaluate not only the thermal discomfort caused by cold drafts in winter, but also the thermal comfort by natural ventilation cooling in summer. Currently, the cooling load fraction of all loads is small. However, considering that abnormally hot days and sultry nights often occur because of the heat island effect and global warming, occurrence of conditions, such as heat stroke and insomnia, have increased. Thus, it is necessary to maintain a suitable indoor temperature during summer.

As mentioned in Section 3.2, natural night ventilation decreased the room temperature during the night by 2.5 °C and the room temperature on the following day by 1.7 °C. Here, thermal storage was possible because of the moderately large heat capacity of soil and wooden building elements. The effect of night cooling was also confirmed by the calculation. However, the increase in the insulation thickness did not affect the room temperature under the presented conditions. This was probably because the increase of the insulation thickness reduced both heat gain through the outer wall during the day and heat discharge to the outdoor air during the night, leading to the offset of the effect of night ventilation on the room temperature. Assuming a complete insulation layer exists on the outside of the soil wall, it is expected that the room temperature will decrease less during night and increase less during the day. Therefore, the timing of opening and closing the doors is significantly important for effective night cooling.

Improving the airtightness of openings has a crucial effect on the Engawa (Figure 4a), making it more effective to use. By suitably changing the degree of closure of the inner and outer doors of the Engawa depending on weather conditions, solar heat can be effectively utilized in winter (similar to a sunroom), and also function as an insulation layer on the outside, thus effectively reducing the heating load and improving the indoor thermal environment.

In contrast, for cooling in summer, proper closure of the doors may be sensitive to the outdoor temperature and solar radiation. In addition, attention should be paid to fittings, such as mosquito nets and bamboo screens (Figure 4c), which are often used in the Engawa and weaken the airflow, requiring varying degrees of closure depending on the internal and external conditions.

The natural night ventilation contributes to suppressing the rise in room temperature during the day, which leads to a reduction in cooling time. The effective use of natural ventilation can provide the resident almost same level of comfort due to air flow even if the temperature is higher than that during cooling. By this, similar effect in cooling load

reduction is expected as the cooling set temperature was raised in Figure 11a. Raising the cooling set temperature by 0.5 °C can reduce the cooling load by around 15%, and raising it by 1 °C, can reduce the load by 28%.

5. Conclusions

This study investigated the energy consumption for heating and cooling in traditional “Kyo-machiya” residences and examined countermeasures to increase consumption efficiency and reduce the impacts of climate change. Field surveys on indoor environments were conducted in both summer and winter and the following results were obtained:

- (1) The heating/cooling load in a traditional dwelling was compared with the minimum requirements of the next-generation energy efficiency standards in Japan, and the possibility of meeting the requirements was discussed by flexibly considering the method of room use or the temperature setpoint to which the resident is adapted.
- (2) Based on the measured and simulated results, the indoor airflow was examined and discussed from both thermal comfort (cooling in summer) and discomfort (cold drafts in winter) perspectives. For these purposes, the importance of building design elements, such as atriums, fittings, and sliding doors for partitioning a house, was discussed.

In terms of air conditioning, spring and autumn are called intermediate seasons, meaning that there is no need for cooling or heating. The duration of these conditions can be extended by suitably controlling the gain/removal of solar heat and adjusting the natural ventilation air volume, resulting in a reduction in heating/cooling energy use. Further analysis is necessary on how long the intermediate season can be extended and how much the cooling load can be reduced by calculating the indoor airflow velocity during ventilation using CFD analysis and estimating the degree of cooling enhancement caused by the wind velocity increase using an appropriate predictive model of thermal sensation.

Although this research evaluated a residential building, “Kyo-machiya”, unique to Japan, it can be considered a useful case study that can contribute to energy saving, which is a global demand, by considering the health and comfort of residents while preserving traditional appearances and lifestyles. As a next step, possible problems, such as condensation, IAQ, and energy consumption when applying the thermal insulation retrofit to the Kyo-machiya, will be examined.

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