Simulation of the thermal and air environment in Japanese traditional architecture

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There are many types of traditional (vernacular) architecture globally. The Encyclopedia of Vernacular Architecture of the World[1] describes vernacular architecture as follows: "All forms of vernacular architecture are built to meet specific needs, accommodating the values, economies and ways of life of the cultures that produce them". In architectural environmental engineering, rediscovering the features of traditional architecture for improving the environment and past ways of life would help preserve cultural heritage and support the sustainable development of society. The thermal and air environment in Japanese vernacular architecture is simulated to rediscover how Japanese architects historically improved the indoor thermal and air environment passively without modern-day appliances. Computational fluid dynamic (CFD) analysis was used to simulate the thermal and air environment for the room space in vernacular Japanese architecture. The CFD analysis quantified the effects of the complex features and designs in Japanese vernacular architecture on the indoor thermal and air environments. Well-designed air pathways allowed fresh air from outside into the room space. Rooms were surrounded by buffer zones such as corridors, verandas or porches, which created a milder, more comfortable thermal environment. Rediscovering and reintroducing some of the complex features of traditional architecture identified in this study will help to achieve a sustainable future through improving quality of life without increasing the environmental load.

Introduction

According to the IPCC AR5, the buildings sector accounted for about one third of total direct and indirect greenhouse gas emissions in 2010, and emissions are expected to increase by 50–150% by the mid-21st century in baseline scenarios. Thus, it is essential to mitigate greenhouse gas emissions in daily life. However, a major challenge is to reduce energy demand and greenhouse gas emissions while maintaining quality of life. Excessive energy saving can reduce comfort and satisfaction. However, examining historical ways of life may provide clues to solve this problem, because comfort was improved without using mechanical appliances and consuming huge amount of energy.

According to The Encyclopedia of Vernacular Architecture of the World, "All forms of vernacular architecture are built to meet specific needs, accommodating the values, economies and ways of life of the cultures that produce them" and thus it is worth investigating the complex and building-specific features of traditional architecture designed to improve the environment. Many studies have examined how our ancestors lived and behaved in their vernacular architecture. However, most of this work has been conducted by historians, and the number of studies focusing on environmental engineering is limited. Therefore, in this work, focus is placed on investigating the domestic thermal and air environment in Japanese traditional architecture.

Selection of traditional architecture

There are many types of traditional architecture and computational fluid dynamics (CFD) simulations of various types of traditional architecture have been reported. However, these CFD simulations are based on various assumptions and the results cannot be verified because most of the traditional types of architecture no longer exist. Therefore, an existing building was selected, namely, Silkworm-raising Building No. 1 of the Hino Sericulture Experiment Laboratory (also called Kuwa House), in Hino, western Tokyo, Japan. The building was finished in March 1932, and it was a national laboratory for sericulture experiments. The silk industry was the main Japanese industry and it was critical to optimize the thermal and air environment for silkworms and maximize the production volume of silks. The sericulture experiment laboratory is a two-story, mixed structure building, with a reinforced structure on the first floor and a wooden structure on the second floor. The total floor area is 570 m, of which 370 m belongs to the first floor. The building is not used, although it is currently being considered for national cultural heritage status because of its great historic value. A report including photos of the building and materials used in the architectural design has been published. Current photos, material properties for each structural member, local weather information, first and second floor plans, and the north, east, and west elevations of the building are shown in Fig. 1, Tables 1 and 2, and Figs. 2–5, respectively. Indoor thermal environment data, such as temperature and relative humidity, were recorded for sericulture experiments and are still available. These records are invaluable for the present calculations and for verifying the results.

Fig. 1. Status photo of the Sericulture Experiment Laboratory taken in 2012.

Members	Materials	Thickness [mm]	Density [kg/m^3]	Specific heat capacity [J/(kg·K)]	Thermal conductivity [W/(m·K)]
First floor exterior wall	Concrete	150	2400	900	1.2
	Daub	18	1000	900	0.7
Second floor exterior wall	Wood	10	300	1300	0.069
	Air (space)	130	1.206	1007	0.0256
	Wood	10	300	1300	0.069
	Mortar	40	2000	800	1.3
Floor of the first floor	Wood	20	300	1300	0.069
Floor of the second floor	Concrete	150	2400	900	1.2
	Daub	18	1000	900	0.7
First floor interior wall	Concrete	150	2400	900	1.2
	Daub	18	1000	900	0.7
Taiko shoji	Paper	0.1	900	1300	0.06
	Air (space)	34.8	1.206	1007	0.0256
	Paper	0.1	900	1300	0.06
Ordinary *shoji*	Paper	0.1	900	1300	0.06
Windows	Glass	15	2190	740	1.38
Doors	Wood	60	300	1300	0.069
Pillars	Concrete	500 × 400	2400	900	1.2
	Daub	18	1000	900	0.7
Beams	Concrete	500 × 300	2400	900	1.2
	Daub	18	1000	900	0.7

Table 1. Material properties for each structural member

	Day in April 1960									
	11	12	13	14	15	16	17	18	19	20
Minimum temperature [°C]	12.5	6.8	8.5	10.3	11.4	7.2	6.0	7.6	5.1	8.0
Wind direction	N	N	N	N	N	N	ESE	N	E	N
Wind power [Beaufort scale]	6.1	0	0.2	0.2	1.7	0.7	0.4	1.7	1.3	0

Table 2. Local weather conditions in mid-April 1960

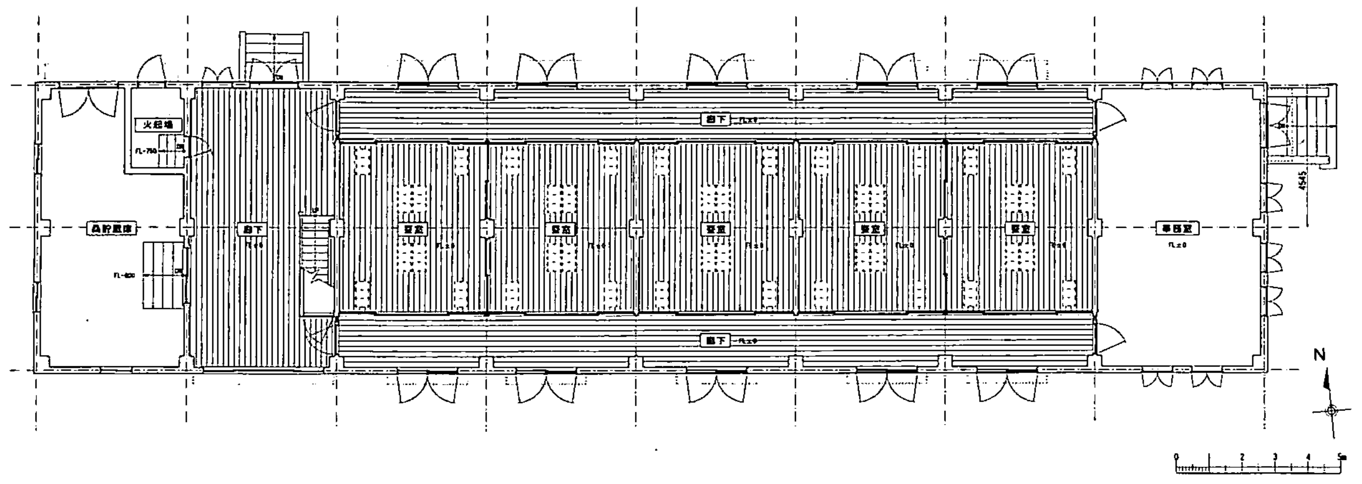

Fig. 2. First floor plan of the Sericulture Experiment Laboratory.
The five rooms in the center of the building are the silkworm-raising rooms, bounded by north and south corridors and divided by shoji. There are two fire pits and four ventilation windows in the center and corner of each of the rooms..

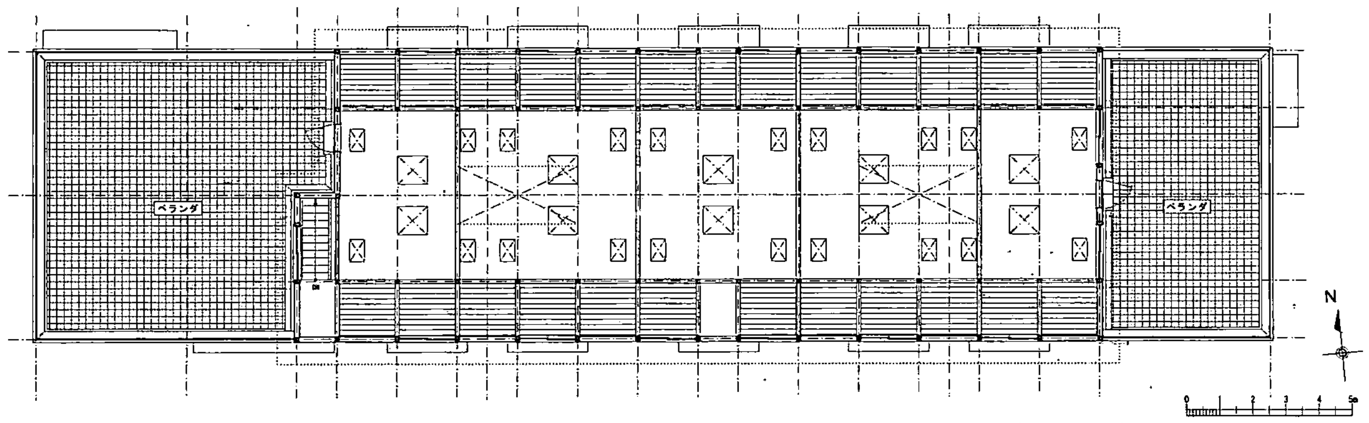

Fig. 3. Second floor plan of the Sericulture Experiment Laboratory.

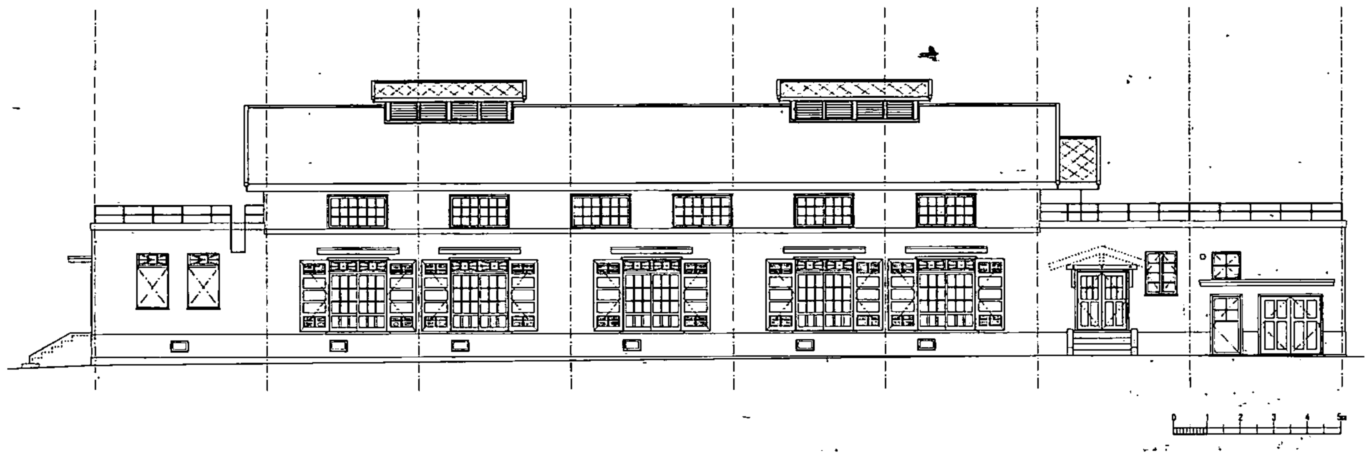

Fig. 4 North elevation of the Sericulture Experiment Laboratory.

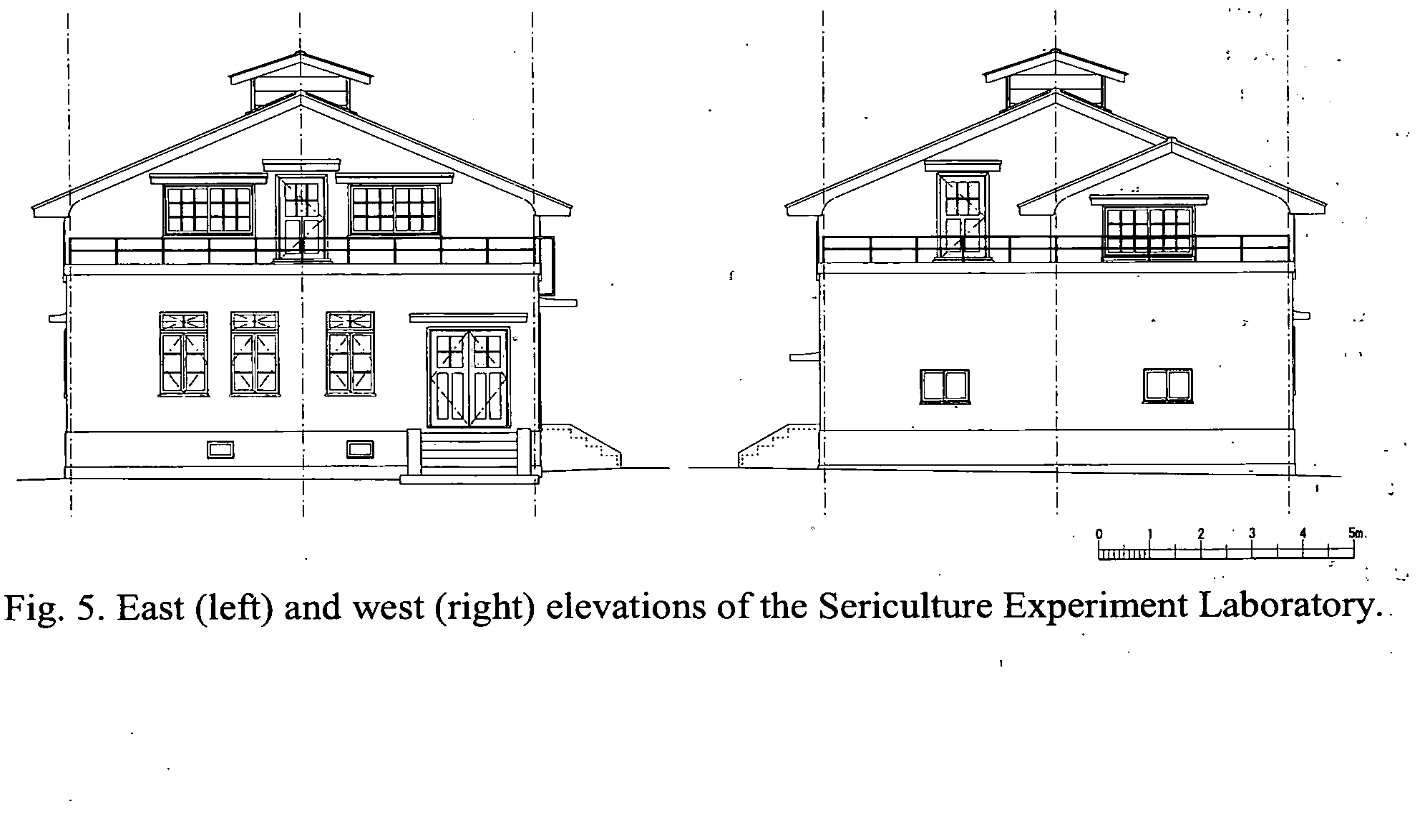

Fig. 5. East (left) and west (right) elevations of the Sericulture Experiment Laboratory.

Table 3. CFD Simulation conditions

Items	Conditions	
Turbulent model	Linear low Reynolds number k-ε turbulent model	
Simulation area	185 × 225 × 41 [m] (x × y × z)	
Number of meshes	Approx. 18,000,000 meshes	
Simulation algorithm	SIMPLE algorithm	
Discretization scheme	First-order upwind scheme	
Buoyancy	Boussinesq approximation	
Inflow and outflow boundary conditions	North face	(Simulation for mid-April: silkworm rearing period) Wind direction: North Wind temperature: 8.3 [°C] Wind velocity: $\frac{V}{V_R} = (\frac{Z}{Z_R})^{\alpha}$ V: Wind velocity at height Z [m/s] V_R: Wind velocity at height Z_R, 0.9 [m/s] Z: Height [m] Z_R: Benchmark height, 10 [m] α: Exponent = 0.2
	South face	Average static pressure: 0 [Pa]
Wall boundary conditions	Temperature	Boundary surface: Insulated boundary condition
		Fluid-solid interface: Logarithmic law heat transfer
		Solid-solid interface: Thermal conduction
	Velocity	Generalized logarithmic law
Heat sources (Fire pit)	Wood coal	1793 [W]
	Firewood	2815.6 [W]
Radiation	View factor method	
Software	STREAM V12 (Software Cradle Co., Ltd.)	

Simulation of thermal and air environment in Japanese traditional architecture

CFD simulation was conducted to reproduce the thermal and air environment inside the building and to verify whether it was an adequate environment for silk production. Simulation conditions are shown in the Table 3.

Two different cases were simulated to examine the effectiveness of historical architectural designs used to improve indoor thermal and air environment. Case 1 was the reference case in which the indoor thermal and air environment was reproduced as accurately as possible. Case 2 was the comparison case in which some of the architectural features were removed. In this study, the Japanese traditional sliding room divider also used for doors and windows (*taiko shoji*), which consists of a wooden frame with air sandwiched between two sheets of translucent paper, were replaced with ordinary *shoji*, which have a single sheet of translucent paper and no airspace. *Taiko shoji* has a similar function to modern-day double glazing in preventing heat conduction and improving insulation. An overview of *taiko shoji* is presented in the Fig. 6. The heated silkworm-raising rooms were expected to be warmer in the reference case (case 1) than in the comparison case (case 2) because of the *taiko shoji*, demonstrating the effect of the passive design

Simulation results

The results of the CFD simulation are shown in Figs. 7–12. Figs. 7 and 8 show the temperature distribution in the east-west cross-sectional view for the reference case. The temperature of the five silkworm-raising rooms in the center of the building remained at 22–24°C, which is consistent with the historical records that state that the room temperature was maintained at almost 24°C, verifying the accuracy of the simulation.

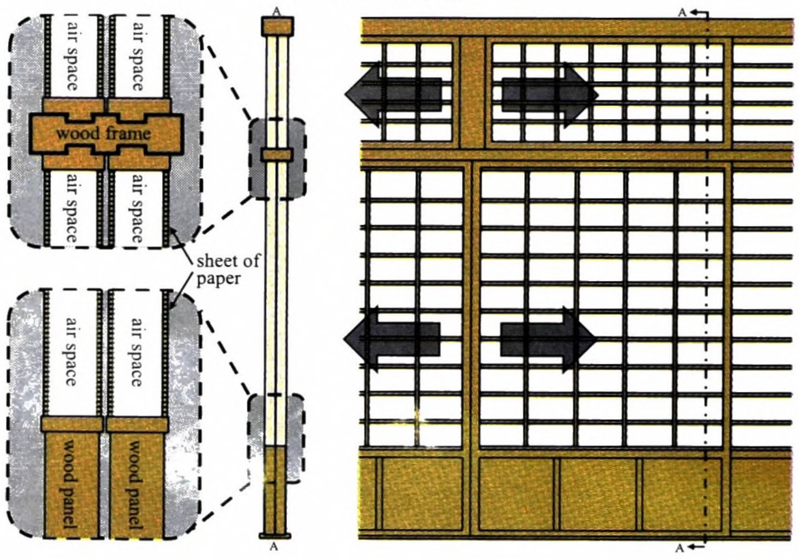

Fig. 6. Overview of the *taiko shoji*

The unheated north and south corridors and the second floor were colder than the silkworm-raising rooms. The temperature of the second floor was slightly higher than that of the north and south corridors on the first floor because warm air rose to the second floor through the ventilation opening installed in the slab. Similar results were observed in Figs. 9 and 10. Fig. 9 shows the wind velocity distribution inside the silkworm-raising room for the reference case. Cold outside air is drawn into the building from

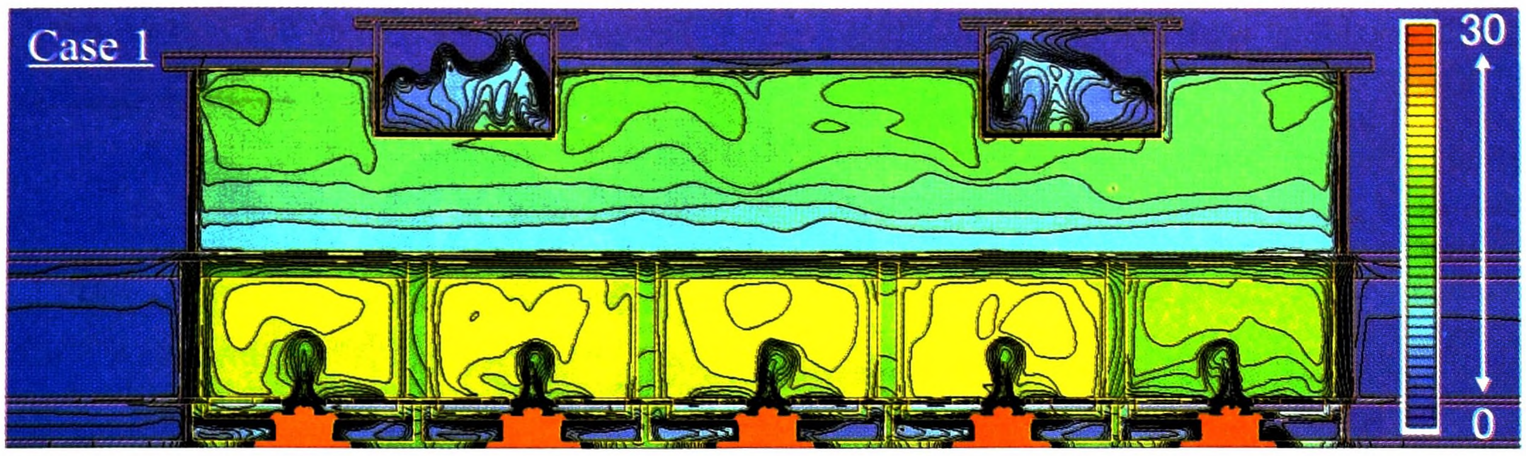

Fig. 7. Temperature distribution [°C] (east-west vertical cross-sectional view).

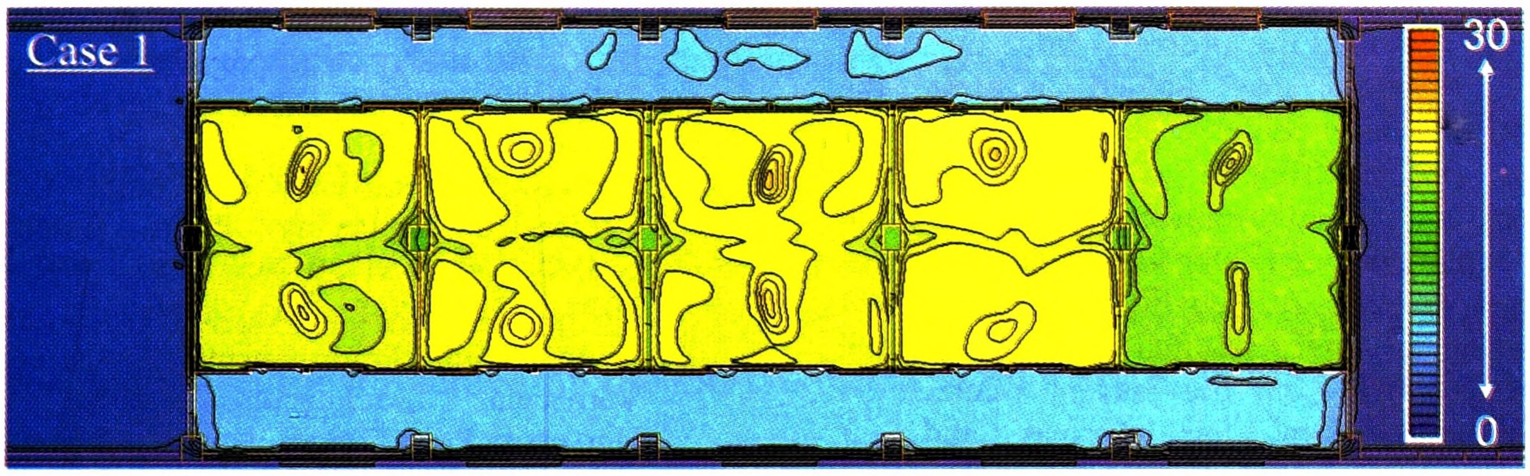

Fig. 8. Temperature distribution [°C] (east-west horizontal cross-sectional view, floor level + 2 m).

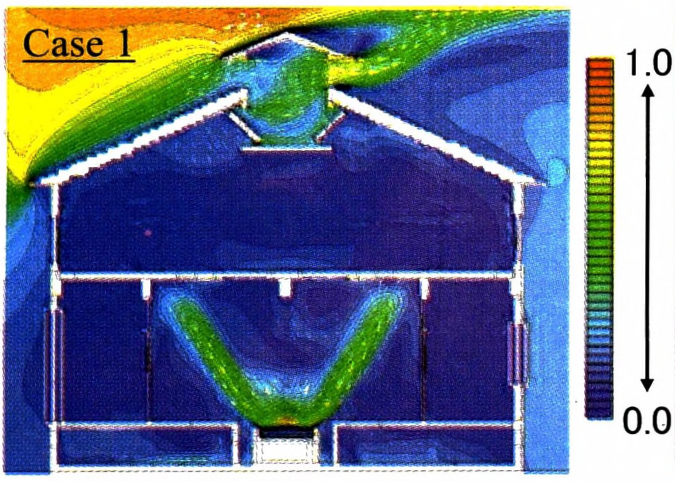

Fig. 9. Wind velocity distribution [m/s] (north-south vertical cross-sectional view).

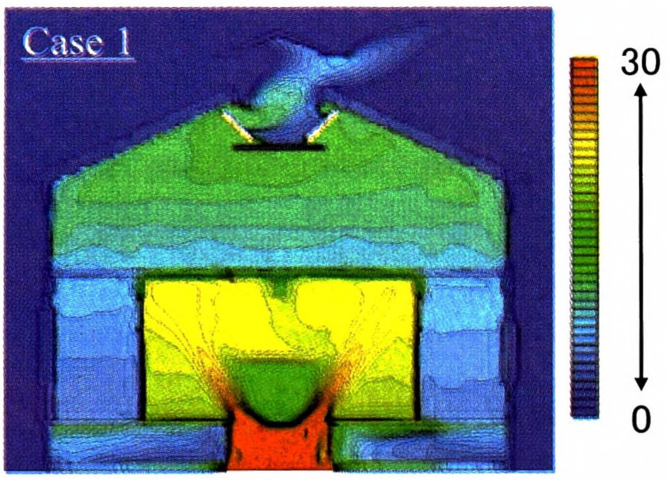

Fig. 10. Temperature distribution [°C] (north-south vertical cross-sectional view).

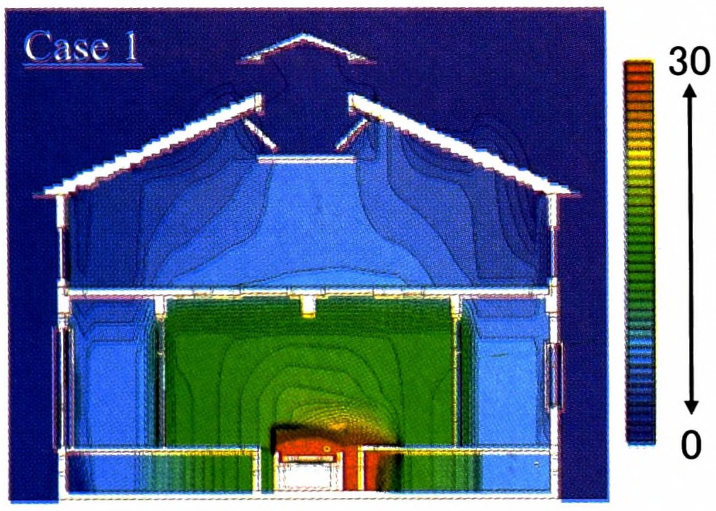

Fig.11. Radiant temperature distribution [°C] (north-south vertical cross-sectional view).

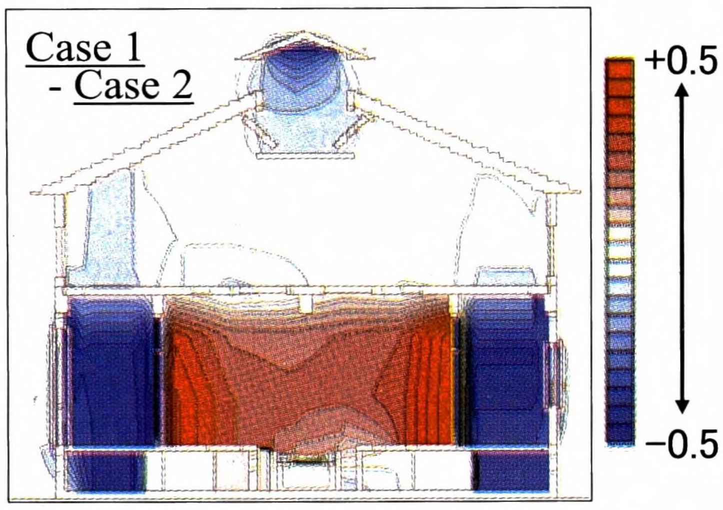

Fig.12. Difference in radiant temperature [°C] between cases 1 and 2) (case 1 - case 2).

air supply openings under the north and south corridor floors, and supplied to the fire pit in the center of the silkworm-raising room. The warm air rises to the ceiling of the first floor, passes through the ventilation window and warms the second floor. This well designed airflow contributed to maintaining a good thermal and air environment. Fig. 10 shows the temperature distribution in the north-south vertical cross-sectional view for the reference case. The north and south corridors were cold, although they played an important role in maintaining the high temperature in silkworm-raising rooms by providing a buffer against the colder outside temperature. Fig. 11 shows radiant temperature distribution in the reference case and Fig. 12 the difference in the radiant temperature between the reference and comparison cases. The mean radiant temperature in the reference case was about 21°C, which was 0.3–0.4°C higher than that of comparison case. This difference was caused by the higher insulation of *taiko shoji* compared with ordinary *shoji*. Adding a single sheet of paper to the ordinary *shoji* created a sealed airspace that helped insulate the silkworm-raising room. The passive airflow design also contributed to creating a good thermal and air environment. These historical architectural features offer valuable suggestions on how to improve quality of life without increasing the environmental load. It is crucial to move away from the current reliance on active control of the thermal and air environment and make more use of passive design and control.

Conclusions

A CFD simulation was conducted to reproduce the indoor thermal and air environment of the historic Japanese silkworm-raising Building No. 1 of the Hino Sericulture Experiment Laboratory, in Hino, western Tokyo. The simulation results showed that indoor air temperature of silkworm-raising rooms was maintained at 22–24°C, which is consistent with historical temperature records. The results show the effectiveness of passive design using *taiko shoji* to prevent heat loss.

Some features of traditional architecture hold valuable lessons in maintaining a comfortable indoor environment without increasing environmental load. These results demonstrate that silkworm-raising Building No. 1 holds important lessons in using traditional technology. Further studies combining historical science and environmental engineering are essential to preserve cultural heritage and sustainable development of society.

Technical support from the project member of discovering inheritance project of Nakada Forest and administrative officers of Hino city is gratefully acknowledged.

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