Study on Reusing Abandoned Chimneys as Solar Chimneys to Induce Breeze in Residential Areas

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ABSTRACT: In this study, we have proposed a passive system in which abandoned chimneys are used as solar chimneys. The system comprises four parts, namely, the earthen tunnel, occupied area, glasshouse, and chimney. The chimney remains untouched; however, a glasshouse is constructed around its foot to generate an updraft exhaust. The performance characteristics of the passive system, such as the airflow, thermal comfort, and so on, have been evaluated based on the results of numerical simulation using TRNSYS, QuickStream, and AMeDAS software.
Keywords: solar chimney, glasshouse, earthen tunnel, thermal comfort, urban heat island, numerical simulation

INTRODUCTION

In dense housing zones of Tokyo, there are many abandoned chimneys of public bathhouses (called *Sento*). The number of public bathhouses in Tokyo reached a maximum of 2,687 in 1968 [1]. However, of these, less than 900 remained in 2008, and 47 closed during the last year itself. Photographs obtained using *Google Street View* have revealed that these 47 closed bathhouses have 28 abandoned chimneys among them (Fig. 1).

The reuse of these chimneys as solar chimneys in the dense housing zones in the Tokyo downtown area is expected to induce breezes that will provide comfortable public spaces. The simplest and cheapest way of reusing a chimney as a solar chimney is to build a glasshouse around its foot. A glasshouse can be used to cultivate common vegetables or to maintain a flower garden.

Figure 1: Abandoned Chimney of Closed Bathhouse Image obtained using Google Street View.

BUILDING MODEL

Figure 2 shows a proposed building model of a public space in which an abandoned chimney is used as a solar chimney. As an average-sized public bathhouse, we consider an area with a length, breadth, and height of 15 m, 10 m, and 3 m, respectively, and a chimney with a height of 15 m. The public space is divided into three zones—earthen tunnel, hall, and glasshouse.

Inlet air cools as it flows through the earthen tunnel, following which it is guided into the hall. It then flows into the glasshouse, where it heats up, following which it is then released through the chimney. In summer, because of the cool wall surface and air, the conditions in the hall can be maintained such that they are comfortable for occupants. The opening of the glass wall in front of the hall is expected to induce air adsorption and breeze outside the hall.

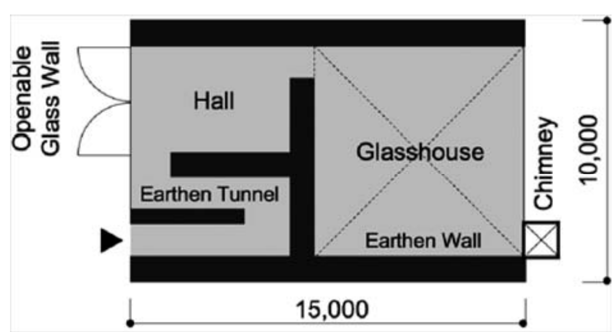

Figure 2: Building Model Plan of Public Space with Abandoned Chimney Reused as a Solar Chimney.

CALCULATION METHOD

In order to investigate the effects of the passive system employed in the building model, the airflow and thermal comfort level are estimated by numerical simulation. *TRNSYS* [2], which adopts the response factor method, is used to determine the surface temperatures; *QuickStream* [3], which adopts the finite difference method, is used to calculate the wind velocities. All meteorological data except for the wind velocities were quoted from Expanded *AMeDAS* (Automated Meteorological Data Acquisition System) [4] standardized data. The wind velocities at the inlet and outlet (above the chimney) are set to 0.1 m/s and 1.0 m/s, respectively. The weather conditions used for the calculations are a clear-sky day on August 22, standardized year.

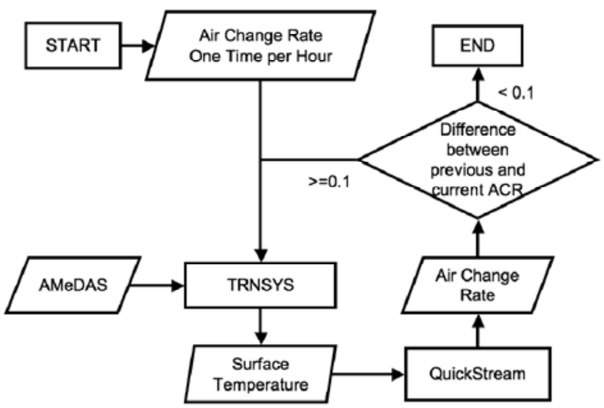

Figure 3: Calculation Flow of Each Time Step.

The time step is set to 1 h. The calculation flow of each time step is shown in Figure 3. Initially, the air change rate on the target day and former days is set to one time per hour for *TRNSYS*. Next, the results of surface temperature are applied to *QuickStream*, which outputs the air temperature and wind velocity distribution. The result of the wind velocity distribution is returned to *TRNSYS* as the air change rate to recalculate the surface temperature. The recalculated surface temperature is reapplied to *QuickStream* to reevaluate the wind velocity. If the difference between the previous and current air change rates exceeds 0.1 times per hour, the abovementioned process is repeated. If not, the time step progresses and the next hour's operation begins.

Given conditions of external wind velocity are 0.1 m/s on inlet and 1.0 m/s on outlet, respectively. The glasshouse and chimney face north (Fig. 4). Air is assumed to be an incompressible and viscous fluid. A laminar flow model with the Boussinesq approach is adopted. The tolerance for convergence is 1.0e–5 m/s, and the mesh number is approximately 30000. These values depend on the result obtained using *QuickStream* through a trial-and-error process.

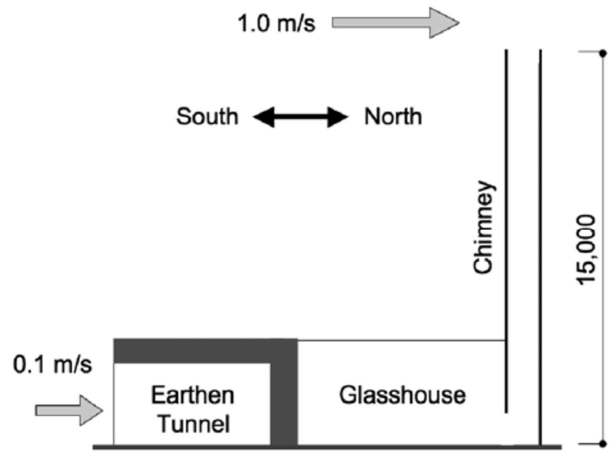

Figure 4: Given Conditions of Wind Velocity and Direction.

CALCULATION RESULT

Figure 5 shows a calculation result of the air temperature distribution at 1300 when the external air temperature is maximum on the candidate day. The air cools down to approximately 27°C when passing through the earthen tunnel. However, in the hall, the high temperature of the internal wall surface causes the air temperature to rise to 31°C. This temperature is considered to be uncomfortable. Therefore, the external clay wall should be thicker or it should be insulated.

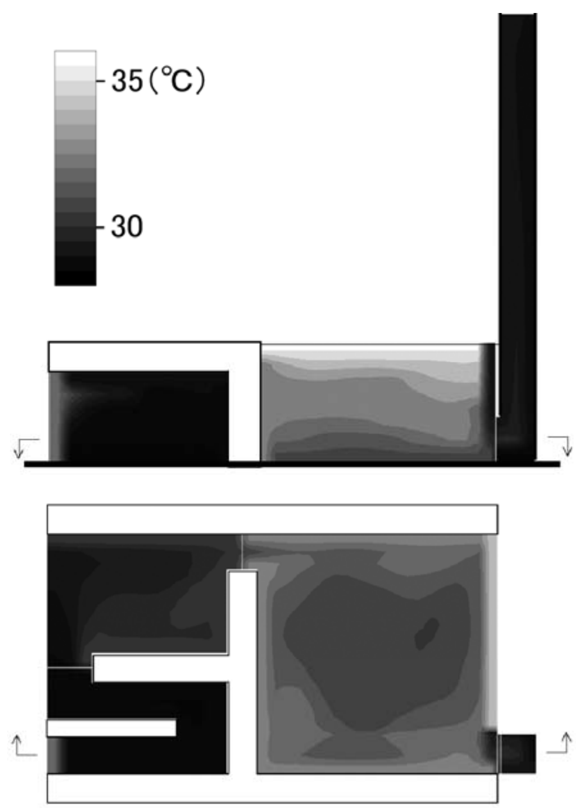

Figure 5: Air Temperature Distribution.
(Calculation Result, 1300, August 22, Standardized Year)

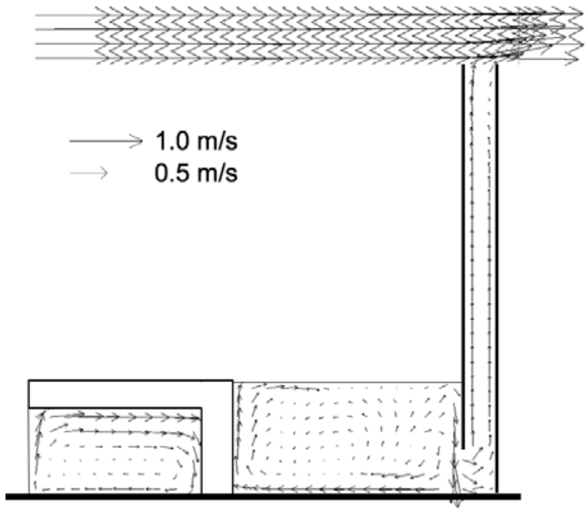

Figure 6: Wind Velocity Distribution.
(Calculation Result, 1300, August 22, Standardized Year)

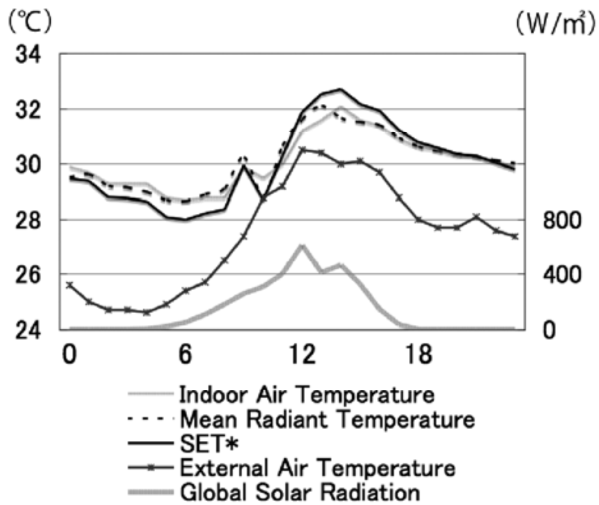

Figure 7: Weather Conditions and Indoor Climate.
(Calculation Result, August 22, Standardized Year)

Although the air temperature in the glasshouse becomes 35°C, that in the chimney decreases to nearly 30°C. The chimney is assumed to be made of concrete. Therefore, its internal surface temperature does not increase easily because of the heat capacity of concrete. The wind velocity ranges from 0.1 to 0.3 m/s in the hall and is therefore hardly comfortable. For SET* (0.3clo, 1met) to yield a comfortable score, the wind velocity must be around 2.0 m/s. A well-designed solar chimney is likely to have a high temperature due to solar radiation; this may lead to the air contained inside the chimney to be released due to the stronger buoyancy of heated air. In this study, we propose the use of a glasshouse since the heating effect will increase the buoyancy of the outlet rapidly and cheaply. However, this requires modifications to make the internal air sufficiently warm to facilitate exhaust and generate comfortable indoor wind.

SPECIFIC EMBODIMENTS

We conducted a case study wherein one architect reused an abandoned chimney located in Inujima Island in Okayama City, Japan, as a solar chimney. In this paper, we call this building “Inujima Art Museum”; this is not the official name. The Inujima Art Museum is a so-called contemporary art museum designed by Hiroshi Sambuichi, and it opened in April 2008. Koichi Asano, Shigemitsu Shuchi, and Kenichi Hasegawa unofficially advised the architect on the passive design of this museum including the application of the solar chimney system. The Inujima Art Museum does not use artificial illumination and air conditioning; instead, it uses daylight and passive heating and cooling techniques.

The abandoned chimneys, which are approximately 30 m high, were built in 1909 as part of a copper-refining plant. In order to reuse one of these as a solar chimney, a glasshouse was constructed at its foot. The glasshouses houses a gallery of art works; however, visitors could not enter these glasshouses due to safety concerns arising from the possibility of the old chimney collapsing. Even if visitors could stand inside the glasshouse, they would feel too hot and uncomfortable, especially during the summer. The exhibition hall, where the air temperature is controlled, is located toward the front of the glasshouse. Cool air flows in through an earthen tunnel, while hot air can flow in through the other glasshouse located at the eastern façade during the winter (Figs. 8, 9, and 10) [5].

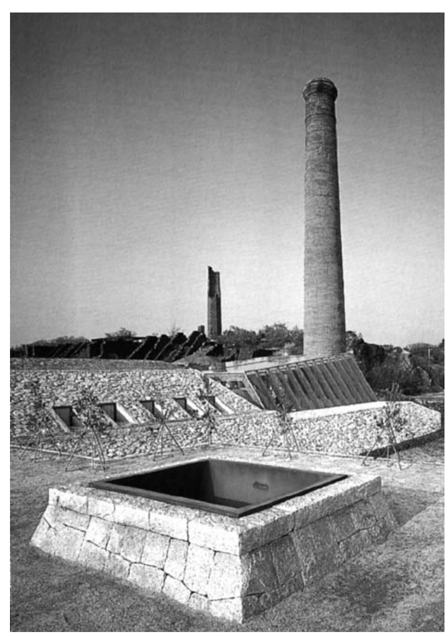

Figure 8: External View of the Inujima Art Museum. [5]

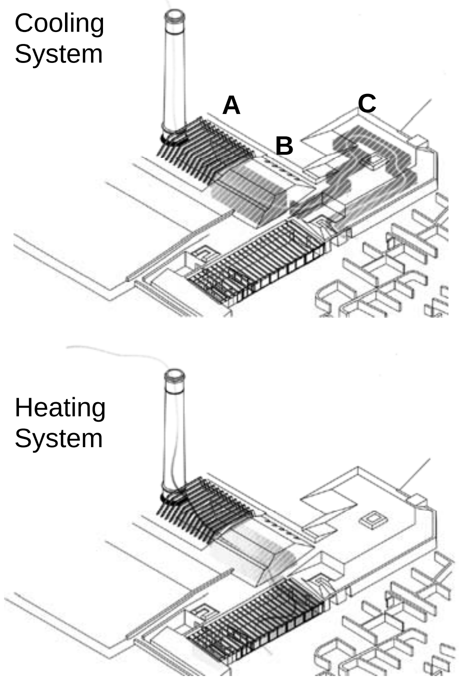

Figure 9: Passive Design System of the Inujima Art Museum. A. Glasshouse, B. Exhibition Hall, C. Earthen Tunnel. [5]

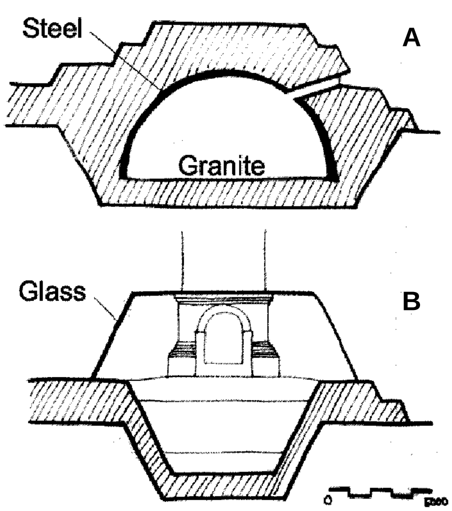

Figure 10: Section of (A) Exhibition Hall and (B) Glasshouse. (Redrawn from [5])

The calculation results and weather conditions on a clear-sky summer day are shown in Figures 11, 12, and 13. In Figure 11, the upper and lower images show the vertical and horizontal sections, respectively. The wind velocity shown in Figure 12 is that at a height of 1.2 m. At the top of the chimney, daytime wind velocities are around 7 m/s. The external air temperature exceeds 29°C; however, the internal air temperature remains under 29°C, and SET* (0.3clo, 1met) of around 26°C produces a “slightly warm” sensation.

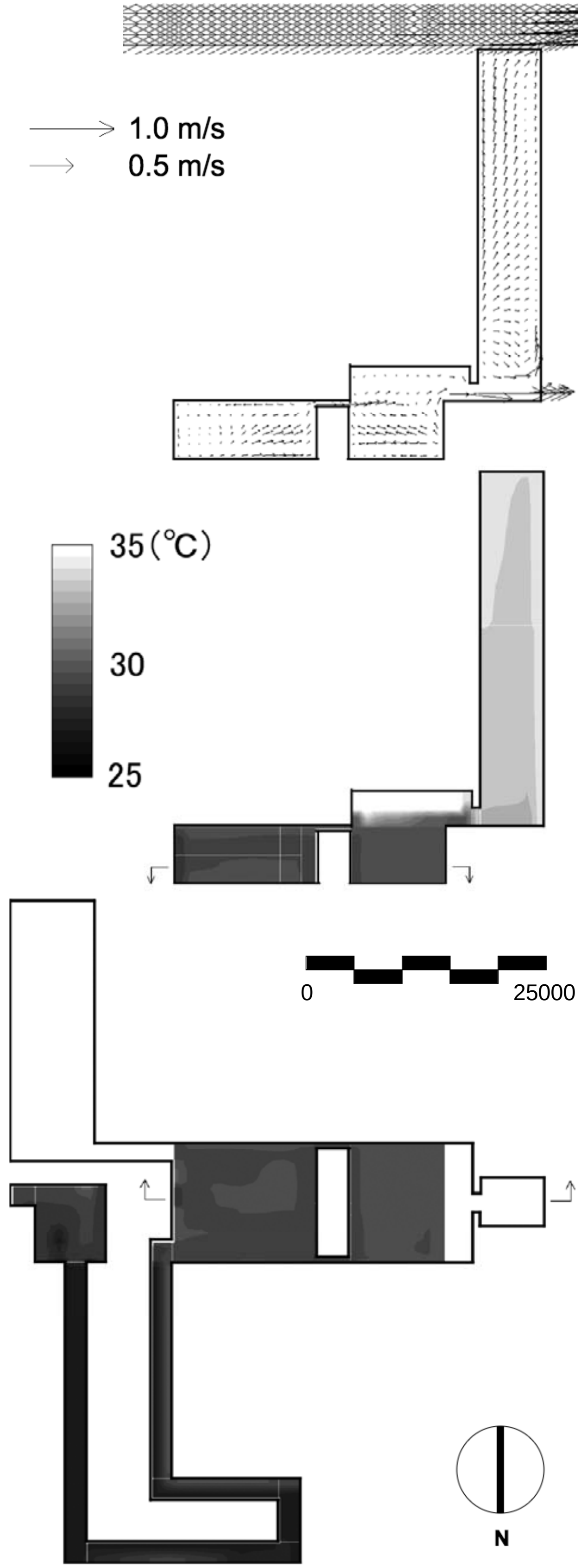

Figure 11: Wind Velocity and Air Temperature Distribution. (Calculation Result, 1300, August 10, Standardized Year)

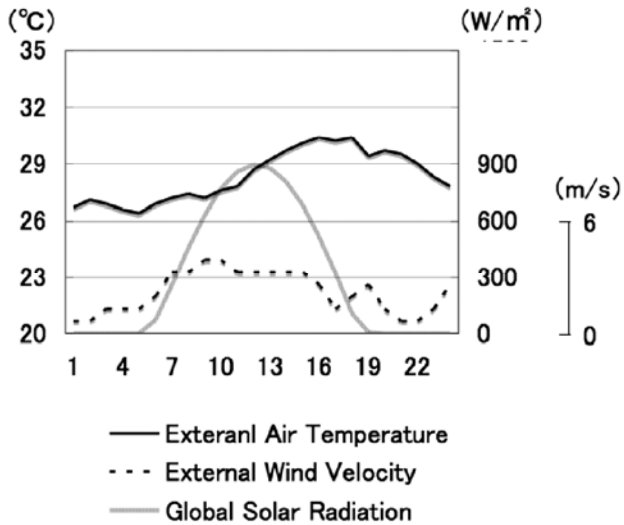

Figure 12: Weather Condition.
(August 10, Standardized Year)

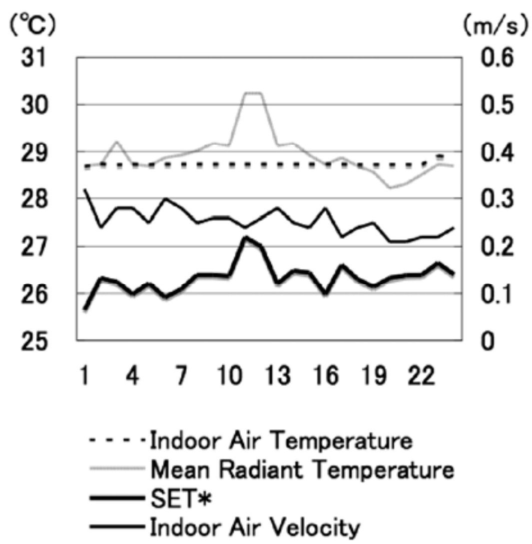

Figure 13: Indoor Climate Calculation Result.
(August 10, Standardized Year)

In winter, the suction pressure generated by the chimney guides warm air from the eastern glasshouse to the exhibition hall (Figs. 14, 15). Although the external air temperature does not exceed 9°C until the afternoon, the temperature of the air inside the exhibition hall remains around 9°C for almost the entire day (Figs. 16, 17). Eventually, SET* (1.5clo and 1met) becomes approximately 16°C, which is equivalent to an "unacceptably cold" sensation. However, if the metabolic rate scores two Mets, SET* reaches 24°C, which corresponds to a "comfortable" sensation. In the chimney, the air close to the internal surface ascends; on the other hand, the air in the center of the chimney void descends.

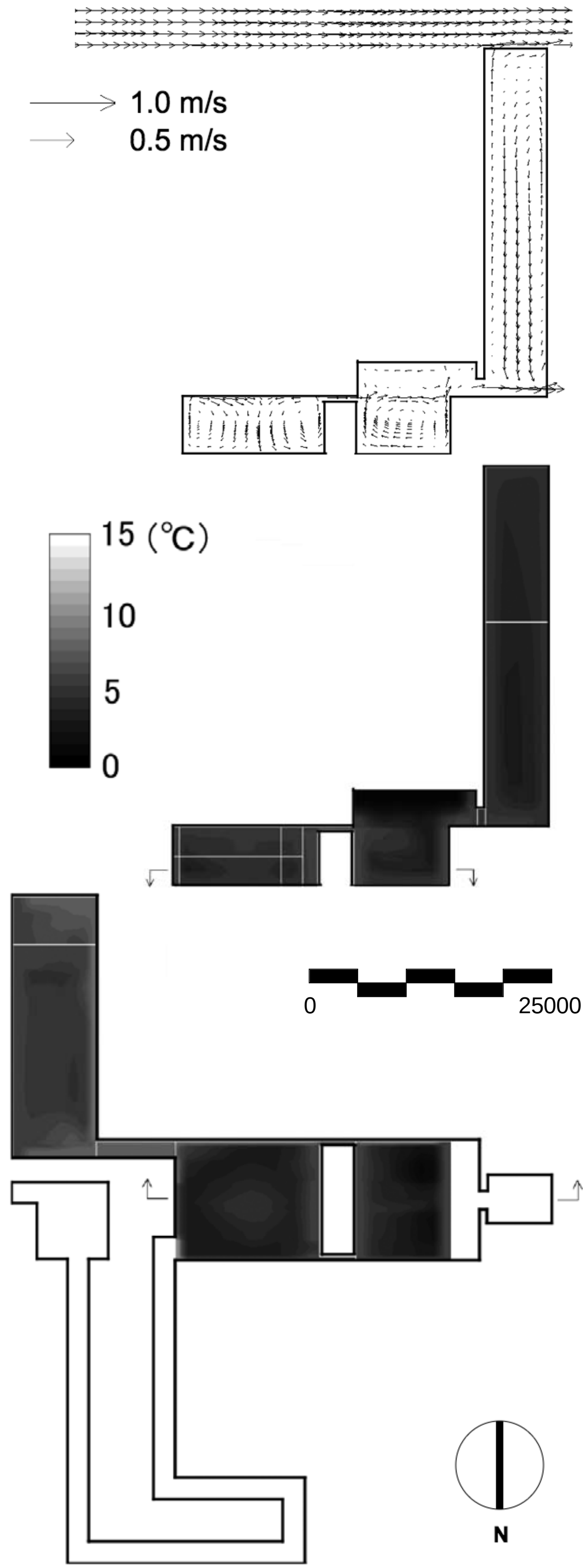

Figure 14: Wind Velocity and Air Temperature Distribution.
(Calculation Result, 1300, February 26, Standardized Year)

Figure 15: Inlet Vent Louver on Eastern Glasshouse.

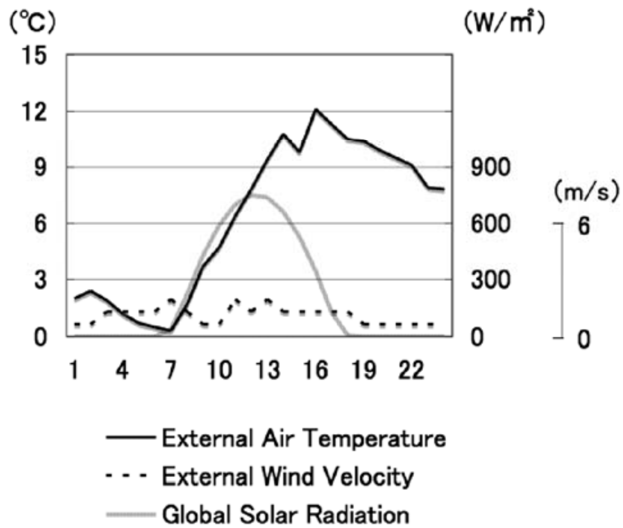

Figure 16: Weather Condition.
(February 26, Standardized Year)

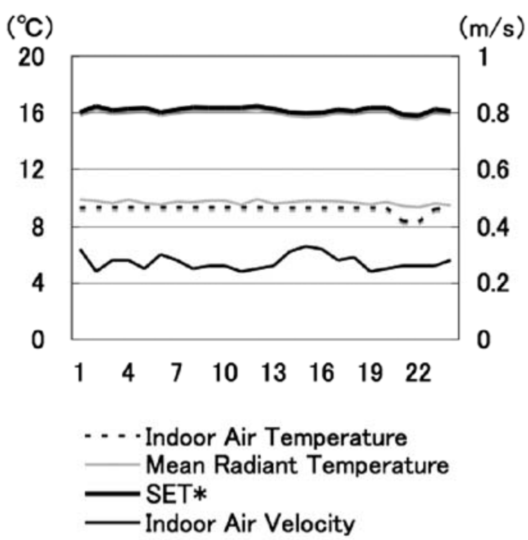

Figure 17: Indoor Climate Calculation Result.
(February 26, Standardized Year)

CONCLUSION

A building model for a public space using an abandoned chimney as a solar chimney is proposed. According to the numerical simulation result of a summer day, the surface temperature of the inside wall increases, creating a potentially uncomfortable indoor climate. It is desirable to modify the building model using a sunshade to screen occupied areas and to use wall insulation. For example, the Inujima Art Museum uses a longer earthen tunnel, taller chimney, and thicker earthen wall. Eventually, this will lead to a comfortable or at least slightly comfortable climate in the exhibition hall over the course of the year. Actually, we found that the solar chimney in the museum functioned more effectively than indicated by the calculation results.

With regard to the chimneys used as solar chimney, taller chimneys may be preferable. The height of the chimney of an abandoned public bathhouse is around 15 m. The height of that in Inujima (a copper-refining plant) is 30 m. The chimney in a certain abandoned garbage incineration plant has a height of approximately 150 m. This height is similar to that of a solar chimney power plant built in Spain [6], and it might be ideal for generating breeze in residential areas.

In the future, a concrete proposal for the use of the abandoned chimneys of closed public bathhouses in dense housing zones should be considered. A chimney also serves as a local landmark. It is often said that the landscape memorized by an individual includes local landmarks such as chimneys, towers, tall buildings, and so on. In addition to creating a cooling area, preserving a chimney as an old landmark could contribute toward helping residents maintain their identities and attachments to their town.

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