From rainy season to summer in Japan, the climate is humid. Especially in these seasons, it is difficult to maintain suitable conditions of temperature and relative humidity in exhibition and storage rooms in museums. Such climate conditions and problems are common to many countries in East Asia. Analysis using computer simulation can be a powerful tool because it is cheap and allows the simulation of a range of conditions without having to make changes to buildings and environments surrounding cultural objects. In this study, a storage building in which there is no air-conditioning unit was chosen as a target. The modelling of temperature and relative humidity in storage spaces was conducted using the Thermal and Airflow Network Model Simulation Program for buildings (NETS). The effect of seismic retro-fitting on the variation of temperature was predicted using NETS and the results were evaluated by comparing with the measured values. As a result, the heat transfer was successfully calculated and the modelled temperature represents the measured values reasonably well. Computing relative humidity by taking into account the effect of porous hygroscopic materials is challenging. In order to overcome this problem, the $\kappa-\nu$ model was adopted. We have some improvements but the study is still ongoing.

**Keywords:** Computer simulation, NETS, Heat transfer, Air transfer, Porous hygroscopic material

**Introduction**

Kirby Atkinson has reviewed the historical background of the widely accepted values of temperature and relative humidity for the conservation of cultural property (Atkinson, Kirby, 2014), and the conditions in museums are often maintained according to these suggested values. For the last several decades, the technological development of air-conditioning units has been remarkable, and it allows us the precise control of temperature and humidity in museums. Recently, from the viewpoint of energy-saving, active debates have been held to reconsider the standard values of temperature and relative humidity for cultural property (Bickersteth, 2014; Staniforth, 2014). It has also been suggested that when collections on loan are transported between regions of different climate, the standard values of temperature and relative humidity should be determined by taking local climate conditions into consideration.

In Japan, although there are currently no common guidelines for temperature and relative humidity, there are some recommended values. Table 1 shows the recommended values of temperature and relative humidity issued by the National Research Institute for Cultural Properties, Tokyo (National Research Institute for Cultural Properties, Tokyo, 2011). For the conservation of cultural property, the recommended temperature is around 20° (de Guichen, 1988). However, seasonal variations are allowed to some extent. Although a suitable value for relative humidity depends on the type of material as shown in Table 1, it ranges from 50 to 60% in general. It must be emphasized that these values were originally suggested for museums in temperate climates such as Western Europe, and may not be appropriate for the climate of Japan. In addition, as a matter of course, care has to be taken that cultural property is not exposed to rapid fluctuations in temperature and relative humidity in order to prevent deterioration such as expansion, contraction, distortion, cracking, and peeling.

However, it is not usually easy to maintain these ideal conditions. Fig. 1 shows a climograph for Tokyo. The recommended conditions for cultural property mentioned above are also depicted as a...
circle. In Tokyo, both temperature and relative humidity are low in winter. However, from the rainy season to summer, the climate is humid and this increases the risk of mould growth. This climate also makes it difficult to maintain suitable conditions of temperature and relative humidity in exhibition rooms and stores of museums. Such climate conditions and problems are common to many countries in East Asia. Therefore, it is important to measure the temperature and relative humidity to understand the current conditions surrounding cultural property. If the environmental conditions are found to be outside suitable ranges because of ageing facilities, equipment and so on, it is necessary to find a means to improve the building environment.

However, for technical and economic reasons, it is often difficult to conduct experiments to investigate environmental conditions, including temperature and relative humidity, in situ or during renovations. In such cases, analysis using computer simulation can be a powerful tool because it is cheap and allows the simulation of a range of conditions without having an impact on cultural property and the environment surrounding it and without making changes in buildings.

In this study, by using a computer simulation program, the environmental conditions including temperature and relative humidity in storage spaces used for cultural property were calculated and this analysis method was evaluated by comparing the calculated results with measurements.

**Analysis using computer simulation**

There are various kinds of simulation methods applied for investigating environmental conditions for cultural property. Computed Fluid Dynamics (CFD) is one of the most popular methods.

One of the studies using CFD is the modelling of the microclimate in a showcase, approximately 6.3 m in height for displaying paintings and folding screens, in Mie Prefectural Museum which opened in 2014 (Mabuchi et al., 2015). This analysis was conducted using the software scSTREAM produced by Software Cradle Co., Ltd. (http://www.cradle-cfd.com). In order to reduce the gradient of temperature and humidity distributions due to heat generation from LED lighting equipment, the specification of this showcase enables air circulation inside it. Three-dimensional temperature and humidity distributions and airflow were computed using scSTREAM and it was predicted before constructing the showcase that the air circulation system would work effectively. After construction of the showcase, it was verified that the prediction obtained from this analysis reproduced the measured results reasonably well.

One of the advantages of CFD is that it can compute airflow precisely and provide three-dimensional distributions of temperature and humidity in spaces. On the other hand, CFD generally requires much processing time. Therefore, it is usually difficult to predict long-term, e.g. seasonal, variations. However, the prediction of long-term variations is important for the research in this paper, so we adopted an alternative method of computer simulation.

**Thermal and Airflow Network Model Simulation Program (NETS)**

Research (Ishizaki et al., 2005; Ishizaki et al., 2006) has demonstrated several kinds of computer simulation programs including CFD for the modelling of temperature, relative humidity and airflow with the specific aim of studying the microenvironment in exhibition rooms, showcases and museum stores. Among the computer simulation programs presented in these papers, Thermal and Airflow Network Model Simulation Program (NETS) produced by a Japanese company, Shimizu Corporation (http://www.nets-club.com/index.htm) is one of the candidate tools for simulating indoor environments (Okuyama, 2006) in order to analyse and evaluate

**Table 1 Recommended values of temperature and relative humidity given to Japanese curators by the National Research Institute for Cultural Properties**

| Temperature | Relative Humidity | Notes |
|-------------|-------------------|-------|
| Around 20°C | 55–65% paper, wood, textiles, lacquer craft work | |
| 50–65% leather, stuffed animals | |
| 50–55% oil painting | |
| 45–55% fossil | |
| < 45% metal, stone, pottery | |

**Figure 1 A climograph for Tokyo.**
long-term variations of environmental conditions like temperature and relative humidity in storage spaces for cultural property.

In the first phase of analysis using NETS, models are constructed by inserting components on plans of buildings on a PC and providing necessary parameters for these components, for instance, building materials, conductance of heat and moisture, and meteorological conditions.

Here we demonstrate how modelling is conducted in NETS by using a simple example (Inuzuka et al., 2015). There are two kinds of network models to be constructed: the thermal network model to calculate heat transfer and the airflow network model to calculate moisture transfer. Both models are combined with each other when the calculations are conducted (Okuyama, 2006). Fig. 2 shows the thermal network model constructed on the floor plan of a shelter for a tumulus in Japan. The shelter has only one room and it is covered with concrete walls and a ceiling.

The problem in this shelter was dew condensation on the floor plan, was conducted as a dedicated component, which is indicated as a dot at the centre of this floor plan, was conducted as follows. The components representing building materials (a ceiling and walls made of concrete and a door made of steel in this example) are placed on the floor plan. These components for building materials contain information about their volumes and compositions. In addition, physical properties such as thermal conductivity, specific heat, and specific gravity are specified for each component of the building materials. The components representing conductance of heat and moisture connect the room and building materials in Fig. 2. The meteorological conditions, including outside temperature, relative humidity, wind velocity, wind speed, intensity of solar radiation and amount of cloud, are also provided as a dedicated component, which is indicated as a dot placed outside the shelter.

As demonstrated above, the method of construction using NETS is intuitive and easy to understand for users, even those who are not well acquainted with building physics. Moreover, NETS does not require much processing time to predict long-term variations like seasonal variations of temperature and relative humidity surrounding cultural property, which is important information for conservators and curators in museums. NETS is also able to determine the buffering capacity of heat and moisture of a building. For example, the previous study (Ishizaki, et al., 2006) made some suggestions to improve environmental conditions around a reconstructed cabin of the Hosokawa family’s ship, displayed in Kumamoto Castle, by using hygroscopic building materials.

On the other hand, NETS predicts only the average values of temperature and relative humidity for each space, because it computes values for only one representative point, as demonstrated in Fig. 2. Therefore, one of the drawbacks of NETS is that it is not easy to provide three-dimensional distributions of temperature and relative humidity in spaces.

**Modelling of a storage building**

The subject of this study is a storage building of Sekisui Museum (http://www.sekisui-museum.or.jp/) in Mie prefecture, Japan, called *Chitose-Bunko*. Mie prefecture is located on the Pacific coast and an area receiving high rainfall. *Chitose-Bunko* was built in 1930 and is a four-storied reinforced concrete building. It is difficult to control temperature and relative humidity in the building because there are no air-conditioning units except for one on the fourth floor. Various cultural properties such as oil paintings, artefacts, folding screens, classical books and ancient manuscripts are stored in the rooms on the second, third and fourth floors of the building. Mie prefecture suffers from earthquakes frequently. In 2009, the building underwent seismic retro-fitting by the addition of concrete to the walls. The concrete was added from inside of the building because it is a registered tangible cultural property and the exterior was not allowed to be modified.

In the same manner as demonstrated in Fig. 2, the thermal network model and the airflow network model were constructed on the floor plans of *Chitose-Bunko* (These models are omitted because they are too complex to be shown here.).

The structure of the wall was investigated by boring. As shown in Fig. 3, the wall turned out to be composed of layers of 20 cm of concrete, 20 cm of air and 4 cm of mortar from exterior to interior. Because of the heat insulating effect of the air layer, the fluctuation of temperature is moderated inside the building. The physical properties of these building materials are as follows. The thermal conductivity, specific heat, and specific gravity are 1.5 W/mK, 0.80 kJ/kgK and 2400 kg/m$^3$ for concrete, 0.022 W/mK, 1.0 kJ/kgK and 1.3 kg/m$^3$ for air, 1.5 W/mK, 0.80 kJ/kgK and 2500 kg/m$^3$ for mortar, respectively (Okuyama, 2006).

In 2009, seismic retro-fitting was carried out, only on the first and fourth floors, by adding 15 cm of concrete in the air space shown in Fig. 3. The effect of this construction on the temperature and relative humidity inside the storage building was investigated by using NETS as shown in the next section.
**Results**

**Measurement of temperature and relative humidity**

It was important to measure temperature and relative humidity in Chitose-Bunko before and after seismic retro-fitting, in order to evaluate the results obtained using NETS. For this purpose, HOBO H8 pro data loggers, produced by Onset Computer Corporation (http://www.onsetcomp.com/), were located in all the storage rooms in the building. In advance of the measurement, the values of relative humidity recorded in these data loggers were calibrated at 25° by using three kinds of saturated salt solution: KCl (84%), NaCl (75%) and NaBr (58%). Measurements using these data loggers were carried out from September 2006 to July 2013, at a logging interval of 10 minutes.

**Temperature**

Temperatures obtained using NETS were compared with temperatures measured in 2006 and 2007. This period was selected to compare the calculated and measured values before the seismic retro-fitting.

Fig. 4 compares the calculated results obtained using NETS and the measured temperature in the storage rooms on the second, third and fourth floors where cultural property is stored. In this figure, the measured and calculated values are represented by black and red lines, respectively. For these storage rooms on different floors, the modelled temperature represents the measured values reasonably well. Therefore, it can be concluded that the thermal network model was well constructed and the calculations of heat transfer were successfully carried out by NETS. This means that the theoretical calculations of temperature using NETS are good predictors of temperatures in the building.

In order to further examine the results for the fourth floor, Fig. 4 (C) is magnified and is shown in Fig. 5. Here, the measured values are represented by the black line and calculated values before the seismic retro-fitting are represented by the red line. However, what we would like to know is how the temperature would be affected by the addition of concrete. It is possible to conduct this kind of prediction, and this is the reason why NETS was chosen in this research. The blue line in Fig. 5 shows the result of changing the thickness of the concrete layer but keeping the meteorological conditions the same. As a result of the calculation, NETS predicted that the fluctuation
of temperature would be moderated because the thermal insulation of the walls was increased by the addition of concrete.

**Measurements after seismic retro-fitting**

Fig. 6 (A) shows the measured temperature in 2006 and 2007, before the seismic retro-fitting. Fig. 6 (C) shows the measured temperature in 2012 and 2013, after the seismic retro-fitting. The fluctuation of temperature after the seismic retro-fitting was small compared with that before the seismic retro-fitting. This phenomenon is consistent with the prediction obtained by using NETS as shown in Fig. 5.

Fig. 6 (B) shows the measured relative humidity before seismic retro-fitting and Fig. 6 (D) shows that after seismic retro-fitting. Because the fluctuation of temperature was moderated, the fluctuation of relative humidity was also moderated after the seismic retro-fitting. As a result of the construction, the relative humidity was stabilized and the environment turned out to be better for the conservation of cultural property stored there.

**Relative humidity**

From the viewpoint of the conservation of cultural property, relative humidity is more interesting and more important than temperature, because the materials from which cultural property is composed in general are more sensitive to the variation of relative humidity than temperature, resulting in deterioration such as expansion, contraction, distortion, cracking, and peeling. However, calculation of humidity is more complex than temperature, and it is a
challenging task if the adsorption and desorption of moisture from the porous hygroscopic materials are taken into consideration, in addition to the moisture transfer in air.

In NETS, the amount of moisture in the air (absolute humidity) is mainly obtained by calculating the air transfer between adjacent zones. The amount of air transfer is governed by, for example, the ventilation rate of the room and the area of openings in the walls between adjacent zones. These parameters are fed into the corresponding components when constructing the airflow network models in NETS. Relative humidity is computed from the values of temperature obtained from the thermal network model and the values of absolute humidity obtained from the airflow network model as described above. If there is little porous material in the zone under consideration, there is less difficulty in computing relative

![Figure 6](image1.png)

Figure 6  Figures (A) and (B) show the temperature and relative humidity before seismic retro-fitting and figures (C) and (D) show those after seismic retro-fitting.

![Figure 7](image2.png)

Figure 7  Comparison of measured relative humidity on the third floor with the calculated results with and without the κ-ν model.
humidity. In this case, the modelled values of relative humidity represent the measured values reasonably well.

Fig. 7 compares the calculated and measured values of relative humidity in the storage room on the third floor. In this figure, the black line shows the measured values and the red line shows the calculated results without taking into account the influence of adsorption and desorption of moisture. As seen in Fig. 7, the fluctuation of relative humidity obtained by NETS becomes remarkably large compared with measurements. The reason for this problem is the presence of porous organic material, for example, amounts of cultural property and walls and shelves made of wood. In this situation, the influence of adsorption and desorption of moisture from the cultural property cannot be ignored (Thomson, 1964) when calculating and desorption of moisture from the surrounding air. Therefore, it is necessary to take into account the influence of adsorption and desorption of moisture from porous organic materials, in order to conduct more realistic predictions.

In general, the adsorption and desorption of moisture from the porous hygroscopic materials, for example, wood, soil, paper, humidity buffers and so on, affect the relative humidity of the air surrounding cultural property. If the relative humidity of the surrounding air becomes high, moisture is adsorbed by the porous hygroscopic materials, decreasing the relative humidity. On the other hand, if the relative humidity of the surrounding air becomes low, the moisture is desorbed from the porous hygroscopic materials, increasing the relative humidity. In these ways, the rapid change of relative humidity is moderated due to the presence of the porous hygroscopic materials (Thomson, 1964). The equilibrium water content, which is a function of temperature and relative humidity, determines the behaviour of adsorption and desorption of moisture. The behaviour of the equilibrium water content depends on the type of material. The equilibrium water content is experimentally obtained for each material.

NETS is able to compute the amount of adsorption and desorption of moisture using the temperature and humidity dependence of the equilibrium water content of materials, according to the so-called $\kappa$-$\nu$ model (Okuyama, 2006). In order to calculate using the $\kappa$-$\nu$ model, the total volume of porous hygroscopic materials and the following two parameters need to be fed into NETS:

$$\kappa = \frac{\partial w}{\partial X} \text{ (kg/m}^3\text{/(kg/kg)) and}$$

$$\nu = -\frac{\partial w}{\partial \theta} \text{ (kg/m}^3\text{K)},$$

where $w$ (kg/m$^3$) represents equilibrium water content and $X$ (kg/kg) and $\theta$ (K) are absolute humidity and temperature, respectively. The parameters $\kappa$ and $\nu$ are represented as the partial derivatives of absolute humidity and temperature, respectively. In this study, the parameters $\kappa$ and $\nu$ are assumed to be constant and the following values were given for the computation: $\kappa = 15\,009$ (kg/m$^3$/(kg/kg)) and $\nu = 6.73$ (kg/m$^3$K). These values were experimentally obtained from the equilibrium water content for Paulownia tomentosa wood (Okuyama, 2006).

As a result of adopting the $\kappa$-$\nu$ model, the calculated relative humidity was modified to the blue line in Fig. 7. The fluctuation was significantly moderated and some improvement was obtained. However, some discrepancies are still observed between the measured values and the calculated results with the $\kappa$-$\nu$ model.

There is still room for improvements. In this analysis, the single constant values of $\kappa$ and $\nu$ were assumed and applied to NETS. However, if the equilibrium water contents for all the hygroscopic materials present in the storage rooms were experimentally obtained, more realistic values of $\kappa$ and $\nu$ could be supplied to NETS and the calculated results would be expected to be improved.

**Summary**

From rainy season to summer in Japan, the climate is humid. Especially in these seasons, it is difficult to maintain suitable conditions of temperature and relative humidity in exhibition and storage rooms in museums. Such climate conditions and problems are common to many countries in East Asia.

Analysis using computer simulation can be a powerful tool because it is cheap and allows the simulation of a range of conditions without having to make changes to buildings and environments surrounding cultural objects.

In this study, a storage building in which there is no air-conditioning unit was chosen as a target. The modelling of temperature and relative humidity in storage spaces was conducted using the Thermal and Airflow Network Model Simulation Program for buildings (NETS).

The effect of the seismic retro-fitting on the variation of temperature was predicted by using NETS and the results were evaluated by comparing with the measured values. As a result, the heat transfer was successfully calculated and the modelled temperature represents the measured values reasonably well.

Computing relative humidity by taking into account the effect of porous hygroscopic materials is challenging. In order to overcome this problem, the $\kappa$-$\nu$ model was adopted. We have some improvements but the study is still ongoing.
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