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Evaluation of Kyogen Costume Storage Environment and Calculation of Proper Temperature Setting for Energy Conservation Effect Using Fungal Index

Edison Suzuki
The American School In Japan, Japan
edomitsu.suzuki@gmail.com

Abstract

The American School in Japan has had a Kyogen club since 1978. Kyogen is a Japanese deadpan comedy with a 650-year history, from the Muromachi period. When performing Kyogen, student actors wear special Kyogen costumes called "sho-zoku." The school stores these costumes in boxes made of paulownia wood in the storage room. However, no studies have been done before on the environmental conditions inside the paulownia box and the storage room to determine if they are suitable for maintaining expensive "sho-zoku." Therefore, in this study, data loggers that can measure temperature, humidity and fungal index were installed on the shelf and inside a paulownia box for 10 months to measure these environmental conditions. As the result of analysis of measured data and calculation, two main results were obtained. The first result was that when the "sho-zoku" were stored in a paulownia box in the storage room, the fungal index value was kept low without undergoing sudden changes in the ambient relative humidity. The second result was that in the summer, if the air conditioning temperature in the storage room is set to 30.4°C, the relative humidity will decrease to 67.5% or less. As a result, the fungal index value will stay below the threshold value of 1, meaning that there would likely be very little mold in the environment. Also, the power consumption of the air conditioner will decrease by 54%.

Keywords: fungal index, paulownia box, relative humidity, psychometrics, energy conservation effect

Introduction

The American School in Japan (ASIJ) has had a Kyogen club since 1978 (The American School in Japan, 2018). Kyogen is a Japanese deadpan comedy with a 650-year history, from the Muromachi period (Salz, 2016). Kyogen masters from the renowned Yamamoto family have been coming to the ASIJ school campus for over 40 years to teach the students to perform. When performing Kyogen, actors wear special traditional costumes called "sho-zoku (Figure 1)." The school stores these costumes in boxes made of paulownia wood, which is said to have moisture regulating effects, and have been used to store books and kimonos for centuries in Japan (Aoki, 1999, Seya & Tazawa, 2016, Angelov, 2019). However, there has been no example of verifying whether the environmental conditions inside the storage room and paulownia boxes are really suitable for maintaining expensive "sho-zoku." Therefore, in this study, devices that can measure temperature, humidity and fungal index were installed on the shelf and inside a paulownia box for 10 months to measure these environmental conditions. Then, the obtained data was used to consider the appropriateness of the current "sho-zoku" storage method. In addition, the obtained actual measurement data was used to derive results of calculating the appropriate temperature and humidity conditions for suppressing mold growth using a psychrometric chart (ASHRAE, 1992, Callahan, 2019) and results of trial calculation of the amount of power consumption reduction.

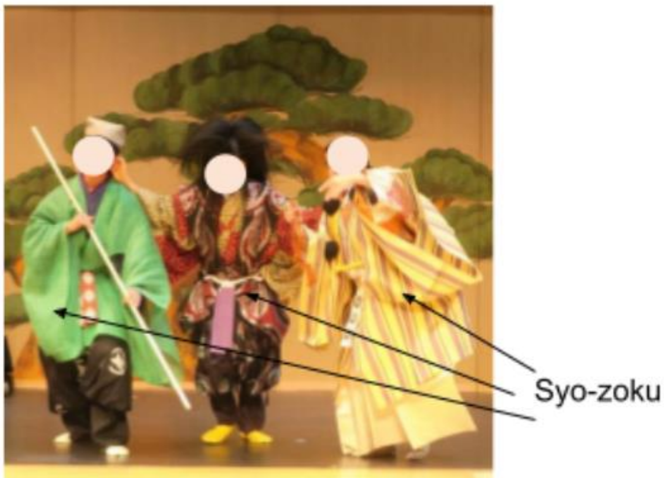

FIGURE 1: A scene from a Kyogen performance (February, 2019, at the American School in Japan)

Materials and Methods

Storage room where measurements were taken

This study was conducted in a storage room in the school that stores costumes for musical drama performances and Kyogen "sho-zoku."

Measurement period

The measurement period was from June 11, 2020 to April 24, 2021. However, from February 4 to 13, 2021, the paulownia box containing one temperature/humidity logger was taken out of the storage room and placed in the backstage area of the school theater, so the temperature and humidity data during that period measured the backstage environment. This data was excluded from statistical data analysis.

Measurement of temperature, humidity and fungal index

The wireless fungal logger LR8520 (Figure 2, HIOKI E.E. CORPORATION, Nagano, Japan) was used to measure the temperature, relative humidity, and fungal index of the environment in the storage room. One logger was installed at the center of the shelf in the storage room. A second logger was installed in a paulownia box containing the "sho-zoku" (Figure 3). The logger measurement interval was set to 10 minutes. From June 11 to December 13, 2020, a third logger was installed in a cardboard box without a lid containing props and also stored on the shelf. The fungal index is an indicator of mold growth in an environment developed by Dr. Keiko Abe. The fungal index was measured and calculated by the fungal sensor where standard fungal spores are enclosed in the paper cell (Abe, 2010, 2012a, 2012b, 2016, Abe & Murata, 2014).

FIGURE 2: A logger placed on a shelf

FIGURE 3: A logger placed inside a paulownia box

The diagram of the relationships among the fungal index, temperature and relative humidity indicates that the fungal index determines spore germination more depending on the relative humidity than on the temperature (Abe, 2012a, 2012b, Kurashima, 2016). The measured fungal index values for various rooms in buildings in Japan have been published previously (Abe, 2012a, 2012b, 2016, Abe & Murata, 2014). A fungal index of around 50 is equivalent to that inside bathrooms in residences in Japan, and a fungal index of 100 or higher is equivalent to that inside air conditioners in residences in Japan (Abe, 2012a, 2012b, 2016, Abe & Murata, 2014, Kurashima, 2016).

Paulownia box

The paulownia box in which the “sho-zoku” were stored are of the following dimensions: length 95 cm, width 42 cm, height 19 cm (Figure 4).

FIGURE 4: A paulownia box storing “sho-zoku”

Statistical processing

The data were found to be nonparametric, and were statistically compared between two groups by the Mann-Whitney U test (Schober et al., 2020) using the IBM Statistical Package for Social Sciences (SPSS) version 27.0 (IBM Corp., Armonk, NY).

Calculation using actual measurement data to find the temperature at which the fungal index does not exceed the threshold of detecting mold

A free Excel™ software add-in “Psychrocals” released by the University of Vermont (University of Vermont, 2021), which is based on the calculation method according to ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) handbook, was downloaded and used in Excel™. Using this add-in, a calculation was performed to find the temperature at which the fungal index remains under the threshold even in the environment where the relative humidity in the measured data is the highest.

Results

Measurements of temperature, humidity and fungal index

The temperature data measured on the shelf and inside the paulownia box for the entire measurement period is shown in Figure 5. The relative humidity data measured on the shelf and inside the paulownia box is shown in Figure 7. The fungal index data measured on the shelf and inside the paulownia box is shown in Figure 9.
The temperature, relative humidity, and fungal index data measured on the shelf and inside the paulownia box for every month during the measurement period are shown in Figures 6, 8 and 10, respectively.

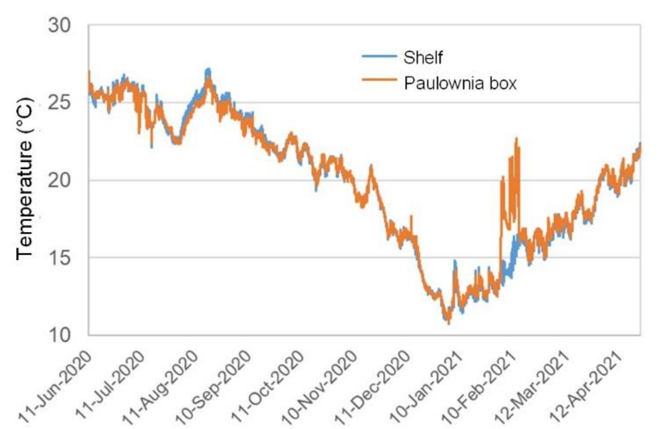

FIGURE 5: Temperature data of the measurement period

The maximum temperature was 27.2 ℃ on the shelf and 27.0 ℃ inside the paulownia box in August 2020. Throughout the measurement period other than February 4-13, 2021, no major statistical differences could be observed between measurements on the shelf and inside the paulownia box (Figure 5).

Every month during the measurement period, there was no significant difference in temperature between measurements on the shelf and inside the paulownia box in June, July, November, and December 2020. In August and September 2020, the temperature on the shelf was significantly higher than that inside the paulownia box (Figure 6, $p < 0.01$), and in October 2020, January, February, March and April 2021, the temperature inside the paulownia box was significantly higher than on the shelf (Figure 6, $p < 0.01$).

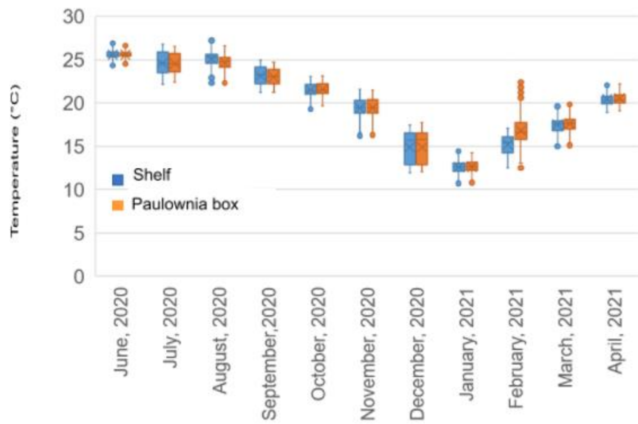

FIGURE 6: Temperature data by month

Over the entire measurement period, the maximum relative humidity on the shelf was 92.0% on July 28, 2020, and the maximum relative humidity inside the paulownia box was 85.0% on August 18, 2020.

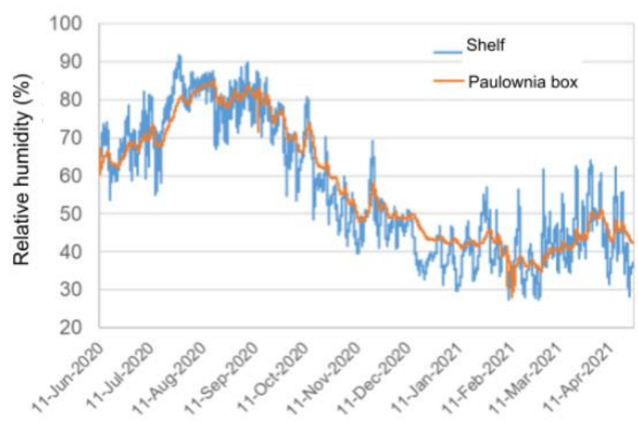

FIGURE 7: Humidity data of the measurement period

Throughout the measurement period other than February 4-13, 2021, the relative humidity (RH) inside the paulownia box (median 52.3% RH) was slightly higher than that on the shelf (median 52.1% RH) (Figure 7, $p < 0.01$).

Every month during the measurement period, RH was significantly higher on the shelf that in the paulownia box in June and July 2020 (Figure 8, $p<0.01$), similar in both locations in August 2020, and significantly higher inside the paulownia box from September 2020 to February 2021, and April 2021 (Figure 8, $p < 0.01$).

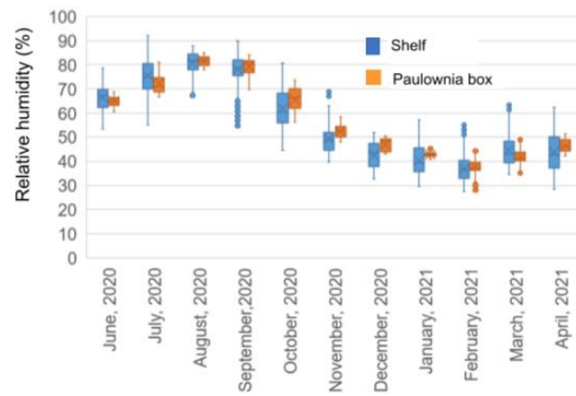

FIGURE 8: Humidity data by month

Throughout the entire measurement period, the maximum fungal index value on the shelf than in the paulownia box was 131 on July 28, 2020 and 77 inside the paulownia box on August 18, 2020. Throughout the entire measurement period, the fungal index inside the paulownia box was significantly lower than that on the shelf (Figure 9, $p < 0.01$).

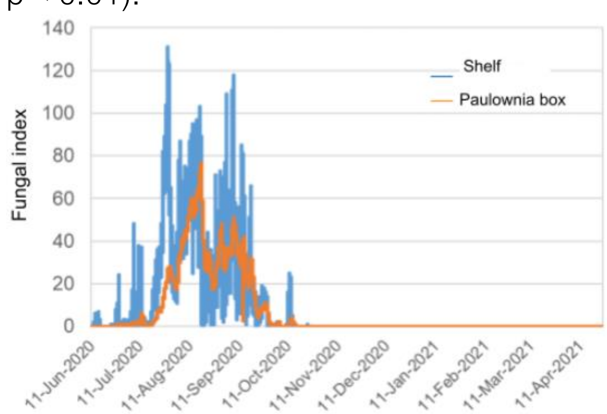

FIGURE 9: Fungal index data of the measurement period

Every month during the measurement period, the fungal index value was significantly higher on the shelf than in the paulownia box in June, July and October 2020 (Figure 10, $p < 0.01$), was similar in both locations in August 2020, and in September 2020 the value was significantly higher inside the paulownia box (Figure 10, $p < 0.01$). The fungal index value remained below the mold detection threshold from November 2020 to April 2021. The measurements indicated that the fungal index was not detected when RH was below 67.5%, and the fungal index was 1 when RH was 67.6%.

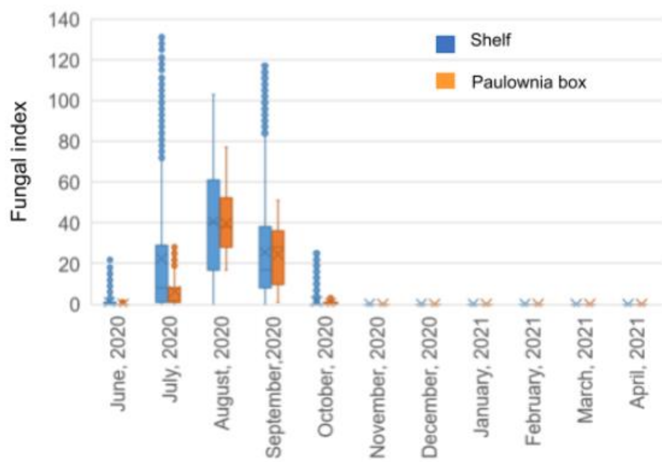

FIGURE 10: Fungal index data by month

A histogram of the temperature data of June, July, August, and September 2020 on the shelf is shown in Figure 11. It was found that the temperature with the most measurement points was 25℃, and for measurement points that exceeded 26℃, the number of measurement points decreased to about 2/5 that of 25℃ (Figure 11). From this, it can be concluded that the air conditioning temperature setting in the storage room during this period was mostly likely 25℃.

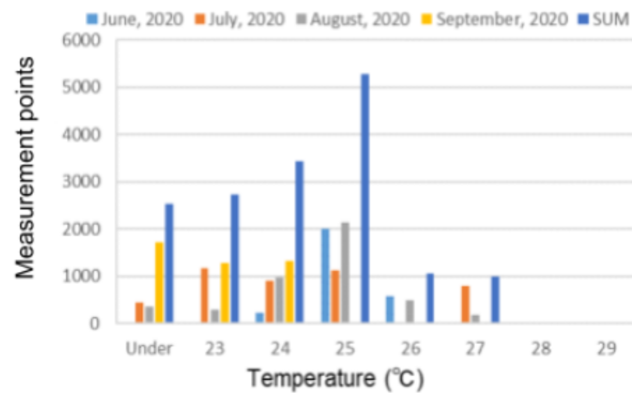

FIGURE 11: Histogram of temperature on the shelf (June, July, August, September 2020)

Calculation of the temperature at which the fungal index is sure not to exceed the threshold of mold detection, using temperature and humidity measurement data and psychrometric charts

From data of actual measurements of temperature, humidity and fungal index in this study, it was determined that the fungal index did not exceed the threshold of mold detection when RH was 67.5% or lower. Psychrometric charts (ASHRAE, 1992, Callahan, 2019) indicate that for a closed space in which the total moisture in the room remains constant (such as the room for storing the "sho-zoku"), an increase in temperature will result in a decrease in RH. For the dates and times of actual measurements showing RH values that were too high, it is worth noting by how many degrees the temperature should have been increased to bring RH down to 67.5%. Psychrometric calculations were performed to derive the temperature at which the fungal index is sure not to exceed the threshold of mold detection, for all cases of measurements of the designated period of time.

Calculations were performed to obtain a psychrometric chart for RH values 92.0% and 67.5% by calculation from the measured data from June 1 to September 30, 2020, the period with the highest RH of all measurement periods in the storage room. The temperature and humidity data during the same duration obtained by installing the 3rd logger in the cardboard box with the top of the shelf unclosed on the shelf was also added for this calculation.

The temperature data measured in this study is the dry-bulb temperatures (Tdb), and the humidity data is RH. All plots of RH versus Tdb (from all data of the 3 sensors of June 1 to Sept 30, 2020, where RH > 67.5%) are shown in Figure 12, indicating that the maximum RH value is 92.0%.

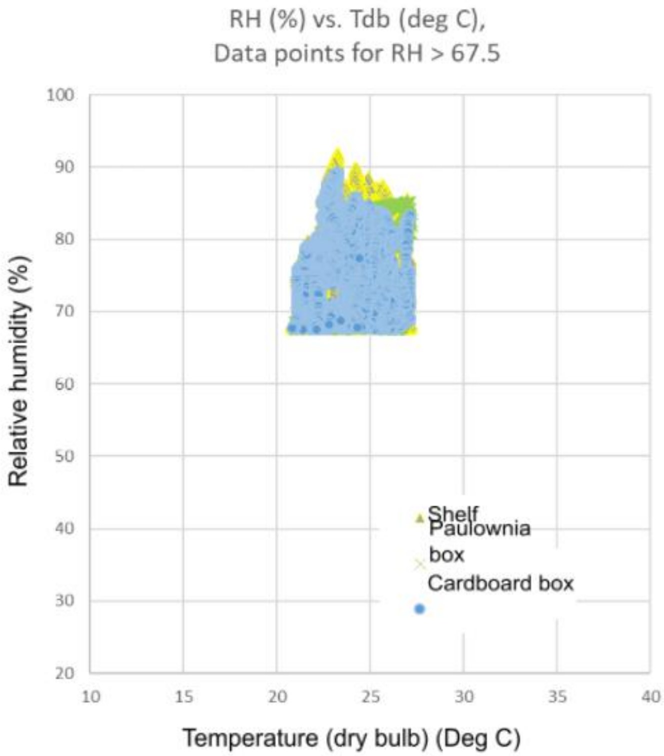

FIGURE 12: The relationship between relative humidity (RH, %) and dry-bulb temperature (Tdb), data points for relative humidity >67.5%.

As the next step, Twb (wet-bulb temperature) was calculated from Tdb, RH, and the atmospheric pressure (which was assumed to be 1 atm = 14.6959 PSIA (absolute pounds per square inch)) according to psychrometric functions (University of Vermont, 2021). Then the Humidity ratio (Hrat) was calculated from Tdb, Twb, and the atmospheric pressure. The plot of the calculated Hrat versus Tdb were shown in Figure 13, showing that the maximum Hrat value is 0.01926.

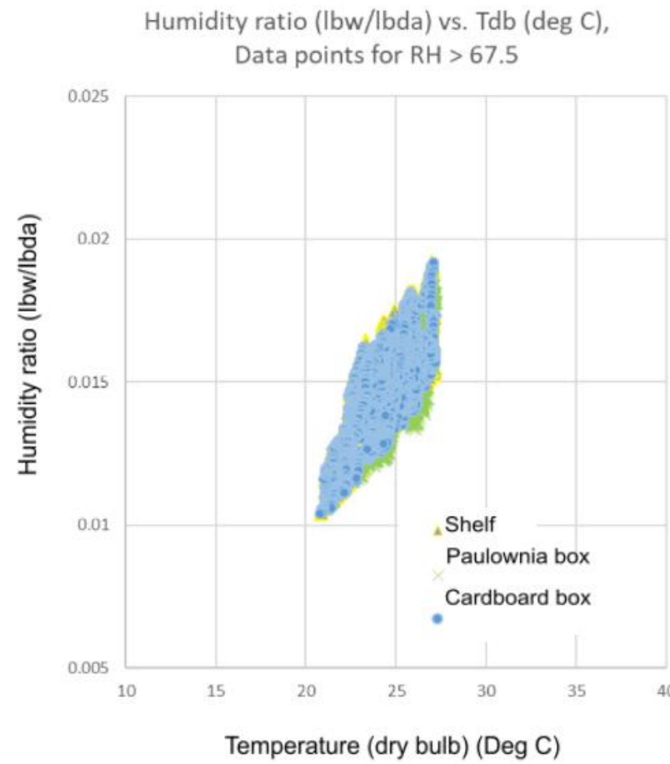

FIGURE 13: The relationship between humidity ratio (lbw/lbda) and dry-bulb temperature (Tdb), data points for relative humidity >67.5%.

Then, the plot of the calculated Hrat versus Tdb for the two cases of constant RH, of 67.5% and 92.0% were expressed in Figure 14. The case of 67.5% RH was plotted because that is the maximum RH value for which the fungal index will not exceed the threshold for detecting mold. The case of 92.0% RH was plotted because that is the maximum RH value for all data of the 3 sensors of June 1 to Sept 30, 2020. Then, in Figure 14, Tdb where Hrat = 0.01926 was found to correspond to 25.8°C when RH = 92.0%. Tdb where Hrat = 0.01926 was found to correspond to 31.2°C when RH = 67.5%. The difference in temperature is 31.2 - 25.8 = 5.4°C. So, by raising the temperature setting of the air conditioner in the storage room by 5.4°C, the resulting RH will be 67.5% or lower, which would minimize the risk of mold growth.

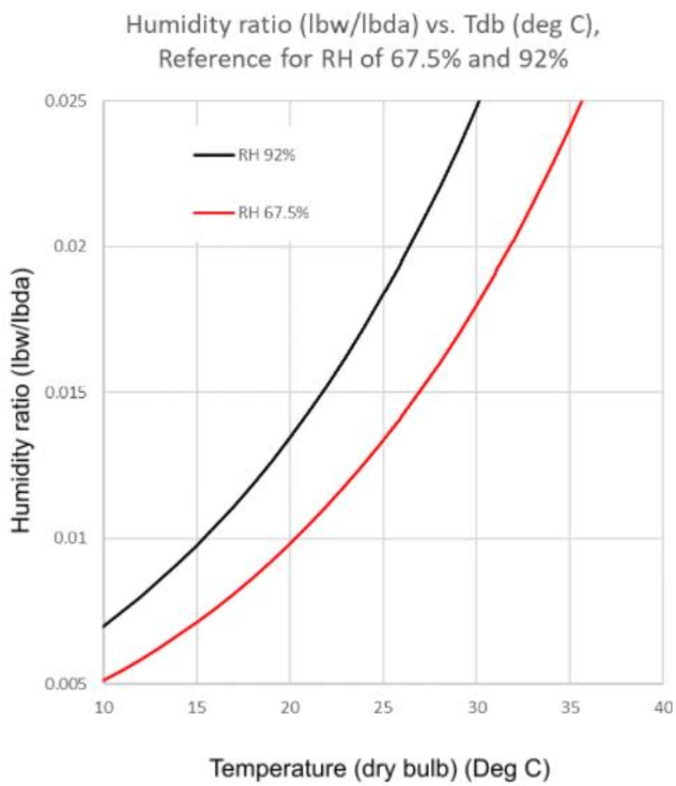

FIGURE 14: The relationship between humidity ratio (lbw/lbda) and dry-bulb temperature (Tdb), reference for relative humidity 67.5% and 92.0%.

Discussion

Environmental conditions for measurement in the storage room on the shelf and in the paulownia box

The fungal index inside the paulownia box was found to be significantly lower than that on the shelf, with the exception of the index found to be high only in September 2020. In September 2020, the humidity change in the storage room was large, and the fungal index on the shelf also changed significantly in response to the change in humidity. However, in the paulownia box, the variation of the monthly RH data was small. From these results, the fungal index was considered to be stable in the paulownia box because it is not easily affected by sudden changes in RH in the storage room, and RH in the box can be maintained with even greater stability.

Not only does the paulownia box prevent dust in the storage room and airborne microorganisms that are attached to dust particles from adhering to the "sho-zoku," storing the "sho-zoku" in the paulownia box helps maintain the fungal index at a low level and avoid mold growth, which are vital to avoiding the deterioration of the "sho-zoku".

Paulownia lumber has long been considered to be excellent for storing and preserving classical books and ancient documents in Japan, and paulownia boxes have long been used as storage containers for various cultural materials. The reason why paulownia is used is that it does not produce tar, is resistant to insect damage, and is also resistant to sudden changes in the humidity of the outside the paulownia box (Aoki, 1999). The results of this study confirmed the effect of the paulownia material in mitigating the effects of the humidity change of the outside air on the humidity inside the paulownia box. On the other hand, even if the fungal index can be kept low in the paulownia box, the inside of the storage room and the paulownia box still need to be cleaned regularly to remove dust and mold spores attached to the dust. Considering the growth time of mold spores, the optimum cleaning time is after October when mold spores grow (Lee et al., 2006).

Storage room environment indicated by fungal index values

The highest fungal index value of 131 obtained on July 28, 2020 on the shelf was equivalent to the environment inside a bathroom in a residential environment or an air conditioner during cooling, and was equivalent to the environment in which it took less than 12 hours for the outbreak of mold and took 2 months until the start of fungal contamination (Abe, 2012a, 2012b, 2016, Abe & Murata, 2014, Kurashima, 2016). The index value of 77 obtained in the paulownia box on August 18, 2020 was also found to be equivalent to an environment in which it took less than 1 day for the outbreak of mold and took about 4 months until start of mold contamination (Abe, 2012a, 2012b, 2016, Abe & Murata, 2014, Kurashima, 2016). It is possible to keep the fungal index value lower by storing the "sho-zoku" in the paulownia box rather than directly placing the costume on the shelf without any box. However, it was still necessary to reduce RH in the storage room so that the median fungal index value in the paulownia box in July, August and September 2020 was 20 or less, which is about the index value found in the average home in Japan.

Reducing relative humidity in the storage room using results of calculation

Since the fungal index depends on RH in the environment, it is effective to lower RH in order to lower the fungal index value in the storage room. For that purpose, options were considered to (1) directly dehumidify the storage room, or (2) raise the control temperature in the storage room to lower RH. Regarding (1), since the storage room air conditioning system does not have a dehumidification mode, it is difficult to reduce RH directly by mechanical dehumidification. Also, if a separate dehumidifier is installed in the storage room, the accumulated water cannot be disposed during the long summer months when the school is closed. Therefore, it is difficult to perform mechanical dehumidification directly. On the other hand, regarding (2), it is possible to raise the control temperature in the storage room as follows.

Within the measurement period, June to September 2020 is the time when the air conditioning setting of the school is in the cooling mode, and even though there are no people and no activity in this storage room, the air conditioning was controlled in the cooling mode all the time. From Figure 11, it was inferred that the upper limit of the control temperature in the storage room was 25°C in the summer. It was estimated that if the air conditioning temperature was set to 30.4°C, which results from the addition of 5.4°C as obtained from the calculations, RH in the storage room would be 67.5% or less, and the fungal index would not exceed the threshold of detecting mold. In the summer, people do not enter the storage room for any activities, so it is not necessary to set the temperature inside the storage room in consideration of thermal comfort for human beings. Therefore, it is considered feasible to set the storage room temperature to 30.4℃ to lower RH.

Energy expected to be conserved by raising the control temperature setting

Furthermore, the reduction of power consumption, that is, the reduction of consumption cost, can be realized by raising the air conditioner control temperature by several degrees. For air conditioning management in offices, there is an idea such as "night setback" that reduces the cost of air conditioning power consumption (Izawa & Fripp, 2018, Pacific Northwest National Laboratory, 2012). During the time when people are in the office, the temperature is set to within the range that people feel comfortable, and during the night when there are no people in the office, this "night setback" is implemented such that the temperature range is set to levels that exceed human comfort (raised in the summer, lowered in the winter).

The storage room where the "sho-zoku" is stored is not a room occupied by people for any extended period of time. Therefore, it is not necessary to set the temperature for time division such as the "night setback," so the storage room environment can be easily adjusted to reduce air-conditioning costs.

According to the Ministry of the Environment in Japan guidelines (Ministry of the Environment in Japan, 2021), U.S. Department of Energy (U. S. Department of Energy, 2021), and North Carolina State government (North Carolina State government, 2010) for controlling greenhouse gas emissions and the optimization of air-conditioning control temperature and humidity, raising the air-conditioning setting by 1℃ will reduce power consumption by about 10%. In the estimation in this study, the control temperature setting was increased by 5.4℃, suggesting that the air conditioning power consumption in the storage room in the summer could be reduced to about 54%, that is, about half of the current settings.

Conclusions

It was found that when the "sho-zoku" Kyogen costumes in the storage room are stored in a paulownia box, which can absorb moisture very well, the fungal index value was kept low without undergoing sudden changes in RH.

In the summer, if the air conditioning control temperature in the storage room is set to 30.4°C, RH will be suppressed to 67.5% or less, and as a result, the fungal index will not exceed the threshold of mold detection, and an energy conservation effect of about 54% can be expected.

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