ABSTRACT

Passive cooling techniques such as evapotranspiration from plants and watering are effective for ameliorating outdoor microclimates in hot summer. Natural ventilation also helps to make an indoor thermal environment more comfortable. However, in Japan’s humid and hot summer climate, there is a limited opportunity to gain a cooling effect by ventilation. Therefore, this study focuses on passive cooling techniques to improve the outdoor microclimate near the window of a residential building to achieve a cooling effect by ventilation despite the hot climate and to reduce the demand for cooling energy. Measurements were conducted two cases during one summer on a target building located in a residential area with a window which located at the floor level to help natural ventilation. The first case had no additional plants in front of the window, and the second case did. The results show that when the ground and in front of the window were kept wet by watering and shaded, the radiant temperature, measured by a thermal infrared camera, was about 1−7 °C lower than the outside air temperature at the 3p.m. Consequently, the air temperature near the window was 2−4 °C lower than the outside air temperature. However, due to watering and evapotranspiring of plants, absolute humidity increased 2 g/kg’ in the after adding plants case in front of the window. Although the indoor wind velocity came to a tenth of the roof wind speed, because of adding plants, inflow rate through the window was not changed. Therefore, the cooling potential was created at the outdoor space by applying the passive cooling techniques. When this cooling potential was used by ventilation, the sensible heat flux decreased 200–300 W through the daytime, and latent heat flux increased 100–300 W at the nighttime.

INTRODUCTION

Natural ventilation is known to be one of the most effective passive methods for creating a comfortable indoor climate and to conserve energy consumption. The outdoor microclimate, including air temperature, humidity, wind velocity, wind direction and solar radiation, has a direct impact on the effectiveness of ventilation for cooling. Fig. 1(b) shows the average, maximum, and minimum monthly temperatures from April to October in Tokyo from 2000 to 2013(Obseved by Japan Meteorological Agency). Maximum temperatures in midsummer (July and August) are higher than 30 °C. Therefore, Tokyo’s air temperatures in July and August are too high to utilize outside air for natural ventilation. Many studies show that maximum suitable outdoor air temperature for natural ventilation is between 28 and 30 °C (Givoni, 1992; Habara et al., 2012). Therefore, not only the indoor thermal environment but also the outdoor microclimate around the house must be improved in order to utilize natural ventilation in the midsummer season.

Many passive cooling techniques and designs have been developed and studied. Solar shading (Nikooofard et al., 2011; Berry et al., 2013) by structures and trees reduces the amount of solar radiation
in the summer season, and contributes to a decrease in a building’s surface temperature and energy demands. The transpiration of trees can prevent increases in the air temperature around trees (Umeda et al., 2006). Atmospheric radiation cooling is a phenomenon by which heat is lost by the emission of longwave radiation toward the sky at night-time. Nocturnal ventilation cooling (Givoni, 1991) with cold storage lowers the daytime temperature and makes possible to reduce the length of the periods requiring the operation of additional cooling systems. Each of these examples is individual approaches to improve and evaluate indoor, and outdoor microclimates. However, there has been little research about evaluating the change of the indoor thermal environment utilizing multiple passive cooling systems.

This study aims to introduce the passive cooling systems at an outdoor space and to evaluate its effect on the indoor thermal climate utilizing the natural ventilation by measurement. We measured the cooling effects of plants and water retentive blocks as well as the negative influences of increased humidity and air flow decrement by analyzing the microclimatic parameters around the actual house quantitatively. Then, we focused on changing the indoor thermal climate by introducing cooled air through an open window which helps the natural ventilation located at the floor level.

![Figure 1](image1.jpg)

**Figure 1** Outlines of measurement
MEASUREMENT DETAILS FOR HORIZONTAL AND VERTICAL AIR TEMPERATURE DISTRIBUTION

In order to adequately investigate the space where cooled air is created and where the air flows into building, the spatial distribution of the microclimatic parameters must be measured minutely. In this section, we propose a method for measuring the air temperature using polyvinyl chloride (PVC) piping with fan-aspirated ventilation. We then, describe the measurement method and the improvements made to the microclimate with plants and watering.

Measurement Method

When the measurement of air temperature and humidity is conducted at the outdoor space, solar and other radiation factors in the immediate surroundings must be removed. To do so, an aspirated radiation shield is often used. However, as the aspirated radiation shield is large, it is not suitable for measuring vertical and multipoint temperature distributions. We used PVC pipes (⌀13 mm) and ventilation fans (air volume: 75 m$^3$/h, static pressure in the pipe: 100 Pa) to measure outdoor air temperature and humidity accurately. Each of the measurement points was connected by piping. The measurement sensors were a thermo-couple (⌀0.1 mm type T thermo-couple) and a resistance change type humidity sensor (TDK, CHS-UPS), which were inserted into a pipe. When taking measurements using the PVC pipe, to prevent overestimation due to radiation from the surroundings, the pipe diameter was controlled to maintain sufficient wind speed (3 to 5m/s) at each measurement point. Ventilation fans were then connected to PVC pipes. In addition, the PVC pipes at the measurement point were screened two times with an aluminum sheet (Fig. 1(c)).

The measurement results using this proposed PVC pipe method were compared with forced ventilation thermometer with aspirated radiation shield to verify accuracy. The measurement comparisons were made at intervals of 10 s for two days (September 21 and 22, 2013). Fig. 1(d) shows the differences in air temperatures between the PVC pipe method and the forced ventilation thermometer. Air temperature is almost identical at night when there is no solar radiation and a temperature error maximum of $+0.9 \degree C$ exists at daytime when insolation is elevated. The results show an accuracy of $+0.6 \degree C$ with a 95% confidence interval.

Measurement Conditions

| Table 1. Details of the measurements of the effect of plants and water retentive blocks |
|---------------------------------|-------------------------------------------------|
| July 15(Case 1)             | August 29(Case 2)                  |
| Condition               | Trees (height 0.8 – 3 m) were 0.7 m away from the window. |
| Watering                | Additional planting, water retentive blocks were added. |
|                         | Automatic watering at 7a.m, 11a.m, 3p.m, and 7p.m by mist sprayer for 5 min. |
|                         | Continuous watering from 7 a.m. to 7 p.m. by hosepipe. |
| Photographs            |                                                                   |

Measurements of the microclimate around the building were made on July 15 and August 29, 2013. The measurement conditions are detailed in Table 1. In the July measurement, there were trees 0.7 m away from the window. There was nothing except the PVC pipe for measurement in front of the window. In the August measurement, we added additional plants and water retentive blocks as passive cooling materials in front of the window. Moreover, the watering method and times were changed to wet more
surfaces of the leaf and block. In addition, vertical measurement points were added in front of the window to measure in detail the cooling effect of the additional plants. The indoor air temperature was measured near the window (A5 in Fig. 1(a)) and in the living room (A6, A7 in Fig. 1(a)).

**EFFECTIVENESS OF EVAPORATIVE COOLING IN CASE OF UTILIZING PLANTS AND WATER RETENTIVE BLOCKS NEAR THE OPEN WINDOW**

In order to analyze the cooling effect around the house, we used the abovementioned method to measure the effects of the passive cooling system applied outside the house. This section focuses on the following factors: improvement in surface temperature, decrease in air temperature, increase in humidity, and wind velocity decrement.

**The Improvement in Surface Temperature**

Thermal infrared images of the area in front of the window were obtained using spherical thermography (Asano, 1996). Fig. 2(a) shows an image obtained at 3p.m on August 29. The surface temperature of the wall was over 40 °C due to the afternoon insolation. However, the surface temperature of leaves and blocks in front of the window (shown in the inside of white rectangle on this thermal image) was 1 °C to 7 °C lower than the air temperature. Therefore, we have confirmed the cooling potential created by additional plants, watering, and shade near the window. In particular, the surface temperature of the water retentive blocks under the window is about 8 °C lower than the air temperature. However, we must also address how to introduce this cooled air into the indoor area.

**The Decrease in Air Temperature**

Fig. 2(b) shows the vertical air temperature distribution in front of the window (A4, Fig. 1(a)). While the vertical distribution was almost similar as that before the additional planting (Case 1), a temperature discrepancy of 2 to 4 °C occurred after the additional planting (Case 2) during the daytime.

An A – A’ cross-section (Fig. 1(a)) of the air temperature distribution can be seen in Fig. 2(c). At noon, the air temperature near the window (A4) was 1.5°C to 2 °C lower than the air temperature outside the target area (A1). At 3p.m, the air temperature near the window (A4) showed a decrease of about 2 °C in comparison with the A1 air temperature in the case 2 measurement, while the air temperature near the window (A4) was 1 °C higher than the A1 air temperature in the case 1 measurement. This difference occurred because the afternoon solar radiation was blocked and evapotranspiring was more conducted by the additional plants, so the A4 air temperature was lower on August 29. In addition, the indoor and outdoor air temperature difference was just 1 °C at night-time. It is clear that the decrease in the nighttime indoor air temperature was due to ventilation.

**The Increase in Humidity**

Fig. 2(d) shows the absolute humidity at each of the measurement points (A1, A4, A5, and A6 of Fig. 1(a)). Before the additional planting (left side of Fig. 2(d)), humidity decreased as the daytime air temperature increase. However, with the additional plants and watering, the humidity of the indoor space (A6) on August 29 had increased to 14 g/kg, while the outdoor (A1) humidity was about 10 g/kg. Thus, even when the initial indoor humidity was higher than the outdoor humidity, the humidity of the indoor space in the case 2 was shown to be 2 g/kg higher than the outdoor measurement.

**The Wind Velocity Decrement**

To analyze the wind flow frequency, we conducted a test on September 13(A5) using a 3D supersonic anemometer. The wind direction on the date of the main measurement and that on September 13 are shown in the left side of Fig. 2(e). The July 15 wind direction (before the additional planting) was a little different than the September measurement. However, wind direction data for the August 29 and September 13 cases, both occurring after the additional planting, are almost identical. Graph, right side
of Fig. 2(e), shows the inflow and outflow frequency at the window. In day-time, the inflow rate was recorded to be 40% on average after additional plants.

Fig. 2(f) shows the decrement of wind speed after the additional planting, both in the velocity at the roof and near the window. However, the difference of the inside velocity in the before and after the additional planting cases near the window was approximately 0.2 m/s. Although wind speed decreased, the results shows that cooled air flowed to the inside area through the window. Thus, the cooled air created in front of the window did effectively replace the indoor air.

Figure 2 Spatial distributions of the microclimates
Evaluation of the Passive Cooling Effect by Heat Flux

In order to evaluate the effect of the passive cooling techniques at the outdoor space to the indoor space, we calculated the sensible and latent heat fluxes using the following equations. A comparison of these fluxes is shown in Fig. 3.

\[
q_s[W] = C_p \cdot \rho \cdot V \cdot (T_{out} - T_{in}) \cdot 1000
\]

\[
q_l[W] = \gamma_f \cdot \rho \cdot V \cdot (X_{out} - X_{in}) \cdot 1000
\]

The August 29 sensible heat flux decreased maximum 200–300 W compared with that on July 15 in the daytime. Furthermore, the length of time when the sensible heat flux was above zero diminished from 9 to 4 h. In the midnight, 100 W or more of sensible heat was removed from the indoors to the outdoors through the window on August 29. Conversely, the August 29 latent heat flux at nighttime was higher by 100–300 W than that of July 15. However, although latent heat flux of August 29 was high, the indoor humidity was lower than that on July 15. It means humidity increases due to the plants and water retentive blocks, however, its effect on the thermal comfort of indoor is small because the absolute humidity is influenced by the weather conditions.

![Figure 3 Estimation of the passive cooling effect near the window](image)

**CONCLUSION**

By locating plants and water retentive blocks in front of a window, we created a cooling potential at the outdoor space. We then quantitatively evaluated the influence of the cooling potential by evaporative cooling using the plants and water retentive blocks on the thermal environment of the indoor space by ventilation through the window.
1) To measure in detail the microclimate around the building, air temperature measurements were taken using a PVC piping method. The accuracy of this method verified to be +0.6 °C with a 95% confidence interval.

2) A decrease in the air temperature was observed 2 to 4 °C by passive cooling due to solar shading and evaporative cooling.

3) Although the wall surface temperature was over 40 °C at 3p.m due to the afternoon sun, the surface temperature of leaves and blocks with watering and shading in front of the window was 1 °C to 7 °C lower than the surrounding air temperature.

4) Due to the presence of additional plants near the window, the inside wind speed came to a tenth of the roof wind speed.

5) The length of time when the sensible heat flux was above zero diminished from 9 to 4 h.

The results show that application of passive cooling techniques can enhance the microclimate at the outdoor space, create a cooling potential around the building in the daytime. And there was little effect of the increase in humidity on the indoor climates by the passive cooling techniques. In the next study, we are going to measure the effect of nighttime ventilation with cold storage at floor and to evaluate how it can control the increase in the indoor daytime air temperature.

NOMENCLATURE

\[ C_p \]: Specific heat at constant pressure of air (=1.006[kJ/kg \cdot °C])

\[ \rho \]: Density of air (=1.2[kg/m^3])

\[ V \]: Air Volume [m^3/s] (=H0.5 [m] × W0.7 [m] × 2 × Wind velocity [m/s])

\[ T_{out} \]: Air Temperature at A4 [°C]

\[ T_{in} \]: Air Temperature at A6 [°C]

\[ X_{out} \]: Absolute humidity at A4 [kg/kg (DA)]

\[ X_{in} \]: Absolute humidity at A6 [kg/kg (DA)]

\[ \gamma \]: Latent heat of vaporization (=2430 [kJ/kg])

Refer to Fig.3 (b) where the detail points are (A4, A6).

REFERENCES


Japan Meteorological Agency: http://www.jma.go.jp
