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Multipoint measurement method for air temperature in outdoor spaces and application to microclimate and passive cooling studies for a house

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A B S T R A C T

We propose a multipoint measurement method for air temperature in outdoor spaces using polyvinyl chloride pipes with fan-aspirated ventilation. The method is applied to microclimate measurement in the outdoor space of a residential house, and the cooling effects of plants and natural ventilation on the house were evaluated. The accuracy of the proposed method was verified in the outdoor space. Average systematic errors of the method were 0.43 °C during daytime on sunny days and 0.16 °C on cloudy days. Application of the method to microclimate measurement shows that air temperatures were reduced by evapotranspiration of plants and watering in the planted space during daytime. By placing the plants near a floor-level window, wind speed inside the window was reduced, although the cooled air flowed into the indoor space through the window. The cooling effects of the plants and watering in the outdoor space kept indoor air temperature cooler during daytime. The period in which the sensible heat flux from the outdoor to indoor space showed positive values, i.e., when there was a sensible heat load in the room, diminished from 9 to 4 h through the cooling effects.

1. Introduction

Global and urban environmental issues such as climate change, the urban heat island phenomenon and energy constraints are becoming increasingly the focus of worldwide concern. Passive cooling is an architectural design that can improve the deteriorated urban microclimate and indoor thermal comfort, while contributing to the energy conservation of buildings in hot and warm climate regions. Much research in the urban- and architectural-environment fields has focused on passive cooling designs and techniques as countermeasures to environmental concerns [3,4,8,23,25,27–30,35].

Passive cooling on the building scale can be defined by two methodologies: (1) the blocking of heat entering the building and (2) the removal of internal heat to the outside. Method (1) mainly controls solar radiation and heat transmission through building envelopes. Artificial structures for shielding solar radiation (such as eaves and awnings), measures using trees and plants (in this case, evaporative cooling can also improve the external environment), an increase in the reflectance of the building (albedo), installation of high insulation materials into building walls can be mentioned in particular. As a method of removing indoor heat, natural ventilation and cross-ventilation are common ways, and they are traditionally used in hot and warm climate regions [7,9–11,27].

Solar shading by structures and trees reduces the amount of solar radiation, and contributes to the decrease in the outdoor air temperature, the building's surface temperature and the energy demands for cooling [1–4,7,8]. Moreover, changing the ground material from concrete to grass, or water-permeable blocks or gravel, can improve the microclimate [5,30]. The transpiration of trees and the evaporation of water-retentive materials can prevent increases in the air temperature around trees and on surfaces [6,35]. Some studies have discussed methods to improve the

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indoor thermal environment by enhancing the microclimate in outdoor spaces with solar shading by trees [7,8].

Natural ventilation has been known as an effective passive method for creating a comfortable indoor climate, and for reducing the cooling load of a house in hot and warm climate regions [9]. Previous studies have shown that the maximum suitable outdoor air temperature for natural ventilation is between 28 °C and 30 °C [10,11]. In the summer season of recent years, there have been many days when natural ventilation was difficult because of the increase in temperature. The average of the maximum temperature of August days has increased by about 1.4 °C (30.7 °C–32.1 °C) in the past 30 years in Tokyo [12], which is too warm to exploit the outside air for natural ventilation. Therefore, the outdoor microclimate around a house must be improved for the use of natural ventilation.

In addition, the capability of natural ventilation is affected by not only temperature, but also the wind speed. However, the wind speed of the Tokyo district observatory (altitude of 25.2 m) has been maintained at approximately 3 m/s, and the wind direction has also changed little in the previous three decades. Furthermore, in the case of a dense residential area, the wind velocity in the urban canopy does not necessarily affect the air change rate of buildings. This is because of the high possibility that the wind direction can change locally, and the wind speed is reduced by adjacent buildings, as has been reported in several papers that deal with the relationship between the air change ratio and building density [13,14]. Based on this knowledge, the air temperature is the focus here to influence the microclimate and natural ventilation rather than the wind velocity.

To increase the efficiency of cooling, the above-mentioned passive methods should take into account aspects that consider the regional climate. However, in the previous research mentioned above, the effectiveness of cool air formed in the outdoor spaces as a microclimate for the indoor thermal environment has rarely been discussed. The present study focuses on evapotranspiration and the shading of plants to reduce the air temperature in outdoor and indoor spaces. Although the Japanese summer is known to be hot and humid, the relative humidity is generally less than 50% in the daytime. It is believed that evapotranspiration has enough cooling potential for outdoor microclimates owing to the vapor pressure deficit of the atmosphere.

For grasping these passive cooling effects, measurements in indoor and outdoor space need to be conducted simultaneously. Furthermore, for increasing the effectiveness of natural ventilation, the spatio-temporal characteristics of such microclimates should be analyzed, i.e., where the cooled air is generated, how it flows into the house, and how much it cools the indoor space. To understand these processes quantitatively, the spatial distribution of air temperature should be minutely measured. For measurement devices, the previous research discussed microclimates and indoor climates with limited measurement points because of the limits of measurement devices. In addition, temperature sensors are easily affected by radiation from the sun and heated urban surfaces, causing systematic error in temperature measurement. The present study proposes a multipoint measurement method for air temperature (T_a) in outdoor spaces by considering a minimization of the systematic error, and confirms the validity of the method for field studies. The method is applied to a field study of an outdoor microclimate for the passive cooling of a house in Tokyo, focusing on the cooling effects of the evapotranspiration of plants and natural ventilation under the hot summer conditions.

2. Methods

2.1. Previous methods for air temperature measurement in outdoor spaces

When a field measurement is conducted in outdoor spaces, the exposure of instruments to the sun and the surrounding radiation field must be considered, such as the shielding and ventilation of T_a sensors, because sensors could be heated by radiation sources. A temperature sensor exposed to solar radiation may overestimate the T_a by several degrees Celsius. Present international standards (e.g., ISO7726 and ISO9001) reported that sensors have to be subject to proper shielding to minimize the radiative exchange between the sensor and its surroundings. Also, sensors should have proper ventilation by using an aspirated shield to maximize convection, and to avoid warm air formation around it [15–17].

The characteristics of T_a measurement in previous studies are summarized in Table 1. Much research did not document the shielding of instruments or sensors. In some studies, the measurement sensors were shielded using aluminum foil [27,29], which can block radiation sources from the sun and surroundings, or a plastic cap or cup [34,36], which cannot block significant radiation sources. Cheng et al. [24] stated that the use of a radiation shield was insufficient, which has led to overestimations of the measured air temperatures. Some studies have used forced ventilation for the temperature sensors [19–22,28]; in other studies, there was no remark about measurement accuracies. The methods carried out in these studies are not enough to evaluate the passive cooling effect in outdoor spaces.

Even though the measurement accuracies were satisfied with shielding and ventilation, the instruments were too large to apply to multipoint measurements [18–22]. In general, a radiation shield with natural ventilation was used [18]. When using a thermocouple and other small sensors, it is necessary to protect the sensors from radiation using shielding, and to remove heated air in the shielding using fans, as with the aspirated radiation shield [19–22]. According to the discussion and Table 1, the following issues were identified in previous researches.

1) Exposure of the measurement instrument to the outdoor radiative environment
2) Dependence on natural ventilation only, without forced ventilation
3) Restrictions related to size or cost of instruments for measurement at multiple points
4) Data synchronization was necessary with the use of numerous data loggers

For simultaneous measurement of T_a in outdoor and indoor spaces, many measurement points and instruments are required, taking into account the aforementioned issues.

2.2. Multipoint measurement method for air temperature

Based on the aforementioned issues of measuring T_a in outdoor spaces, we proposed the multipoint measurement method using polyvinyl chloride (PVC) pipe with an aspirated ventilation fan (Fig. 1). A PVC pipe was chosen because it is anti-corrosive compared with wooden pipes, is cheaper than metal or aluminum, and is easily cut and connected. Also, the thermal conductivity is somewhat lower than other possible materials. Ends of the PVC (A-type) pipes were set at several positions for T_a measurement, and the other ends were connected to a wider (B-Type) pipe with a central ventilation fan. In addition, to minimize the fluctuation of internal pressure inside the pipes by the