OUTDOOR SCALE MODEL EXPERIMENTS OF THE LOCAL BULK TRANSFER COEFFICIENT FOR URBAN SURFACES WITH A WATER EVAPORATION METHOD

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Abstract

Recent urban canopy models express the turbulent transfers as a network of resistances between the air and surfaces. However, there are very few studies about these resistances (or transfer coefficients) for urban surfaces. In this study, the local bulk transfer coefficients of regular cubic arrays were measured with outdoor scale model using a water evaporation method, and they were compared with the wind tunnel experiments using the same evaporation method. Besides, to check the analogy between heat and mass transfer, the mass transfer coefficient with the evaporation method was also compared with the heat transfer coefficient with a heat balance method about each face of the urban canopy.

Key words: canopy model, heat balance, scale model experiments

1. INTRODUCTION

To simulate the heat balance of an urban area in detail, one should know the turbulent transfer from all active surfaces as well as the radiative fluxes. Recent urban canopy models, such as Masson's (2000) TEB (Town Energy Balance) model, express the turbulent transfer as a network of resistances between the air and surface. However, there are very few studies that provide values of these resistances (or transfer velocity) for urban surfaces; therefore, the parameterization of these processes has been empirical or based only on the drag from vertical wind profiles above a series of street canyons (Kusaka et al., 2001). Comparisons with field data have been partially performed (Masson et al., 2002), however systematic validation of dynamic processes has been required particularly for turbulent fluxes.

In this study, the local bulk transfer coefficient of regular cubic arrays was measured with outdoor scale model using a water evaporation method. This method has been already applied to wind tunnel experiments (Narita, 2003). One of the main purposes of this study is to compare the results of transfer velocity in wind tunnel with that of outdoor experiments in natural wind. And regarding the heat-mass transfer analogy, it has been validated only restricted condition such as horizontal surface. Therefore, the comparison of mass transfer coefficient (C_E) with the heat transfer coefficient (C_H) with heat balance method is another important purpose of this study.

2. SCALE MODEL SITE

In our scale model site 'COSMO' (Comprehensive Outdoor Scale MOdel experiment for urban climate), there are two kinds of scale model: larger one (1/5: 1.5 m cube) and smaller one (1/50: 0.15 m cube). Here, the results with the latter 0.15m cubic arrays in natural wind were compared with the wind tunnel experiments using the same evaporation method (model dimension = 0.05 m).

This site is located in the campus of Nippon Institute of Technology, Saitama prefecture, Japan (36°01'N, 139°42'E). The model surface geometry consisted of concrete blocks, regularly distributed on flat concrete plates (total area of 12 m x 12 m) with plane area density 0.25. The same concrete material was used for cubic block and basement. The reference wind speed and direction were measured with a compact sonic anemometer with 0.05 m sensor-span and 50Hz sampling frequency (Kaijo TR90-AH). It was installed 11 m downstream from the fetch at a height of 0.3m (Z/H=2), where H is the cube height. Its position was changed seasonally considering dominant wind direction: NE in winter and SE in summer. Upward and downward short wave and longwave radiation were measured separately using a radiation balance meter (Eko MR-40) 0.7 m above the ground near the center. A total of 72 heat plates (0.05m

Fig.1 Outdoor scale model site

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x 0.05 m, 0.4-mm thickness; Captec HF-50) cover a unit of constituent surfaces including four vertical walls, roof, and floor. The whole surface is painted with same color to uniform the surface radiative properties.

3. WATER EVAPORATION METHOD

For the water evaporation method, we prepared the special acryl cubic models (Fig. 2). We pasted filter paper on this model surface and moistened it sufficiently but not so much that it drips. This wetted model was set in a scale model arrangement for twenty or thirty minutes, and the weight loss during this period was measured using an electric balance (resolution 1 mg). The filter paper was 1 mm thick, and its side surfaces were treated with a waterproofing agent. A fine thermistor sensor having a diameter of 1 mm was inserted from the side surface just below the paper surface to measure evaporating surface temperature. During the weighing, the building model sample was packed in an airtight plastic bag.

The total weight of the model was about 200 g for wall surface and 90 g for roof and floor, and the weight loss was typically about 1-6 g. Then the mass transfer velocity (Wt) or mass transfer coefficient (C_E) was calculated as

$$Wt = C_E U = E / (\rho_s - \rho_a), \qquad (1)$$

where E is the evaporation rate [$kgm^{-2}s^{-1}$], U is the mean wind speed at reference height (2H) [ms^{-1}], ρ_s is the saturated water vapor density at evaporating surface temperature [kgm^{-3}], and ρ_a is the vapor density of the ambient air [kgm^{-3}] measured using a thermistor and capacitive hygrometer at a height of 1.5 m. Measurements were recorded at 1 Hz for these temperatures and humidity.

Measurements were conducted for five or six kinds of surfaces simultaneously including the roof surface every time (Fig. 4). Because the surface temperature is measured at only center part of filter paper, we avoided measuring about the partly shaded facets. All results in the current work were acquired with the condition of a local source, that is, only measured surfaces within the entire model were wet. Therefore, the boundary layer of a measured scalar (water vapor) is not developed like that of wind velocity.

4. RESULTS

4.1 Characteristics of natural wind

At first, some characteristics of natural wind were analyzed. In field experiments, the effect of wind-direction fluctuation is important point for the comprehension of the results. Fig.5 shows the relation between standard deviation of wind direction and mean wind speed during each experiment (20 or 30 minutes). Fluctuation of wind direction is remarkable especially in calm condition: less than 1 ms^{-1}.

4.2 Test of the water evaporation method in outdoor experiments

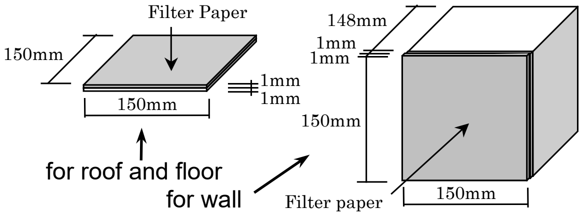

Fig.2 Models for water evaporation method

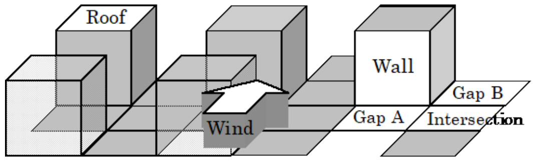

Fig.3 Position of sampling surface.

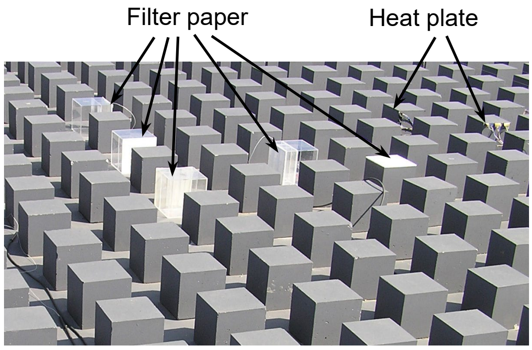

Fig.4 Setting of models for measurement

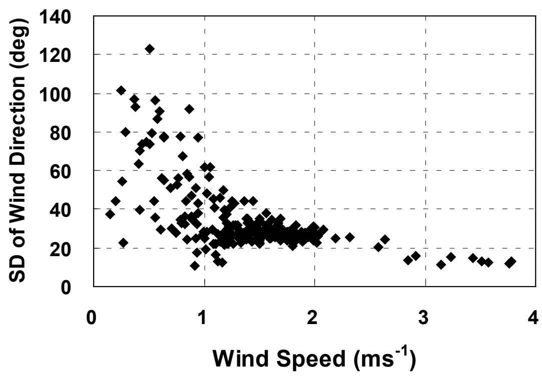

Fig.5 Standard deviation of wind direction

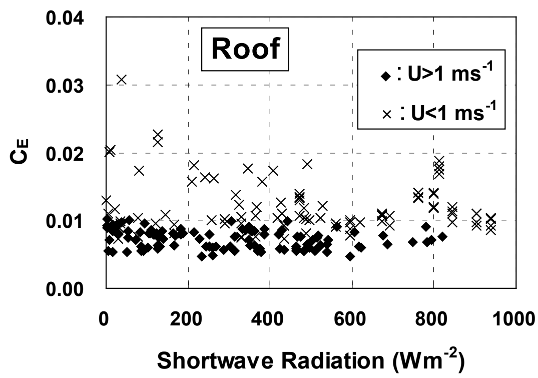

Fig.6 Consideration of the solar radiation effects on the C_E measurement with the water evaporation method

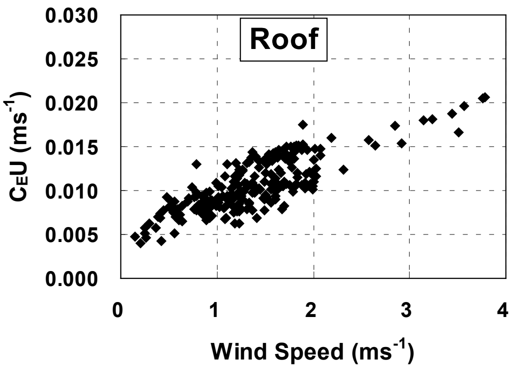

Fig.7 Relation between the mass transfer velocity and mean wind speed for roof surface

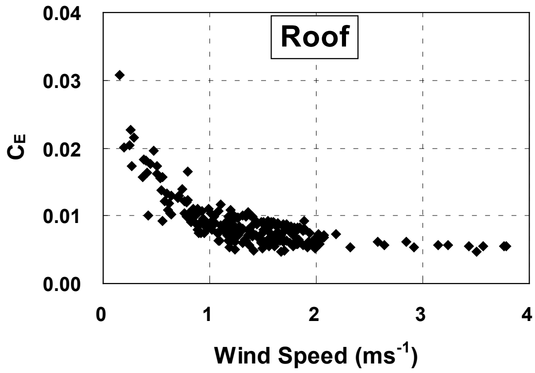

Fig.8 Relation between the mass transfer coefficient and mean wind speed for roof surface

The water evaporation method using filter paper has already tested indoor experiments and its experimental error was also estimated about 4% in the case of wind tunnel. However, when it is adopted in field experiments, there are some additional error factors to be required the consideration. Fig.6 is the result to check the effect of solar radiation. There is no clear dependency of the mass transfer coefficient on the solar radiation, which means surface temperature was measured precisely even beneath the sun.

4.3 Mass transfer coefficient for the roof surface

According to the comparison among reported full-scale measurements and wind tunnel experiments (Hagishima et al., 2005), the 'absolute' values of local bulk transfer coefficients have a scale dependency and are currently difficult to determine through a simple formulation. Therefore, we focus on the 'relative' values of the individual local bulk transfer coefficient, because such a relative values are expected to be robust and be irrespective of measuring method and scale (Kanda et al., 2005). As for the reference value, we select the transfer coefficient of the roof surface because it is insensitive both to wind direction and to the model density (Narita, 2003).

Fig.7 shows the relation between mass transfer velocity for roof surface and mean wind speed at reference height. They show almost liner relationship. But if that so, it dose not pass through the origin and has an intercept. Therefore, the mass transfer coefficient has a wind speed dependency (Fig.8). In the range of less than 1 ms^{-1}, the mass transfer coefficient increases steeply as the reference wind speed decreases. In windy condition, the mass transfer coefficient is almost constant.

4.4 Normalized transfer velocity for the wall and floor surfaces

In Fig.9, we show the change of the normalized mass transfer velocity due to wind direction for the wall and floor surfaces. As for the floor, they were divided into two groups: the facet between the models (Gap) and the facet of intersection. According to the result of Fig 8, the plots were distinguished by the wind condition. The definition of wind direction for each kind of facet is

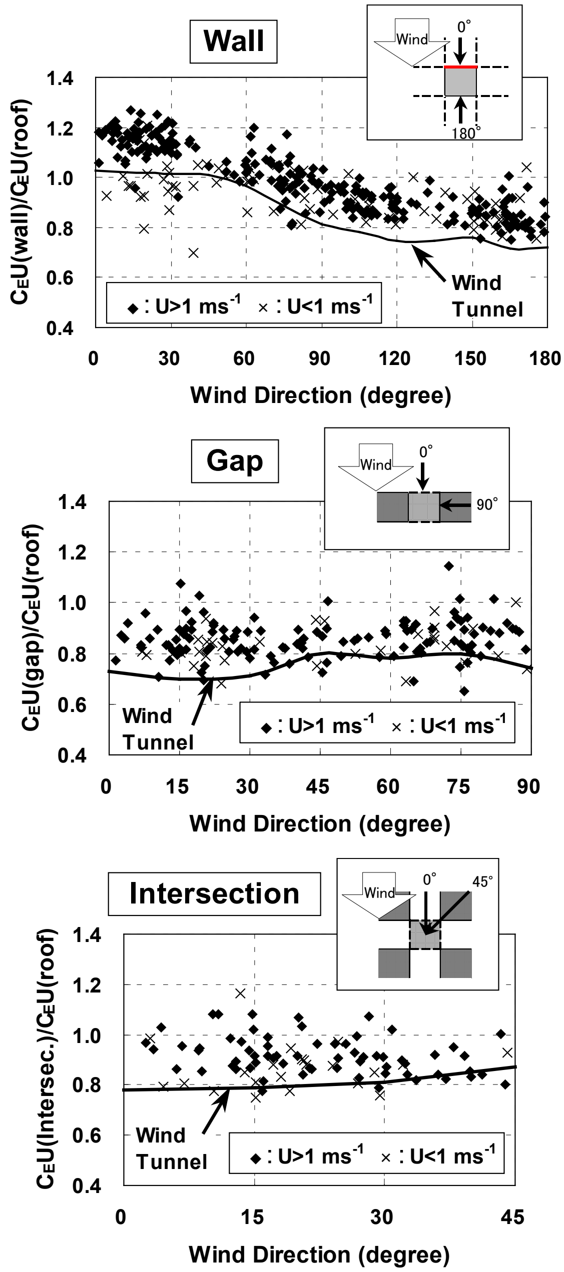

Fig.9 Change of the normalized transfer velocity due to wind direction for the wall and the floor

shown in the figure, respectively.

In these figures, the results of wind tunnel experiments are also described as the smoothed curves. These were measured in the same density arrangement of 0.05m cube models with the same water evaporation method for every 15 degrees of wind direction. As for the wall surface, the mass transfer coefficient in windward condition is almost same as that of the roof surface. In the leeward condition, it decreases about 70% of the roof surface. On the contrary, the value for floor surface has a weak dependency on the wind direction about both Gap' and 'Intersection'.

The plots of outdoor experiments show the similar tendency to the curves of wind tunnel except for the calm condition. Concerning the absolute value of normalized transfer velocity by the roof surface, outdoor results were generally larger than that of wind tunnel.

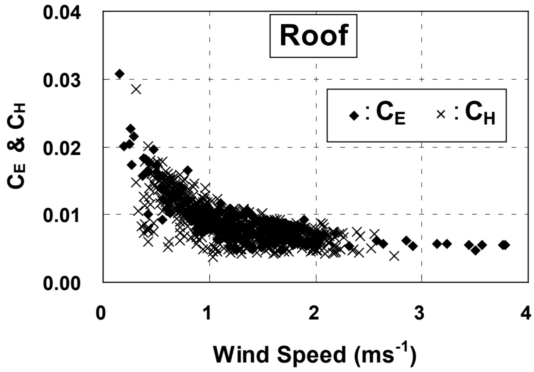

Fig.10 Comparison between the mass transfer coefficient and the heat transfer coefficient for the roof surface

4.5 Heat-mass transfer analogy in city-like setting

In order to check the heat-mass transfer analogy in such city-like setting, the heat balance method is also adopted in same outdoor scale model. The conductive flux was measure with heat flux plate and net radiation of each facet was calculated using radiation model (Kanda et al, 2005a). The comparison between the mass transfer coefficient and the heat transfer coefficient for the roof surface is shown in Fig.10. The heat transfer coefficient for the roof surface was in accordance with those of mass transfer, though their scalar boundary conditions were considerably different for each other. This result implies that the development of scalar boundary layer dose not significantly influence the local transfer coefficient at least for the roof surface.

5. CONCLUSIONS

The local bulk transfer coefficient for regular cubic array was measured by outdoor scale model experiments. We focused on the 'relative' values of local transfer velocity and its variation due to the wind direction. The reason why we take such a strategy is that these relative values are expected to be robust and irrespective of measuring method and scale. Here, the roof surface value is adopted for the reference.

The results of such relative values with a water evaporation method show the similar wind-direction dependency to that of wind tunnel. However, the absolute value of this normalized transfer velocity is slightly different between outdoor experiment and wind tunnel. It needs moor consideration for this discrepancy.

As for the heat-mass transfer analogy, the heat transfer coefficient with the heat balance method is quite agree with the mass transfer coefficient with the water evaporation method for the roof surface.

Acknowledgement

This research was financially supported by CREST (Core Research for Evolutional Science and Technology) of JST (Japan Science and Technology Cooperation) and by Grant-in Aid for Scientific Research from the Ministry of Education, Science and Culture of Japan.

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