ESTIMATION OF THE HEAT TRANSFER RESISTANCE IN THE REAL URBAN CANOPY

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1. INTRODUCTION

The heat transfer resistance is a key parameter for the canopy modeling. Barlow and Belcher (2001) and Narita (2003) determined experimentally the transfer resistance at building walls, roofs and canopy floor surface. But very few studies have investigated the transfer resistance between inside and above canopy (roof level transfer) in the real urban area. Most of modeling studies apply the forest canopy parameterization. This study evaluated experimentally the transfer resistance at the canopy level between the inside urban canopy airmass and the above air.

2. METODROGY

Figure 1 illustrates a schematic of heat flow in an inner court canyon. The heat flux at the top of the airmass (roof level) can be written as

$$H_{top} = C_P r\,(1/r_{can})(T_{canyon} - T_{roof}), \qquad (1)$$

where r_{can} is the heat transfer resistance. T_{canyon} and T_{roof} is the air temperature inside canyon and above roof level respectively. The heat flux at the roof level H_{top} is determined as a residual of heat budget equation for the canopy airmass,

$$dQ = H_{wall}S_{wall} + H_{window}S_{window} + H_{ground}S_{ground} - H_{top}S_{ground} \qquad (2)$$

where H is the sensible heat flux, S is the surface area. dQ is the heat storage in the airmass,

$$dQ = C_P r V \Delta T_{canyon} / \Delta t \quad . \qquad (3)$$

In (2), we neglected the advection term, because we picked up an inner court in this study which is surrounded completely by building walls.

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From eqs. (1)-(3), we get

$$1/r_{can} = \frac{-dQ + H_{ground}S_{ground} + H_{window}S_{window} + H_{wall}S_{wall}}{C_P r\,(T_{canyon} - T_{roof}) \times S_{ground}} \quad . \qquad (4)$$

In evaluating the sensible heat flux at three surfaces, we used a bulk parameterization,

$$H = c_p r C_H U (T_s - T_a) \quad . \qquad (5)$$

where C_H is the bulk heat transfer coefficient. In this study, we tested five different C_H in the previous studies of and evaluated how this surface C_H influences on r_{can}. We also measured the heat storage at a specific part of the building wall. At the part of wall, the sensible heat flux was acquired as a residual of dry surface heat budget and compared to H from (5). They agreed within 16 Wm^{-2} RMS difference.

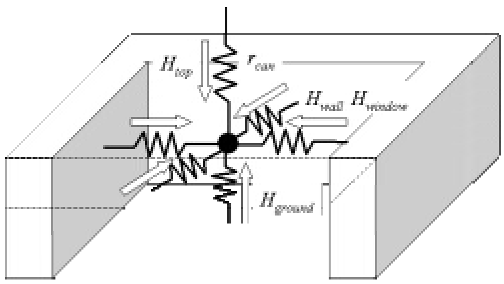


Fig. 1 Schematic illustration of heat flow in the inner court canyon and definitions. The heat flux into the airmass is positive

3. OBSERVATION

The observation campaign continued 9 moths from Feb. 2002. The size of canyon is L = 60, W = 31 and H_b = 13 m. W is the court width along the leading wind direction. The window occupies 29% area of walls. Air temperature inside (14 points) and above roof (4 points) was measured by the thermocouple with a forced-ventilation shelter. The surface temperature of walls and canopy floor ground was measured by thermocouple and IR thermometer. The horizontal component of wind speed was measured at the roof and the ground. 3D wind speed was measured at north and south wall by the sonic anemometers.

4 REUSLTS AND TRANSFER EFFICIENCY VS. WIND SPEED RELATIONSHIP

Figure 2 shows the resulted heat transfer efficiency $1/r_{can}$ in three fine days. The horizontal axis is the wind speed above the roof. The marks show the 10-min average in a fine daytime and data are shown for the T_{canyon} - T_{roof} > 0.2 ^{o}C cases. Here T_{canyon} is average of measured temperature at 14 points inside canopy. The heat transfer efficiency increases according to the increase of the wind speed, which is qualitatively reasonable. In a quantitative aspect, $1/r_{can}$ is about one order larger than those at the building surface (c.a. 0.01 m/s at 13 m height). This feature is also reported in Barlow and Belcher (2002).

The error bar indicates an error range caused by the spatial variation of surface temperature and wind speed, which are represented by the data of a few points inside canopy. The averaged error was 23 %. The bulk coefficient at walls and floors are uncertain and it also causes error of $1/r_{can}$. The range of the bulk coefficients that were presented in the literatures (Fukumoto and Hirota, 1994; Yoshikado et al., 2002; Hagishima et al., 2001; Kondo, 2000; Sugawara, 1994) resulted max. 26 % difference in the $1/r_{can}$ estimates.

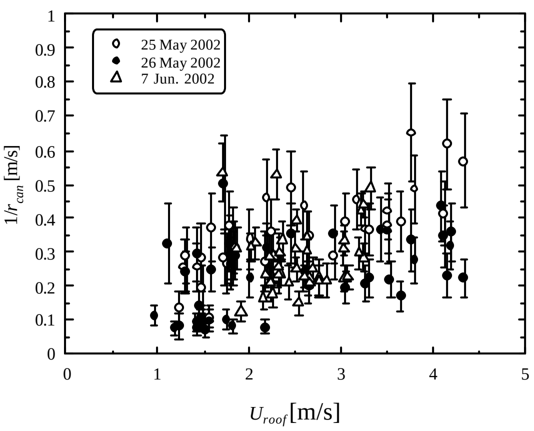
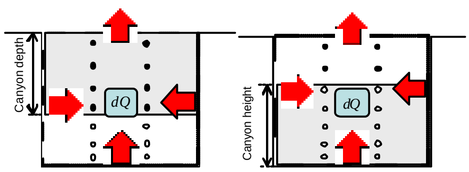


Figure 2 Wind speed – heat transfer coefficient relationship.

5 EFFECTIVE CANOPY AIR TEMPERATURE FOR THE HEAT EXCHANGE

In the last section, T_{canopy} is the average of all measurement points, which would represent the whole canopy. In this section, the local average temperature rather than whole canopy average is used as T_{canopy}. We tested several cases of different averaging, and evaluated the effective canopy air temperature for the heat exchange between inside and above canopy. The effective temperature, which is an average of active parts in the canopy for the roof level heat exchange, would make less scatter of $1/r_{can}$ in Fig. 2.

Figure 3 explains the averaging area for the T_{canopy}. We evaluated two types of averaging method. A) The top of averaging area is fixed and the depth is 13, 12.3, 11.5, 9.5, 7.5, 5.5, and 3.5 m. These temperatures should be effective temperature when the lower part of canopy does not influence on the roof level heat exchange. B) The bottom is fixed and the height is 11.5, 9.5, 7.5, 5.5, 3.5, 1.5, and 0.7 m.



(A) Fixed top (B) Fixed Bottom

Fig. 3 Schematic illustration of averaging method.

Figure 4 shows the wind speed – heat transfer coefficient relationship. Figure 4 (a) indicates that the scatter of $1/r_{can}$ is least when the depth is 13 m. On the other hand in Fig. 4 (b), the scatter does not depend on the height of averaged airmass, which means that the airmass around the canopy bottom does not affect the roof level heat exchange solely. Therefore, the effective canopy air temperature for the roof level heat exchange is an average of whole canopy airmass. The reason should be that the mechanically induced turbulence whose size is similar to the canopy depth controls the heat exchange between inside and outside of canopy. The fact that $1/r_{can}$ does not depend on a thermal stability inside canopy (figure omitted) support above idea.

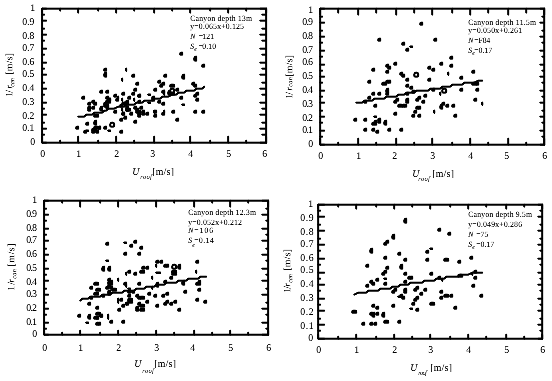


Fig. 4(a) same as Fig. 2 but for averaging area of T_{canopy}. Fixed top case.

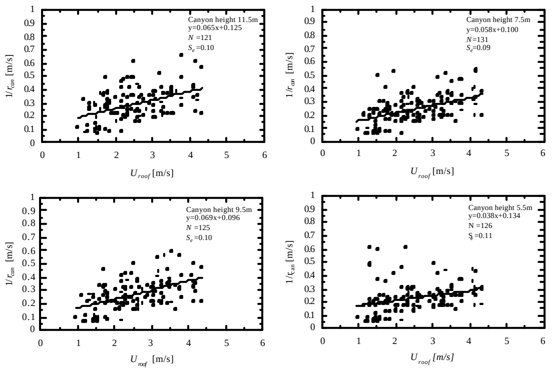


Fig. 4 (b) Fixed bottom case.

6 SYNOPTIC FRONT CASE

The $1/r_{can}$ is evaluated also during a passage of synoptic cold front as well as on fine days. The methodology is same as that for fine days shown in the previous section. The reason why we analyzed such uncommon condition in urban climate study is the higher accuracy in the $1/r_{can}$ estimate. The $1/r_{can}$ error which would be caused by the spatial variation of surface temperature and wind speed was 10 % in front case, although 23 % for fine days. The error due to uncertainty of the bulk coefficient was max. 16 % in front case. On fine days it is 26%. During the front passage over urban canopy, air temperature inside canopy changes according to the vertical advection and the influence of heat flux from walls or canopy floors is not so large. Therefore, $1/r_{can}$ estimation is robust for the heat flux error on walls and canopy floors.

Figure 5 shows the result. The data on cold front passage agree well with those on fine days. As mentioned before, in our case (H_b/W = 0.22 to 0.42), airflow inside canopy is mainly caused mechanically and the thermal instability has little influence on it. Therefore, $1/r_{can}$ on fine days and in cold front passage should agree.

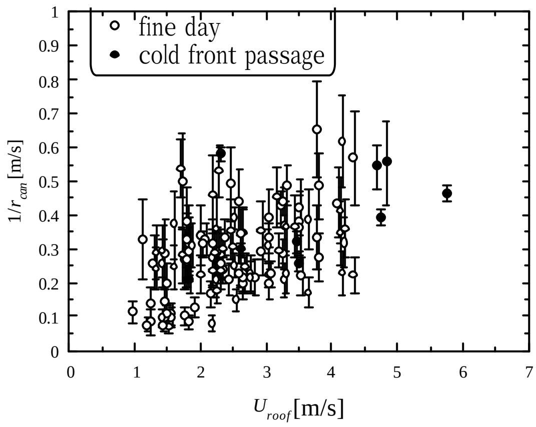


Fig.5 Wind speed – heat transfer coefficient relationship. The open circle indicates the results on fine days and closed one was data in the synoptic cold front passage.

5. CONCLUSION

We evaluated the heat transfer resistance to transport out of the urban canopy in the real outdoor buildings. The estimated heat transfer resistance r_{can} was two orders less than those at the building surfaces and it decreases according to the wind speed increase. The wind speed - transfer coefficient correlation showed that the representative canopy air temperature was average of whole canopy. The results support our idea that the mechanically induced turbulence whose size is similar to the canopy depth controls the heat exchange between inside and outside of canopy.

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