Experimental Determination of Heat Transfer Resistance in Urban Canyon Environments

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Abstract

The heat transfer resistance between a building canyon and the overlaying atmospheric boundary layer was evaluated in a long-term field observation. The recorded case is of a courtyard canyon of a university campus. The canyon has an aspect ratio of 0.22 and height of 13 m. The resulting resistance was observed to be clearly dependent on the wind speed and atmospheric stability in the range of 1.6 to 20 m^{−1}s. The random error in the measurement of resistance was estimated to be 27%; however, this does not nullify the above findings. The adequate lower-level reference temperature for the transfer parameterization was found to be the average for the entire canyon volume. This is because vortex-type airflow controls the heat transfer.

1. Introduction

Cities have grown to the point that, at present, they contain almost half of the world's population (UNFPA 2007), thereby making urban amenities inadequate. The city environment is affected by local urban warming. This poses a health hazard, for example, lack of sleep on extremely hot summer nights (Genchi and Ihara 2009). One of the causes of such extreme temperatures is the reduction in ventilation due to the geometrical features of the building canopy. However, little is known about turbulent heat transfer in a street canyon compared to the other causes of urban warming, e.g., anthropogenic heat (Ichinose et al. 1999), the lower evaporation on paved roads (Sugawara and Kondo 1995), larger heat capacity of urban canopy (Sugawara et al. 2001), and lower albedo (Aida 1982) as compared to rural areas. Here, a street canyon refers to the 3D space along a street surrounded by building walls. It is a basic approach in urban climate studies to split an urban canopy

into canyons and roof surfaces (e.g., Masson 2000; Sugawara and Narita 2009). Hereafter, we will use the term “canyon flux” to indicate the turbulent heat flux at the top of a canyon. Recent studies discuss how the canyon flux can be expressed by a numerical model. Canyon flux is often parameterized using transfer resistance r (Harman et al. 2004),

$$\frac{H}{c_p \rho} = \frac{\Delta T}{r}, \quad (1)$$

where H is the heat flux resulting from the temperature difference, ΔT , between the two heights. Note that this expression is commonly used for scalar transfers, but is slightly different from those in Kondo (1994, 1975). The value of r had not previously been determined in a real urban area; therefore, in this study it was evaluated experimentally.

In previous studies on urban canopy models (e.g., Kusaka et al. 2001; Masson 2000) r was acquired by integrating the universal function of the Monin–Obukhov similarity theory (hereafter referred to as MOS). However, many experimental studies have pointed out that MOS does not seem to hold its original form in an urban boundary layer (Feigenwinter et al. 1999; Moriwaki and Kanda 2006), especially in the canopy layer below the roof level. In other studies (e.g., Kondo and Liu 1998)

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r was evaluated using the mixing length theory, which was originally established for a vegetation canopy. Its application to cities might be problematic. An urban canopy layer has different airflow features than a forest canopy. There is vortex-type airflow in an urban canyon, hereafter referred to as a canyon vortex, whose size is equivalent to the building height (Eliasson et al. 2006; Sugawara et al. 2008). This canyon vortex is an important feature in an urban canopy and it can rarely be observed in a vegetation canopy. The canyon vortex possibly influences the heat transfer between canyon and upper air as it does the pollutant transfer (Baik and Kim 2002).

To determine r , we need to measure the heat flux. Measuring the canyon flux is technically difficult. There are two difficulties. First, we must give serious attention to safety because the canyon is a public space. Under Japanese regulations, it is almost impossible to install a platform tower as in Eliasson et al. (2006). We have to look for an alternative technique in an actual city, where it is not possible to install our instruments at the exact location. Even if we could install our instruments anywhere we wanted, there is a second difficulty involving the measurement principle for the canyon flux. As defined before, the canyon flux is the heat flux at the top of the canyon. Although the eddy covariance technique is the most reliable way to measure turbulent heat flux, a canyon vortex keeps its location and avoids this technique. A sonic anemometer could measure only its upward or downward flow. The turbulent motion at the top of the canyon does not satisfy the condition $= 0$, which is a major premise of the eddy covariance method. Even the coordinate rotation method (McMillen 1988) is ineffective because the sonic anemometer should be located in a certain part of the canyon vortex. The scintillation technique (Roth et al. 2006) can be used to measure the area-averaged flux; however, it relies on MOS. Some previous studies have tried to measure the heat flux by measuring the vertical velocity (Nakamura and Oke 1988) or analyzing the heat budget of a canyon volume (Yoshida et al. 1990).

This study used budget analysis and acquired the canyon heat flux as a residual. The biggest problem in this budget analysis was the horizontal advection. The horizontal gradient of the temperature is so minute that it could not be measured with sufficient accuracy. The heterogeneous distribution of temperature in an urban canopy (Narita 1997) also makes advection measurement difficult. To overcome this difficulty, we made our observations in a courtyard that was completely surrounded by building walls. Such a courtyard is a common structure in European cities. In addition,

Fig. 1. Schematic of heat flow in the courtyard canyon. The positive heat flux was transferred from the surface to the airmass or from the canyon to the upper air.

a Japanese urban canyon often has a dead end or T-junction; therefore, the ventilation might be similar to that in a courtyard.

The following section introduces the methodology for our observation and an evaluation of the transfer resistance. It also includes an error evaluation. The third section discusses the results. The fourth section compares our results to those obtained in previous studies. A physical inspection of the canopy heat transfer is also discussed. The fifth section concludes our study.

2. Methodology

2.1 Theory

Figure 1 is a schematic of the heat flow in an inner courtyard canyon. The heat budget for the canyon air-mass is:

$$Q = H_{\text{wall}}S_{\text{wall}} + H_{\text{window}}S_{\text{window}} + H_{\text{ground}}S_{\text{ground}} - H_{\text{top}}S_{\text{top}}, \quad (2)$$

where H is the sensible heat flux, S is the surface area, and Q is the heat stored in the air-mass. The subscripts denote the positions of measured quantities. Ground refers to the bottom of the canyon. H_{top} is the canyon flux, or heat flux at the roof level. Eq. (2) does not include the horizontal advection term because an inner courtyard is completely surrounded by building walls. The radiative cooling and heating of the air-mass is neglected because of its small volume. The heat flux at the roof level, H_{top} , is determined as a residual of the budget. On the other hand, the canyon flux can be expressed by the heat transfer resistance, r_{can} ,

$$H_{\text{top}} = c_p \rho (1/r_{\text{can}})(T_{\text{canyon}} - T_{\text{roof}}). \quad (3)$$

T_{canyon} and T_{roof} are the air temperature inside the canyon and above the roof level, respectively. From

Fig. 2. Instrument arrangement. The right side of the picture is north.

Eq. (2) and (3), we obtain the following equation:

$$r_{\text{can}} = \frac{c_p \rho (T_{\text{canyon}} - T_{\text{roof}}) \times S_{\text{top}}}{-Q + H_{\text{ground}} S_{\text{ground}} + H_{\text{window}} S_{\text{window}} + H_{\text{wall}} S_{\text{wall}}} \quad (4)$$

The stored heat, Q , is evaluated using the following:

$$Q = c_p \rho V \frac{dT_{\text{canyon}}}{dt} \quad (5)$$

dT_{canyon}/dt is the heating (or cooling) rate of the airmass. V is the volume of the canyon airmass. The surface sensible heat fluxes, H_{wall} , H_{window} , and H_{ground} were evaluated from the temperature difference between the surface (T_s) and air (T_a),

$$H = c_p \rho C_H U (T_s - T_a), \quad (6)$$

where $c_p \rho$ is the heat capacity of air, C_H is the surface heat transfer coefficient, and U is the wind speed. $C_H U$ is acquired from the parameterizations presented in previous studies, which is noted in Section 2.3. The surface sensible heat flux was evaluated separately for the sunny and shady areas of each wall and ground surface. The heat flux at a wall window was also evaluated using the measured surface temperature. The ratio of sunny and shady areas was calculated geometrically using the solar position.

2.2 Observation

The observations began in February of 2002 and continued for 8 months. A courtyard surrounded by buildings on the campus of the National Defense Academy of Japan (35.26N, 139.72E) was chosen as the observation site (Fig. 2). This courtyard has a width of 60 m (N-S,

dominant wind direction), a length of 31 m (E-W), and a height of 13 m. The vertical aspect ratio of canyon in N-S direction is 0.22. Windows occupy 29% of the wall area. The courtyard was covered with bare soil and short grass (approximately 20 cm high). There was no anthropogenic heat source in the courtyard.

The dominant wind direction at this site is north or south. Thus, the instruments were set up mainly in N-S vertical cross-section of the courtyard. This N-S cross-section could also include both sunny and shady areas. We eliminated the data in the early morning and late afternoon when the E-W thermal contrast should be large because the measured cross-section was located at the middle of the E-W axis. The air temperature was measured using 14 thermocouples inside the courtyard and four thermocouples above the roofs (Fig. 2). The thermocouples were covered by forced-ventilation shelters to prevent any undesirable heating of the sensor by solar radiation. The temperature measurement error was less than 0.2°C. The response of the thermocouple was less than 10 s. To evaluate Eq. (6), the surface temperatures of the walls and ground at the bottom of the canyon were measured using thermocouples and an IR thermometer. Four sonic anemometers measured the 3D wind speed near the walls. The wind speed was also measured above the roof and at the ground using cup anemometers. An aerovane at a 50-m tower measured wind speed. The tower was located 100 m from the observation site.

Analyses were performed for: 1) fair days with a typical diurnal variation in temperature, and 2) periods of cold front passage in which larger air temperature changes were observed. More accurate analyses were

Fig. 3. Validation of surface heat flux evaluation at the wall. Results from Eq. (6) (line) and those from budget residual Eq. (7) (mark) are shown.

possible for the cold front days compared to the fair days because of the larger dT_{canyon}/dt values. All the analyses were performed using 10 min average data for fair days and 1 min average data for cold front days. The average from the 14 points in the courtyard was used as the value of T_{canyon} in Eqs. (2) and (3).

2.3 Validation of surface heat transfer coefficient

When calculating the surface heat flux with Eq. (6), we used the parameterization of $C_H U$ given in Hagishima et al. (2001) for the walls and that given in Sugawara and Kondo (1995) for the grass-covered ground. These parameterizations express $C_H U$ as $aU + b$, where a and b are the constants. The $C_H U$ for the walls was validated by our observations as follows. As the reference for validation, the surface sensible heat flux was estimated as a residual of the surface heat budget:

$$H = R_{\text{net}} - G, \quad (7)$$

where R_{net} and G are the net radiation flux and wall storage heat flux, respectively. The latent heat flux was neglected because of the dry wall surface. R_{net} was evaluated from the measured downward shortwave and longwave radiations at the roof. Multiple reflection of shortwave radiation in the canyon was considered following Kusaka et al. (2001). Measured parameters of albedo and emissivity on the surfaces were used. The longwave radiation emitted from facing walls and the ground was considered in the R_{net} evaluation. G was measured by a heat flux plate glued to the wall. The flux evaluated by Eq. (7) and that by Eq. (6) are compared in Fig. 3. Except for a few hours in the morning and evening in which the validation is threatened by the rapid changes in the sunny and shady areas, the two flux evaluations agree well. The root mean square difference of flux during the daytime was 13 Wm^{-2} .

2.4 Error evaluation

The random error of the evaluated heat transfer resistance is as follows. From Eq. (3),

$$r_{\text{can}} = \frac{c_p \rho (T_{\text{canyon}} - T_{\text{roof}})}{H_{\text{top}}}. \quad (8)$$

The errors of H_{top} and $T_{\text{canyon}} - T_{\text{roof}}$ are random and independent of each other. Thus, the error in the measurement of r_{can} is:

$$\frac{\delta(r_{\text{can}})}{r_{\text{can}}} = \sqrt{\left(\frac{\delta(H_{\text{top}})}{H_{\text{top}}}\right)^2 + \left(\frac{\delta(T_{\text{canyon}} - T_{\text{roof}})}{T_{\text{canyon}} - T_{\text{roof}}}\right)^2}. \quad (9)$$

Here, δx indicates the random error of value x in the measurement. The error in the measurement of H_{top} is derived from Eq. (2) as follows:

$$\frac{\delta(H_{\text{top}})}{H_{\text{top}}} = \sqrt{\left(\frac{\delta H_i}{H_i}\right)^2 + \left(\frac{\delta S_i}{S_i}\right)^2 + \left(\frac{\delta S_{\text{top}}}{S_{\text{top}}}\right)^2 + \left(\frac{\delta Q}{Q}\right)^2}. \quad (10)$$

The subscript i denotes the walls, windows, and ground. We use representative values of δH_i , H_i , δS_i , and S_i rather than evaluating them for each of the surfaces. From Eq. (5), the error in the measurement of Q is:

$$\frac{\delta Q}{Q} = \sqrt{\left(\frac{\delta V}{V}\right)^2 + \left\{ \frac{\delta(dT_{\text{canyon}}/dt)}{dT_{\text{canyon}}/dt} \right\}^2}. \quad (11)$$

The heat flux error at the surfaces was evaluated in the previous section, $\delta H_i = 13 \text{ Wm}^{-2}$. Table 1 lists the evaluated errors for each term in Eq. (9), (10), and (11). These were determined based on the fluctuation of the measured values and instrument error. The time errors were negligible because the data loggers were synchronized within 1 s. The relative error in value of r_{can} is:

$$\frac{\delta r_{\text{can}}}{r_{\text{can}}} = 0.269. \quad (12)$$

Table 1. Random measurement errors.

	Average or typical	Error
$T_{\text{canyon}} - T_{\text{roof}} [^{\circ}\text{C}]$	0.5	0.05
$S_i [\text{m}^2]$	60×31	0.1×0.1
$V [\text{m}^3]$	$60 \times 31 \times 13$	$0.1 \times 0.1 \times 0.1$
dT_{canyon} in Eq. (11) [$^{\circ}\text{C}$]	0.2	0.1
$H_i [\text{Wm}^{-2}]$	60	13

Fig. 4. Example air flow pattern at vertical cross section of the canyon (12:00, May 26). Black arrows present N-E and vertical winds. These were measured by 3-D sonic anemometers. Gray arrows represent horizontal wind direction and speed estimated from 2-D wind sensor data.

3. Results

3.1 Heat flux

Figure 4 shows an example of the airflow in the canyon. A vortex-type flow pattern can be seen whose size is as large as that of the canyon. The airflow above the canyon enters it at the leeside wall, moves downward along this wall, and levels off at the ground. The flow pattern of a vortex in a canyon is also shown in Eliasson et al. (2006) and Sugawara et al. (2008). According to Oke (1987), an isolated roughness flow could be seen in such a low aspect ratio (0.22) canyon, rather than a vortex. The 3D geometry of the courtyard canyon at our site created a vortex.

Figure 5 shows the heat fluxes measured at the four walls and the ground. The canyon flux, H_{top} , is also shown. The diurnal pattern of the surface heat flux was caused by that of the incoming solar radiation. The south wall was in the shade at almost all hours and had a very small flux. The west wall had a peak in the morning, and the east wall had one in the evening. The difference in the sizes of the peaks for the west and east walls

Fig. 5. Diurnal variations on May 26: (a) transfer resistance r_{can} ; (b) surface heat fluxes, Q and H_{top} ; (c) wind direction and speed above roof level; and (d) air temperature. Canyon temperature is the average of 14 points measured in the canyon.

were due to a larger wind speed in the evening as well as the heat storage at the west wall, which suppressed a surface temperature rise in the morning.

Figure 6 compares H_{top} and vertical heat fluxes measured by the eddy covariance (EC) method. Two sonic anemometers were installed on the north and south walls at the roof level. Because the mean vertical component was not zero, the axis rotation methodology of McMillen (1988) was adopted in the EC calculation. The EC flux (H_{EC}) differed largely from the canyon flux (H_{top}) evaluated as a budget residual. H_{EC} had peculiar negative or small values, even though H_{top} showed a reasonable diurnal variation. H_{EC} at the upwind side was less than that at the downwind side, which was clearly shown by the change in the wind direction at 09:30. The sonic anemometers were set 1 m away from the walls,

Fig. 6. Diurnal variations in heat flux measured by eddy covariance method on May 26. The sonic anemometers were installed at the roof level near the north (H_{EC_N}) and south walls (H_{EC_S}). H_{can} indicates flux at the roof level evaluated from the budget.

which should have placed them partially in the wake region of the walls. The measured flux should have been influenced by eddies smaller than 1 m. The larger value of H_{top} compared to H_{EC} may indicate that the canyon flux was caused by a canyon-scale eddy that was larger than that measured by the sonic anemometers.

3.2 Transfer resistance

In Fig. 5, the evaluated heat transfer resistance, r_{can} , shows a significant variation in value. It is negative for a few hours around sunrise when the temperature difference ΔT is negative. The occasional jump in r_{can} during the daytime is possibly due to a change in wind direction. The smaller r_{can} value in the afternoon compared to that of the morning is probably caused by an increase in the wind speed. In the following discussion, we use the data for the large temperature difference during the daytime (08–17 JST), $T_{canyon} - T_{roof} > 0.2$ K. Figure 7 shows the wind speed dependency of the heat transfer efficiency, $1/r_{can}$. It increases with an increase in the wind speed, and such a change is qualitatively reasonable. From a quantitative perspective, $1/r_{can}$ is approximately one order larger than the bulk coefficient, $C_H U$, at the building surface (c.a. 0.01 m/s at a height of 13 m) owing to the absence of surface friction.

The value of r_{can} was also evaluated during the passage of a synoptic cold front in the same manner as fair

Fig. 7. Heat transfer efficiency ($1/r_{can}$) and its dependence on roof level wind speed. Fair day results (open circle) were filtered for time (09 to 17 LST) and temperature gradient ($T_{canyon} - T_{roof} > 0.2$ K). Results for cold front passage are indicated by filled circles (no rain during passage) and half filled circles (passage with rainfall).

days. A total of 9 front passage cases were analyzed. The values of r_{can} during the passage of fronts agreed well with those for fair days (Fig. 7). Note that the budget analysis under rainy conditions might be problematic because we could not consider heat conduction between the raindrops and walls. Figure 8 shows an example of the temperature change in the canyon during a front passage. During the passage of a front, the wind direction at the roof level was 330° , or almost perpendicular to the canyon. A time series shows that the temperature at the windward side (south) started to decrease, following that at the leeward side to recover. The delay time between the upper and lower positions reveals that the time scale for mixing the cold air that intruded into the canyon from above was less than one minute. The contour plots should make it easier to understand the upper air intrusion. A cold air mass moves into the canyon from above near the windward wall, and then progresses across the bottom to the leeward side. This downward intrusion flow is most likely thermally accelerated. In a similar manner, the sun-heated wall accelerates the upward flow on a fair day (Kovar-Panskus et al. 2002). This thermal acceleration should contribute to the agreement between the values of r_{can} for the cold front passage case and those for fair days.

A warm front passage may produce a different value

Fig. 8. Air temperature time series and distribution in canyon cross-section during cold front passage on April 9, 2002. (a) Contour plot for temperature distribution at cross-section of canyon (hatched area in the schematic illustration). (b) Time series of temperature. S and N in the legend indicate measurement locations on the south and north sides of the canyon, respectively. The number following is height in meter above ground.

of r_{can} , perhaps larger, because of the negative buoyancy of the warmer downward flow. However, there were no warm front events in our observations. Therefore, we show the dependence of r_{can} on the atmospheric stability (Fig. 9). These data were acquired on fair days, including nights. The bulk Richardson number, R_b , was eval-

uated using just the surface temperature of the ground with no walls included. The value of r_{can} increased as the atmosphere became more stable. A weaker dependency of r_{can} on R_b was observed for unstable conditions.

Fig. 9. Dependence of transfer resistance (r_{can}) on atmospheric stability (bulk Richardson number, R_b).

4. Discussion

4.1 Effective canopy air temperature for heat transfer parameterization

We discuss a problem related to the heat exchange at the roof level. How can the aerodynamic surface temperature, T_0 , be observed for a real canopy? The MOS theory introduces the T_0 at a height of $d + z_T$ by extrapolating the temperature profile above the canopy layer, where d is the displacement height and z_T is the roughness length for heat. However, in a real canopy, the temperature at $d + z_T$ is not equal to T_0 .

It causes a problem when we compare the numerical model results and observations. Single-layer canopy models (e.g., Kusaka et al. 2001; Masson 2000) output T_0 as the representative air temperature for the canopy. With no bases, we have chosen the surface measurement

at 1.5 m above the ground and validated the model output with it. This is a fragile method of validation under the thermal heterogeneity found in cities. The air temperature in a canopy differs greatly from place to place. Sugawara et al. (2008) showed a 1 to 2 K vertical difference in air temperature in an urban canyon. A maximum horizontal difference of 2 K was seen between N-S and E-W oriented canyons (Narita 1998).

In such a heterogeneous temperature field, what temperature gradient drives the heat exchange between the inside of the canyon and above it? Is there any possibility that the upper part of the canyon adjacent to the outer air makes the main contribution to the heat exchange? To determine the effective canopy air temperature for this heat exchange, we tested the local average value for T_{canyon} . Only the air temperature data from certain layers were averaged, although the T_{canyon} values in Figs. 5–9 are averages of all the measurement points in the canyon.

Figure 10 illustrates the averaging area for T_{canyon} . T_{canyon} is an average for the upper part of the canyon in the fixed-top case shown in Fig. 10a, and that of the lower part of the canyon for the fixed bottom case in Fig. 10b. The depth (d_c) and height (h_c) values represent the averaged layer. Seven cases were taken for the fixed top, with depths of 13, 12.3, 11.5, 9.5, 7.5, 5.5, and 3.5 m. For the fixed bottom, the height was 11.5, 9.5, 7.5, 5.5, 3.5, 1.5, or 0.7 m. The heat transfer efficiency, $1/r_{\text{can}}$, was plotted against the wind speed at the roof level. $1/r_{\text{can}}$ should be proportional to the wind speed, and an inadequate T_{canyon} would cause a large scatter in the graph. The root mean square error of the fitting (RMSE) is used to discuss the relevance of each case. Note that $1/r_{\text{can}}$ can depend also on the atmospheric stability. Data from unstable atmosphere were used here, as noted in Section 3.2, and $1/r_{\text{can}}$ does not strongly depend on the stability in the unstable condi-

Fig. 10. Schematic of averaging area. Filled and open circles indicate temperature measurement points. Gray area is the averaging area for temperature.

Fig. 11. Wind speed dependency of $1/r_{can}$ with different averaging areas for canyon air temperature, T_{canyon} , for fixed-top case.

Fig. 12. Variation in RMSE due to canyon depth (left panel) or height (right panel) change.

tion in Fig. 9. Thus we can expect proportionality for the wind speed.

Figure 11 shows the relationship between the roof level wind, U_{roof} , and $1/r_{can}$. The error of the linear fitting is shown at the top of each panel. The surplus data in the panels are the result of quality control of $T_{roof} - T_{canyon} > 0.2$ K. A linear relationship can be found most clearly at $d_c = 13$ m, in which T_{canyon} is an average of the entire layer in the canyon. Figure 12 summarizes the RMSE values for the linear fitting. In addition, in the fixed bottom case, the minimum RMSE is for the average of the entire layer ($h_c = 12$ m). Therefore, the average temperature of the entire layer was found to be the best representative canyon temperature in the heat transfer parameterization.

The RMSE variation in Fig. 12 indicates the effec-

tiveness of each layer. The RMSE quickly drops at $d_c > 12$ m in the fixed top case, suggesting that the bottom layers of the lowest 2 m influence the canyon heat transfer more than the upper layers. This can be understood from the airflow pattern (Fig. 4). The canyon vortex causes a direct interaction between the upper air and canyon bottom. It introduces outer air into the canyon bottom layer, and also takes the bottom air out of the canyon. However, this bottom layer cannot sufficiently represent the heat transfer. This can be seen from the decreases in the RMSE according to increases in h_c in the fixed bottom case.

In addition to the airflow pattern, the superiority of the bottom layer in canopy heat transfer can also be understood by the temperature profile (Fig. 13). The bottom layer has a higher temperature due to the sun-heated

Fig. 13. Temperature profile during daytime for three fair days. Vertical broken line shows the average temperature (23.6°C) below the roof level.

ground surface. This warm air is possibly transported out of the canyon by the canyon vortex. Therefore, the representative temperature for the canopy heat transfer should include this warm layer. The homogeneous temperature profile for the middle and upper layers below the roof level causes the nearly constant RMSE at $d_c < 12$ m, as seen in Fig. 12. This thermally homogeneous layer might be maintained by turbulent mixing.

4.2 Comparison with previous studies

The values for r_{can} were compared to those from previous studies. Harman et al. (2004), hereafter referred to as H04, introduced the scalar transfer resistance in the free shear layer. We will call this r_H ,

$$r_H = \frac{\Delta U}{u_*}, \quad (13)$$

where ΔU is the wind speed difference between two levels around the roof level and u_* is the friction velocity. Although H04 used u_* values acquired above the roof, we used u_* values measured at the roof level because we could not measure u_* above the roof. Two sonic anemometers were set in the vicinities of the north and south walls (see Fig. 2). Thus, the r_H values from the northern and southern u_* were denoted as r_{HN} and r_{HS} , respectively. Here, in our evaluation, u_* includes a lateral component (Rotach et al. 1993),

$$u_* = \sqrt{\sqrt{u'w'^2 + v'w'^2}}. \quad (14)$$

Fig. 15. Comparison of transfer efficiencies: r_{YS} represents that in Yang and Shao (2006) and r_{DS} that in DePaul and Sheih (1985).

u' , v' , and w' are the turbulent component of 3D wind. For ΔU we used wind speed difference between above roof and canyon bottom. The diurnal variation of r_H and r_{can} is shown in Fig. 14. The wind direction above the roof is simplistically shown in the top panel, the details of which were shown in Fig. 5. Basically, r_H agrees with r_{can} for its time variation and absolute value. The sharp difference from approximately 8:00 to 10:00 should be due to an improper r_{can} , which would have been caused by a variation in the wind direction. Among the two values of r_H , the leeward one is larger due to the smaller u_* value for the leeward wall. A smaller u_* at the leeward wall was also reported by Eliasson et al. (2006). Regardless of which u_* is used, r_H is larger than r_{can} for the south wind. There are two possibilities for low r_H . First, r_H expresses a small scale local transfer owing to the use of the local u_* . On the other hand, r_{can} relates to the vertical motion of the canyon vortex, which is much larger than the local u_* . Second, ΔU depends on the levels where it is defined. Our trial with ΔU between above roof and canyon bottom may not be adequate. Therefore, the key point in the H04 parameterization is how to acquire an adequate u_* and ΔU for an urban canyon.

The second study we discuss is that of Yang and Shao (2006). They showed the transfer resistance between a canyon recirculation region and the inertial layer above

Fig. 14. Comparison of r_{can} and r_{HN} and r_{HS} , transfer resistances by Harman et al. (2004). r_{HN} and r_{HS} were evaluated using friction velocities near north and south walls, respectively.

Fig. 16. Schematic of canopy heat transfer and its reference levels.

it. We call this transfer resistance r_{YS} .

$$r_{\text{YS}} = \frac{1}{ku_{*a}} \ln \left(\frac{z_{\text{ref}}}{z_c} \right) \quad (15)$$

where z_{ref} and z_c are the upper and lower reference heights, respectively, where the scalar concentration is defined in the flux parameterization. z_{ref} was set as the measurement height for the temperature and wind above the roof ($1.2 z_b$). Although Yang and Shao (2006) suggested that z_c would be $0.2 z_b$ based on their trial calculation, we also tried $0.5 z_b$ because we used the averaged temperature value for the entire canyon layer. u_{*a} is the friction velocity of the canyon air, which can be evaluated using the drag partitioning methodology (Yang and Shao 2006). In our u_{*a} evaluation, $0.7 z_b$ was adopted for the zero plain displacement height and wind speed at the 50-m tower was used. A neutral stability atmosphere was employed for the analysis. A comparison

of r_{YS} and r_{can} is shown in Fig. 15. Unfortunately, our tower aerovane was not synchronized with the canyon measurement. Thus, we will discuss the wind speed dependency of these transfer resistances. In Fig. 15, the slant hatched area between the two broken lines indicates r_{YS} with $z_c = 0.2 z_b$. The horizontally hatched area represents $0.5 z_b$ and includes some overlap with that of $0.2 z_b$. Although there is a large scatter in r_{can} (filled circles), r_{YS} with $0.2 z_b$ seems to agree better with r_{can} . The adequacy of $0.2 z_b$ is a result of the lower reference height agreeing well with the conclusion of the previous Section (4.1). From these analyses, one tentative conclusion can be established: the lower reference height for canopy transfer is possibly located between 0.2 and $0.3 z_b$. The two items illustrated in Fig. 16 support this idea. First, the heat is transferred by the canyon vortex (Fig. 4). This vortex transfer process can be expressed by the scalar gradient between the top and bottom of the vortex (Fig. 16a). Second, warmer air exists at the bottom of canyon (Fig. 13) during the daytime. This layer is possibly a heat source, and its temperature should be included in the transfer parameterization (Fig. 16b).

The transfer resistance of pollutants in cities has been discussed in many previous studies (e.g., Depaul and Sheih 1985; Lee and Park 1994). As a third comparison, we discuss the ventilation velocity of pollutants, V_V (DePaul and Sheih 1985, hereafter DS85). Pollutant flux F is expressed by V_V in the study conducted by DS85 as given below:

$$F = V_V (C_c - C_a), \quad (16)$$

where C is the concentration, and the subscripts c and a represent the canyon and ambient air, respectively. Assuming an analogy between pollutants and temperature,

Fig. 17. Standard deviation of surface temperature (26 May 2002)

we get the following expression:

$$\frac{1}{r_{\text{can}}} = V_V. \quad (17)$$

Figure 15 compares $1/r_{\text{can}}$ and V_V in DS85. DS85 determined V_V by measuring the SF_6 concentration in a street canyon with an aspect ratio $z_b/W = 1.5$ and with a wind direction perpendicular to the canyon. V_V was determined from the retention time of concentration at canyon bottom. Thus their V_V should represent ventilation between the levels of canyon bottom and above canyon. Although their canyon was much narrower ($z_b/W = 0.2$) and had a different structure (street versus courtyard) than ours, the results agree well.

To discuss the influence of the canyon structure on the transfer coefficient, we next refer to Lee and Park (1994, hereafter LP94). LP94 developed a numerical model with k-ε turbulent parameterization for the concentration distribution in a 2D canyon. They evaluated the retention time, τ , which was related to V_V , as,

$$\tau = \frac{z_b}{V_V}. \quad (18)$$

LP94 presented the results for different canyon aspect ratios and different ambient winds. LP94 recorded a retention time of 23 s at $z_b/W = 0.3$ for an ambient wind speed of 5 ms^{-1} . The results of our observation showed a retention time of 26 s for 5 ms^{-1} , which agrees well with the results obtained by LP94. On the other hand, LP94 recorded a larger τ for a narrower canyon; for example, $\tau = 197 \text{ s}$ at $z_b/W = 1.5$. Their results seemed to be more sensitive to the change in z_b/W compared to ours and those obtained by DS85. Because their simulation was two dimensional, it might have overestimated the dependence of τ on the canopy geometrical structure.

Finally, a comparison with previous studies is discussed in terms of the mixing length (L_m). Watanabe and Kondo (1990) presented a parameterization of mixing length,

$$L_m = 2k^3 \frac{1}{ca} \left\{ 1 - \exp\left(-kca \frac{z}{2k^3}\right) \right\} \quad (19)$$

where k is the Karman constant, c is the drag constant (0.1) and a is a parameter of canopy packing. With the a calculated by a procedure in Kondo and Liu (1998), L_m was evaluated at various heights; 1.0 m at $0.2z_b$, 2.6 m at $0.5z_b$, and 5.2 m at z_b . Also, r_{can} was converted to L_m from

$$r_{\text{can}} = \int K^{-1} dz = \int L_m^2 \left| \frac{\partial U}{\partial z} \right|^{-1} dz. \quad (20)$$

K is the turbulent diffusion coefficient. We could not obtain a wind speed profile in the canyon from the observations, thus only the vertically-averaged mixing length could be acquired. Given the lower reference height is $0.2z_b$ for the integral in Eq. (20), the mixing length for our site is evaluated as 2 to 3 m. This is roughly equal to, or a little less than the estimation from Eq. (19) shown above.

4.3 Heat transfer between canyon and outer layer: advection or diffusion?

There are two processes in the scalar transfer between a canyon and the layer above it: turbulent transfer at the roof level and advection owing to the canyon vortex. Previous studies have raised a controversy over which is the major process for the scalar transfer. A good summary of this argument can be found in the work of Baik and Kim (2002). They performed a numerical experiment and concluded that diffusion was dominant, rather

than advection. Although any conclusion must depend on the canyon aspect ratio, in our case ($z_b/W = 0.2$) advection seemed to be dominant. One of the two bases for the predominance of advection is already shown in Fig. 12. The advection controls the canyon transfer, and thus the reference level is at the lower part of the canyon. Another basis is that the $1/r_{\text{can}}$ during a cold front passage has a value similar to those on fair days (Fig. 7). This could possibly mean that the transfer processes during these situations is similar. As shown in Fig. 9, during a cold front passage, advection from above the canyon would transfer the heat and determine the temperature distribution.

4.4 Spatial heterogeneity of surface temperature

The surface sensible heat flux was evaluated using Eq. (6) separately for the sunny and shady areas of each wall and ground surface. Although the surface temperatures do not have homogeneous distribution, instrument limitation forced us to measure temperature at one point for each. If spatial heterogeneity of temperature in the canyon had been significant, it might nullify our results. Here, we show thermal homogeneity and its influence on $1/r_{\text{can}}$ evaluation. We checked the spatial anomalies in surface temperature utilizing an infrared camera. The infrared camera (AVIO TVS-610) acquired thermal images of wall, window, and ground once an hour. Figure 17 shows the standard deviation of temperature on each surface on a fine day (26 May 2002). Shady areas could not be measured in daytime due to the limited view field of the camera. By filling the lack of shady area values with an average in nighttime, influence of surface temperature heterogeneity on $1/r_{\text{can}}$ was evaluated from Eq. (6) and (9)–(11). It was 24% on 26 May, and 10% on another cloudy day (9 April 2002).

The evaluation above is rough. Variation of surface temperature does not solely give influence on the surface heat flux, but it does in combination with air temperature as shown in Eq. (6). In addition, we had the infrared camera measurements available for only a few days. Therefore the evaluation above was not included in Section 2.4.

Figure 17 Standard deviation of surface temperature (26 May 2002).

5. Conclusion

With the goal of clarifying the heat transfer process in an urban canopy layer, the heat budget was observed in a courtyard canyon. The structure of this courtyard enabled us to evaluate the heat budget precisely and avoid any uncertain evaluation of horizontal advection. The height and aspect ratio of the canyon were 13 m and

0.22, respectively. Intensive observations were carried out from Feb. to Sep. 2002. In addition to fair days with typical diurnal variations, the heat transfer during the passage of cold fronts was also acquired.

A vortex-like airflow pattern was seen in the canyon. The air temperature distribution in the canyon also showed a vortex pattern when a cold front passed over the canyon, in which the outer cold air moved into and dispersed within the canyon. This vortex airflow controlled the heat transfer between the canyon air and the outer air above it. Therefore, the sensible heat flux at the top of the canyon, which was evaluated as a budget residual, was much larger than the local eddy-covariance flux at the top of the canyon.

Based on the observed data, we evaluated the heat transfer resistance between the canyon air and the overlying urban boundary layer. The transfer resistance in a real urban canyon was determined in few previous studies, even though it is a fundamental parameter for describing the urban heat island phenomena. The resulting transfer resistance was a clearly dependent on the wind speed and atmospheric stability in the range of 1.6 to 20 m^{-1}s . These dependencies were considered valid even with the 27% random error in measurement found during the evaluation. The transfer resistances evaluated on fair days and those experiencing the passage of a cold front agreed quite well. This was possibly due to similar processes of cold air intrusion, since a vertical advection into the canyon would control the heat transfer between the canyon and the air above it.

The resulting resistance values agreed well with those of pollutant transfer values obtained from previous studies. Our results also agreed with the theoretical evaluation of the resistance values measured by Yang and Shao (2006) given a lower reference height of $0.2z_b$, where z_b is the canyon height. A reference height of $0.2z_b$ is reasonable, considering the airflow pattern of the canyon vortex and the air temperature distribution. Through calculations with various reference temperatures, the average for the entire canyon volume was also shown to be an adequate lower reference temperature for the transfer parameterization. This would be because the canyon vortex, whose size is similar to the canyon height, controls the transfer. More often than not, the average temperature appeared at $0.2z_b$. This is possibly the reason that the reference height of $0.2z_b$ supports the agreement of our results with those of Yang and Shao (2006). As shown in previous studies, the flow pattern in an urban canyon depends heavily on the canyon aspect ratio. The findings here may also depend on the canyon structure.

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