INVESTIGATION ON TRANSFER COEFFICIENT FOR VARIOUS GEOMETRIC TYPES OF URBAN-LIKE ROUGHNESS BASED ON THE SALINITY METHOD

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Abstract

The authors performed systematic series of wind tunnel experiments to grasp how urban geometry affects on the scalar transfer process in urban areas. Scalar transfer coefficient ($C_E$) represented several street blocks for various types of 3D urban-like roughness was intensively measured using the salinity method. The series of experiments mainly focused on the major three points. Regarding the first point, the effect of scalar source size on $C_E$, the so-called scale effect was discussed for both square and staggered arrays. Secondly, we estimated the effect of vertical turbulence generated by obstacles on $C_E$. The last one is to investigate how “horizontal randomness” of roughness allocation affects on $C_E$.

1 INTRODUCTION

Urban geometry strongly affects on dispersion in urban areas. Hence the authors have performed several series of wind tunnel experiments to grasp the morphological effect on the scalar transfer rate, namely scalar transfer coefficient (hereafter $C_E$) using regular arrays consist of rectangular blocks with various conditions of packing density, layout and height variability on a basis of salinity method. The previous our results were summarized as follows; 1) $C_E$s of square arrays decreased with the increase of plan area density $\lambda_p$, 2) $C_E$s of staggered arrays increased under sparse conditions but decreased under dense conditions, 3) $C_E$s of arrays with non-uniform height of obstacle were smaller than those of uniform arrays for a range of $\lambda_p$ below 17.4%, and for $\lambda_p=30.9\%$, $C_E$s of arrays with non-uniform height were larger than those of uniform array. In this measurement, we used the same size of scalar source. However several researchers pointed out that the scalar transfer rate of urban surface is strongly affected by the size of scalar source, e.g. Barlow et al. 2004, and Narita 2007. Under these circumstances, we focus on the effect of scalar source size on $C_E$ in this paper. Scale effect is discussed for both square and staggered arrays with three different conditions of source size. In addition, we discuss how both vertical turbulence generated by obstacles and horizontal advection affect on the scalar transfer process based on the comparison between square array and staggered array. Moreover we investigate the effect of ‘geometrical randomness’ of arrays. The flow over uniform array has been studied by a number of researchers, and some works focus on the effect of height variation of obstacles. However, horizontally random arrays have not been well investigated. Therefore we measured $C_E$s of arrays with “horizontal randomness”, where ‘random arrays’ was defined as uniform rectangular blocks arrayed with random rotation angles.

2 EXPERIMENTAL SET-UP

2.1. Wind tunnel

The experiment was performed in the open-circuit wind tunnel as shown in Figure 1. The test section is a water tank of 720 mm wide, 720 mm long and 50 mm depth, which is mounted in a square cavity of the floor of the wind tunnel, as shown in Figure 2. The free stream velocity in the wind tunnel is about 2 ms$^{-1}$. The fetch is 130 times as long as the obstacle to generate the appropriate boundary layer above the test section.
2.2. Rough surfaces

The obstacles were wooden cubes of 25mm and two types of rectangular blocks with the size of $25 \times 25 \times 37.5$ mm and $25 \times 25 \times 75$ mm, hereafter we call the length 25 mm as L. As indicated in table 1, six types of the arrays were used for measurement at three different conditions of $\lambda_p$, i.e. $\lambda_p = 7.7\%$, $17.4\%$, and $30.9\%$.

To confirm the scale effect of wet source, we performed the additional measurement of $C\varepsilon$ using wet filter papers with the same dimension of test section. By arranging them on the upstream floor in front of water tank, we generated additional two cases of source sizes with two times and three times of the test section.

The staggered array of obstacles rotated randomly (hereafter R1) was used to investigate the horizontal randomness. The rotation angles of each obstacles were defined based on random numbers with the range from $-22.5^\circ$ to $22.5^\circ$ and its average was $-0.625^\circ$.

<table>
<thead>
<tr>
<th>Name</th>
<th>Layout of obstacle</th>
<th>Remarks (dimension of obstacle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sq1</td>
<td>Square</td>
<td>Cubical arrays ($L \times L \times L$)</td>
</tr>
<tr>
<td>St1</td>
<td>Staggered</td>
<td>Uniform arrays with tall rectangular blocks ($L \times L \times 1.5L$)</td>
</tr>
<tr>
<td>St1.5-Sq</td>
<td>Staggered, square for tall blocks</td>
<td>3:1 combination of cubes ($L \times L \times L$) and tall rectangular blocks ($L \times L$ x 3L). Standard division of heights is 0.87</td>
</tr>
<tr>
<td>St1.5-St</td>
<td>Staggered, staggered for tall blocks</td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>Staggered, individual obstacle rotate random angles</td>
<td>Cubical arrays ($L \times L \times L$)</td>
</tr>
</tbody>
</table>

2.3. Measuring method

Salinity method was used to measure scalar transfer rate. Test section filled with salt water, exposed to constant air flow for two hours. During the exposure, dew-point temperature, air temperature, water surface temperature and wind speed were measured. The total scalar flux from the water surface $E$ was obtained using measured salinity of the salt water before and after the exposure based on the following equation

$$E = \frac{\rho_{water} \cdot V}{\Delta t \cdot A} \left( S_b S_a - 1 \right),$$

(1)

Where $\rho_{water}$ [kgm$^{-3}$] is water density, $V$ [m$^3$] is volume of test section, $\Delta t$ [s] is exposure period, $A$ [m$^2$] is test section area, $S_b$ [psu] and $S_a$ [psu] are salinities of the salt water before and after the exposure.

Scalar transfer coefficient $C\varepsilon$ is represented as nondimensional number:

$$C\varepsilon = \frac{E}{\Delta X \cdot \rho_{air} \cdot U_{ref}}.$$  

(2)

$\Delta X$ [kg/kg] is difference of the absolute humidity between water surface and main stream air at a referential height, $\rho_{air}$ is the density of air and $U_{ref}$ is the reference wind speed. In this paper, we defined the referential height as 20L high, which is well above the boundary layer.

The referential wind speed was measured by a pitot tube connected to a differential pressure sensor. Wind speeds within boundary layer were also measured by a hot-wire anemometer.
3 RESULTS AND DISCUSSION

3.1 The effects of source size

Figure 3 shows $C_E$s for different source area as a function of $\lambda_p$. $C_E$ of the all arrays decreases with the increase of scalar source area, which caused by the development of a boundary layer for vapor. And the discrepancy of $C_E$ between triple (hereafter $C_{E3}$) and double source area (hereafter $C_{E2}$) is smaller than that between double and single (hereafter $C_{E1}$).

Figure 4 indicates $C_E$s normalised by $C_{E1}$. The decreasing rates $C_{Ei}/C_{E1}$ are greater than those of $C_{Ei}/C_{E1}$ for both staggered and square layouts, and the decreasing rates of Sq1 and St1 are approximately equal even though different $\lambda_p$s. It implies that the development rate of a boundary layer for scalar above rough surfaces is not sensitive to the geometry of arrays. Also it indicates that the tendency of $C_E$ for arrays with various conditions in terms of layout and $\lambda_p$ under a single source area is somewhat universal even if a different source size is deployed.

3.2 The effects of vertical turbulence on $C_E$

It is assumed that scalar transfer of rough surfaces strongly depends on both mean wind reduction near surface due to surface drag and vertical turbulence mixing caused by vortex around obstacles. The former will decrease $C_E$, in contrast the latter will encourage the transfer. We investigate the relation between geometry of arrays and effect of vertical turbulence on $C_E$ by comparing with different referential heights for $U_{1.5L}$, $U_{2.5L}$ and $U_{20L}$ as the default setting.

Figure 5 shows the results from $C_{Ei}$ based on $U_{1.5L}$ and $U_{2.5L}$. In comparison of $C_{Ei}$ between Sq1 and St1 (show in Figure 5 (a) and (b)), $C_{Ei}$ of Sq1 are almost constant for different $\lambda_p$ conditions even though referential height was changed. On the other hand, $C_{Ei}$ of St1 increase with the decrease of reference height at $\lambda_p = 17.4\%$. This might be caused by the fact that vertical turbulence was active in vicinity of the surface of staggered array at $\lambda_p = 17.4\%$. In the same way, $C_{Ei}$ of St1.5-Sq and St1.5-St with non-uniform height (show in Figure 5 (c) and (d)) are observed to be greater than $C_{Ei}$ of St1.5 with uniform height over the $\lambda_p$ when referential height was near the floor. It indicates that vertical turbulence is more active in an array with non-uniform height compared with arrays with uniform height.
3.3 CE of the arrays of blocks with random rotation angle

Figure 6 shows CE of St1, St1.5, and R1 for various frontal area density λf. Three types of the arrays show almost consistent tendency against λf. CE gradually increase when λf is less than 17.4%, but decrease under the dense conditions. Considering the fact that the layout of R1 is staggered, the effect of layout of arrays is more dominant in CE than that of random rotation of individual obstacle. And the effect on CE by obstacles randomly rotated can be estimated fairly by consideration for frontal projected area of obstacles.

4. CONCLUSIONS

This study focused on the effects of scalar source size, vertical turbulence, and geometrical randomness of arrays on the scalar transfer rate based on the wind tunnel experiments. The conclusions were summarized as follows:

1) The scale effects for CE of cubical arrays of square and staggered with different λp condition were almost same, thus it would seem that development rate of scalar boundary layer is impervious to geometry of arrays.

2) Increase of CE due to the lower height of referential wind speed was remarkable for the cubical staggered array compared with the square array under the condition of λp=17.4%, and the array with non-uniform height showed the similar tendency comparing the uniform arrays. It indicates that vertical turbulence was more active in the vicinity of obstacles of these arrays.

3) The layout of array with uniform height is a dominant factor of CEs even if the obstacles are individually rotated in a random manner. In addition, relation between CE and λf is universal for staggered arrays with uniform height.

References
