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_Es of square arrays decreased with the increase of plan area density λ_p, 2) C_Es of staggered arrays increased under sparse conditions but decreased under dense conditions, 3) C_Es of arrays with non-uniform height of obstacle were smaller than those of uniform arrays for a range of λ_p below 17.4%, and for λ_p=30.9%, C_Es 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_Es 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.

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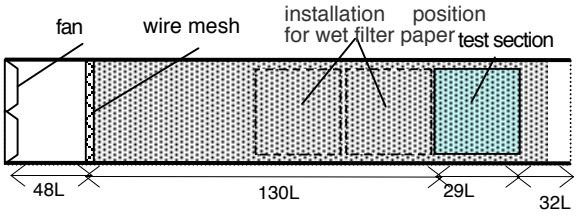


Figure 1 Schematic plan view of open-circuit wind tunnel

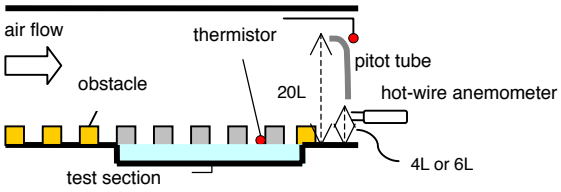


Figure 2 Sketch of test section

2.2. Rough surfaces

The obstacles were wooden cubes of 25mm and two types of rectangular blocks with the size of 25×25×37.5 mm and 25×25×75 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 λ_p i.e. λ_p = 7.7%, 17.4%,and 30.9%.

To confirm the scale effect of wet source, we performed the additional measurement of C_E using wet filter papers with the same dimension of test section. By arranging them on the upstram 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° to 22.5° and its average was -0.625°.

Table 1 arrays used for measurement

Name	Layout of obstacle	Remarks (dimension of obstacle)
Sq1	Square	Cubical arrays (L × L × L)
St1	Staggered	
St1.5		Uniform arrays with tall rectangular blocks (L × L × 1.5L)
St1.5-Sq	Staggered for all blocks, square for tall blocks	3:1 combination of cubes (L × L × L) and tall rectangular blocks (L × L × 3L). Standard division of heights is 0.87
St1.5-St	Staggered for all blocks, staggered for tall blocks	
R1	Staggered, :individual obstacle rotate random angles	Cubical arrays (L × L × L)

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

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

Where ρ_{water} [kgm^{-3}] is water density, V [m^3] is volume of test section, Δt [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_E is represented as nondimensional number:

$$C_E = \frac{E}{\Delta X \cdot \rho_{air} \cdot U_{ref}}. \quad (2)$$

ΔX [kg/kg'] is difference of the absolute humidity between water surface and main stream air at a referenctial height, ρ_{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_Es for different source area as a function of λ_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_Es normalised by C_{E1}. The decreasing rates C_{E2}/C_{E1} are greater than those of C_{E3}/C_{E1} for both staggered and square layouts, and the decreasing rates of Sq1 and St1 are approximately equal even though different λ_ps. 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 λ_p under a single source area is somewhat universal even if a different source size is deployed.

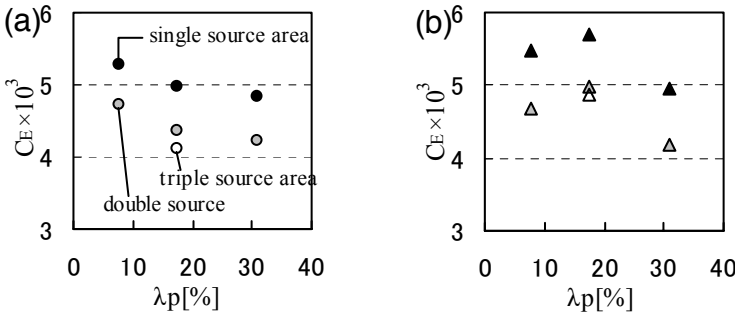


Figure 3 C_Es for different source area. (a) Sq1 arrays, and (b) St1 array. Black, gray, and white marks refer C_Es of arrays with single, double, and triple source area, respectively.

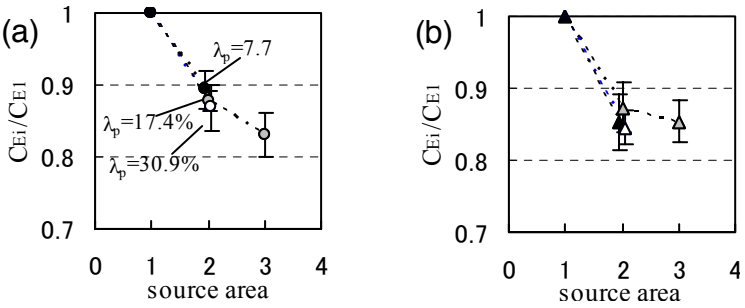


Figure 4 C_Es normalized by C_{E1}. (a) Sq1 array, and (b) St1 array. Black, gray, and white marks refer C_Es in λ_p=7.7%, 17.4%, and 30.9%, respectively. Bars indicate experimental errors

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_Es based on $U_{1.5L}$ and $U_{2.5L}$. In comparison of C_Es between Sq1 and St1 (show in Figure 5 (a) and (b)), C_Es of Sq1 are almost constant for different λ_p conditions even though referential height was changed. On the other hand, C_Es of St1 increase with the decrease of reference height at λ_p =17.4%. This might be caused by the fact that vertical turbulence was active in vicinity of the surface of staggered array at λ_p =17.4%. In the same way, C_Es 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_Es of St1.5 with uniform height over the λ_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.

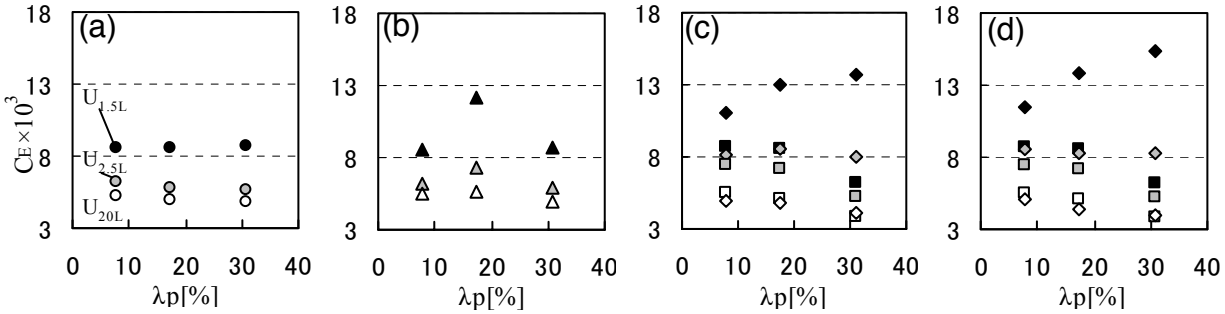
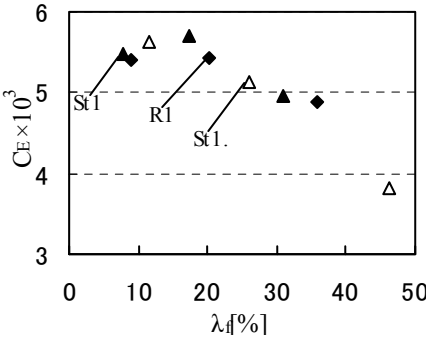


Figure 5 *CE*s based on a referential wind speed at different heights. (a) Sq1 array, and (b) St1, (c) St1.5-Sq, and (d)St1.5-St. Square marks plotted on (c) and (d) are *CE*s of St1.5. Black, gray, and white marks refer to *CE*s by U1.5L, U2.5L, and U20L, respectively

3.3 C_E of the arrays of blocks with random rotation angle

Figure 6 shows *CE*s of St1, St1.5, and R1 for various frontal area density λf. Three types of the arrays shows almost consistent tendency against λf . *CE*s 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 C_E than that of random rotation of individual obstacle. And the effect on *CE*s by obstacles randomly rotated can be estimated fairly by consideration for frontal projected area of obstacles.

Figure 6 *CE*s of St1, St1.5, and R1 for frontal area density λf. Black triangle, white triangle, and daiamond refer *CE*s of St1, St1.5, and R1, respectively.



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 C_E 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 C_E 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 *CE*s even if the obstacles are individually rotated in a random manner. In addition, relation between C_E and λf is universal for staggered arrays with uniform height.

References

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Barlow, J.F., Harman, I.N., Belcher, S.E., 2004. Scalar fluxes from urban street canyons. Part 1:Laboratory simulation, *Boundary-Layer Meteorology*, 113, 369-385.