A Study on the Similarity between Scalar and Momentum Roughness Lengths based on the Scalar Concentration Measurement

N.I.Izual[1,2,*], N.Ikegaya[1], A.Hagishima[1], J.Tanimoto[1] and J.Chung[1]

[1]Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, 6-1 Kasuga-koen, Kasuga-shi, 816-8580, Japan
[2]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

ABSTRACT

The understanding on how urban roughness affects the transport mechanisms of momentum, heat and scalar between urban surfaces and atmosphere is an important issue to be investigated from both the viewpoints of urban climatology as well as building physics. This is to account for accurate estimation of thermal behaviour of an urban area consisting of buildings. Under these circumstances, this study reported the result of wind tunnel experiment on both transfer coefficients and profiles of absolute humidity over block arrays with sufficient scalar source size. In addition, the roughness length for scalar included in logarithmic equation for scalar concentration was estimated based on its measurement. The result suggested the possibility that the universal relationship of roughness length for momentum and scalar expressed by roughness Reynolds number for both a smooth wall and scaled block arrays exists.

KEYWORDS

Scalar concentration, scalar roughness length, scalar displacement height, scalar boundary layer, wind tunnel

1. INTRODUCTION

In recent years, urban heat island phenomena have become a great matter of concern especially in low to middle latitude. In an urban region, various surface obstacles such as buildings and vegetation, anthropogenic heat release from HVAC system and traffic, and decrease of natural land surface alter the meso-scale thermal balance and flow field, resulting in temperature increase compared with a surrounding rural area. Contrastingly, it is known that artificially modified urban climate increases the cooling demand of buildings due to high air temperature and attenuates ventilation of both urban street and interior space of buildings. Although outdoor climate condition had been recognized as only input variables for a building thermal system (defined by observation data of weather station for decades in the research field of numerical simulation on building thermal behaviour and HVAC system), a whole thermal

* Corresponding author email: nik@kyudai.jp

system consists of urban atmosphere and buildings has become an issue to be investigated from viewpoints of both urban climatology and building physics.

For accurate simulation of an urban thermal system comprises of buildings, atmosphere and soil, understanding and modelling of transfer processes of momentum, heat and vapour between an urban complex surface and atmosphere is essential. Therefore various studies have been performed based on field surveys in real cities (e.g., Voogt and Grimmond, 2000). In addition, reduced scale physical models have been applied to investigate the holistic relations between surface geometry and physical processes dominated by turbulence within and above an urban canopy layer.

To describe vertical profiles of velocity, temperature and humidity over an urban area, the Monin-Obukhov Similarity Theory (MOST) framework has been widely used in the research field of atmospheric boundary layer. MOST can be simplified as the logarithmic profiles under the neutral condition as follows:

$$\frac{u(z)}{u^*} = \frac{1}{\kappa}\ln\left(\frac{z - d_m}{z_m}\right) \quad (1)$$

$$\frac{S_{surf} - S(z)}{S^*} = \frac{1}{\kappa}\ln\left(\frac{z - d_s}{z_s}\right) \quad (2)$$

where $u_{(z)}$ is measured at vertical velocity, $S_{(z)}$ and S_{surf} are the absolute humidity of saturated between water surface. z_m and z_s refer to roughness length for momentum and scalar, d_m and d_s are displacement heights for momentum and scalar. z_m and d_m are length scales for the aerodynamic effect of urban roughness and defined by urban geometry. u^* is friction velocity and S^* is friction concentration. Therefore, numerous studies have investigated the relation between urban geometry and the parameters z_m and d_m (e.g., Grimmond and Oke, 1999). In contrast, the parameters for scalar transfer phenomena z_s and d_s have not been fully examined. Kanda et al. (2007) and Kanda & Moriizumi (2009) revealed that the universal relationship between the roughness Reynolds number and the Stanton number (the Dalton number for scalar) proposed by Brutseart (1982) for a smooth wall exists for block arrays with various length scale based on a series of field experiment. This significant finding implies the possibility that experimental data using scale models can also be applied to the estimations of the scalar roughness length for real urban surfaces.

Under these circumstances, we have performed a wind tunnel experiment on the scalar transfer coefficient of street surface of urban-like block arrays with various geometry conditions based on salinity method (Ikegaya et al. 2012a). In addition, we estimated the roughness length for scalar based on the measured profiles of absolute humidity (Ikegaya et al. 2012b). However, these previous experiments were done using relatively small size of scalar source, thus, the argument on similarity between momentum and scalar presented in Ikegaya et al. (2012b) is still to be reinvestigated.

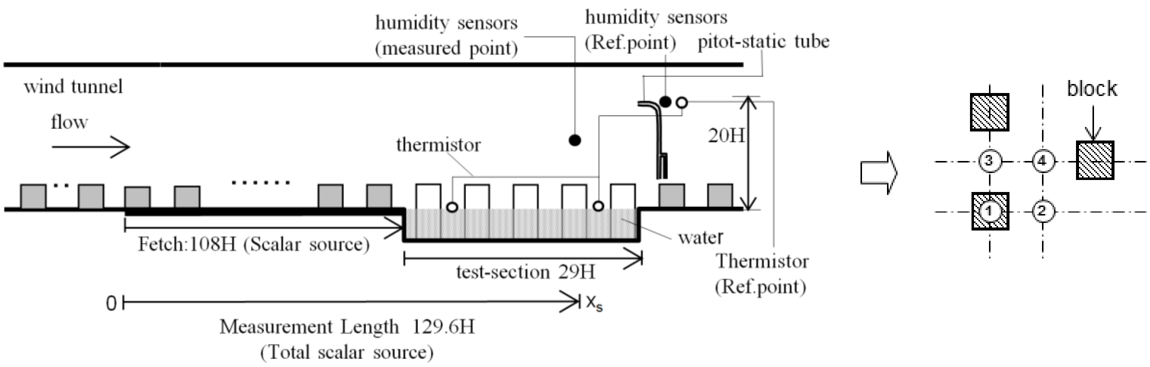
Therefore, in this paper we reported the result of wind tunnel experiment on both transfer coefficients and profiles of absolute humidity over block arrays with sufficient scalar source size, and discuss the similarity for scalar transfer process.

2. EXPERIMENTAL SETUP

2.1 Wind Tunnel device and scalar source

The experiment was conducted by using an open-circuit wind tunnel device as shown in Figure 1(a). The wind tunnel was located in an indoor environment (room). The air temperature of the room was maintained at a constant value using air-conditioning and flow generated by 4 propellar fans set in the upwind edge of the wind tunnel was kept at approximately 2 m/s during the experiment.

A square tank with the base of 0.72×0.72 m^2 (29*H*×29*H*, *H* is the block height) filled with water is installed on the wind tunnel floor, and a block array was immersed in the tank. The surrounding areas of the tank are covered by wet filter papers, on which blocks are arranged regularly. The geometry of the block array of the surrounding area and the water tank is identical. In other words, boundary layers for momentum and vapour develop over a whole test section with a streamwise length of 21.6*H*.



(a) (b)

Figure 1. *(a) Schematic diagram of the wind tunnel and (b) Plan view of staggered block array, the numeral refers to a measurement point of humidity profile.*

2.2 Measurement items and instrumentation

The vertical profiles of absolute humidity concentration were measured at 4 points in a horizontal plane of unit area at 22 altitudes from 0.25*H* to 20*H* as shown in Figure 1(b) by using humidity sensors (Sensiron, SHT11) with a size of 5×4 mm^2. The measurement for each point was done by traversing for 1 minute with a frequency of 10 Hz, hence, the total measurement duration for 4 profiles was around 3 hours. The temperatures of water surface, reference absolute humidity at a height of 20*H* and reference wind speed were measured simultaneously to eliminate the effect of fluctuation of background condition.

Furthermore, the scalar transfer coefficient defined by the following equation was measured for each array based on the salinity method. The details of the measurement procedure are given in Ikegaya et al. (2012a):

$$C_E = \frac{E}{U_{ref}\left(S_{sat} - S_{ref}\right)} \tag{3}$$

S_{sat} and S_{ref} are the absolute humidity of saturated water surface and air at a referential height, respectively; E [kgm^{2}s] is the evaporate rate, ρ_{air} [kg/m^3] is the density of air and U_{ref} [m/s] is the reference wind speed.

2.3 Geometry of block array

The rough surfaces used for measurement were regular arrays of sharp-edged blocks made from wood and glued onto filter paper and thin plastic plates. All blocks had a uniform base of 25 mm × 25 mm. Three types of staggered cube arrays with three λ_p conditions: 7.7, 17.4 and 30.9% were used for measurement. Note that the configurations are similar as those adopted for estimation of drag coefficients and scalar transfer coefficients in Hagishima et al. (2009); Ikegaya et al. (2012a) and Ikegaya et al. (2012b).

3. RESULTS

3.1 Spatial distributions of scalar concentration

Figure 2(a) shows the vertical profiles of absolute humidity at a streamwise distance

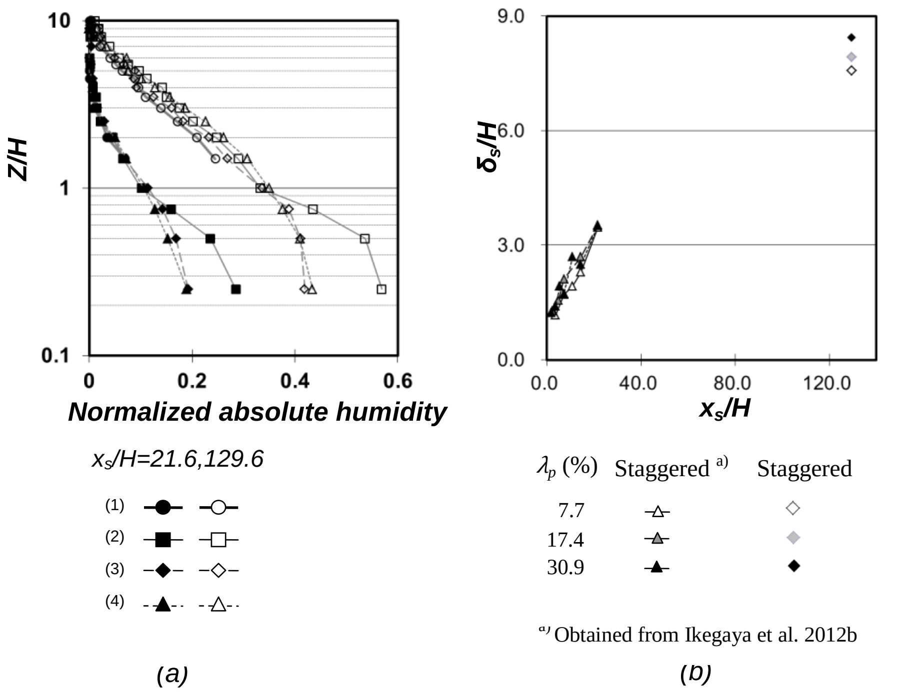


Figure 2. *(a)Vertical profiles of normalized absolute humidity ($S_{(z)}$-S_{ref})/(S_{surf}-S_{ref}) for λ_p =17.4%, The data for x_s=21.6H shown in Ikegaya et al.(2012b) is included for a comparison (b) Relation between scalar boundary layer height δ_s and distance from the leading edge x_s*

from a leading edge of a scalar source x_s = 129.6H for staggered array with λ_p = 17.4%. The values are normalized by the difference of absolute humidity between saturated water surface and reference height. The data at a streamwise distance of x_s = 21.6H presented in Ikegaya et al. (2012b) are also included for comparison. Within a canopy layer, the humidity in position (2) between leeward and windward walls of blocks is the highest among 4 points; which may be due to the wake flow. In addition, the data of humidity at x_s = 126.9H are higher than those at x_s = 21.6H because of the development of scalar boundary layer.

3.2 Height of Scalar Boundary layer

The height where normalized absolute humidity equals 1% δ_s is estimated as a boundary layer height in the same manner of 99% boundary layer depth for momentum. Figure 2(b) shows the relation between scalar boundary layer height δ_s and the streamwise distance from a leading edge of scalar x_s. Although the data for different conditions of fetch length are limited, the graph indicates that the boundary layer depth rapidly increases near the leading edge, and the developing rate becomes mild in the downwind region.

3.3 Log law fitting of humidity profiles

We determined the scalar roughness length z_s included in equation (2) under the assumption of d_s = d_m. by using measured profiles of humidity based on log-law fitting. Friction scalar concentration $S*$ was derived from the measured transfer coefficients. Estimated parameter z_s and transfer coefficients C_E are shown in Table 1. Theoretically, the logarithmic similarity is satisfied within a layer where the airflow is uniformed in a horizontal plane and not affected by each underlying obstacle, and the turbulent scalar flux is constant with a height, so-called log-layer. However, we did not measure the vertical profiles of turbulent scalar flux, and thus, we could not specify the depth of log-layer. Therefore, we estimated the parameters for various vertical ranges of the profile; and adopted the parameters having the minimum difference between estimated data and measured ones.

Table 1: Estimated scalar transfer coefficients and roughness lengths for scalar

λ_p (%)	C_E	z_s	z_s [a)]	z_m [a)]	d_m [b)]
7.7	0.0040	0.0014H	0.0023H	0.1322H	0.26H
17.4	0.0047	0.0031H	0.0041H	0.1122H	0.90H
30.9	0.0045	0.0082H	0.0029H	0.0728H	0.52H

[a)] refers to the data of Ikegaya et al. (2012b) obtained in the experiment for short scalar source condition, (x_s=21.6H), [b)] indicates the data from Hagishima et al. (2009)

The estimated values of z_s of both the present study and Ikegaya et al. (2012b) are much smaller than z_m. This is consistent with the fact that the scalar transfer on a surface is dominated by only the molecular diffusion. On the other hand, the momentum transfer is governed by both pressure drag and friction drag. In addition, the present estimation of z_s under the long scalar source size is smaller than the data of Ikegaya et al. (2012b) under the short scalar source size. It might be due to the effect of development of scalar boundary layer.Figure 3(a) and (b) show the comparisons of

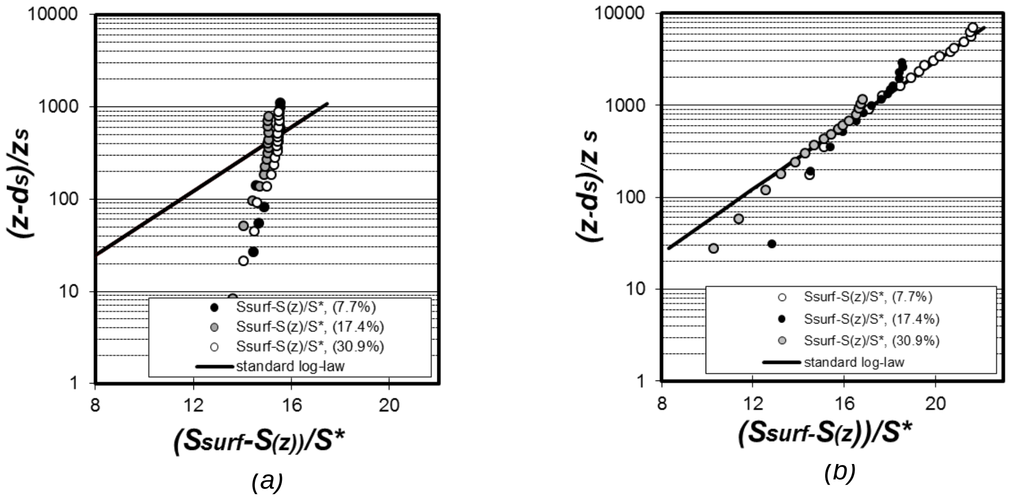


Figure 3.*(a) Spatially averaged means scalar concentration normalized by S* for conditions of short scalar source size x_s=21.6H, and (b) long scalar source size x_s=129.6H.*

scalar profiles between measurement and estimation for x_s*=21.6H* and x_s*=129.6H*. The log-law fitting of Ikegaya et al. (2012b) does not show good agreement with measurement profiles (see Figure 3(a)). In contrast, as shown in Figure 3 (b), the measurement data and the estimated log-law agree well for long fetch with each other within a log-law layer, thus, the present experiment is supposed to be done under the sufficient boundary layer development for scalar.

3.4 Scalar and Momentum Roughness Lengths

The theoretical relationship between the scalar and momentum roughness was presented by Brutsaert (1982) for a smooth surface as the following equation:

$$\kappa B^{-1} = a\left(\mathrm{Re}^{*}\right)^{0.25} - 2.0 \qquad (4)$$

$$\kappa B^{-1} = \frac{\ln z_m}{\ln z_h} \qquad (5)$$

where a represents the empirical coefficients, Re* is roughness Reynolds number defined by friction velocity and momentum roughness length, z_h are roughness length for heat. Kanda et al. (2007) and Kanda and Moriizumi (2009), on the other hand, examined the relation between Re* and κB^{-1} based on two types of outdoor experiment with different size of block arrays.

Figure 4 shows the relationship between Re* and κB^{-1} of the Brutsaert (1982); Kanda

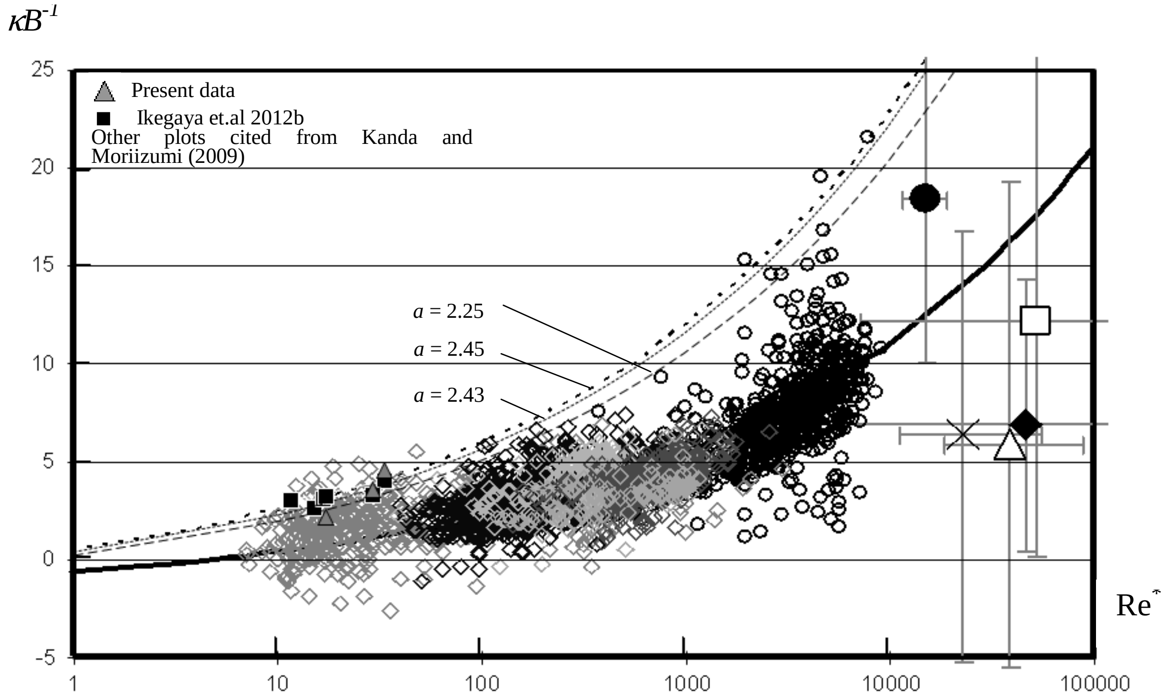


Figure 4. *Relationship between the Dalton number and roughness Reynolds number*

et al. (2007) and Ikegaya et al. (2012b) and the present data. The data of both the present experiment and Ikegaya et al. (2012b) based on a scaled block array with the block size of 25mm are almost consistent with the relation presented by Brutsaert (1982) for a smooth wall. The coefficient *a* obtained by the least square method using the present study is *a* = 2.43. In contrast, Brutsaert (1982) obtained *a* = 2.45 for heat and *a* = 2.25 for vapour. In addition, plots of the present data range within the scatter of the data of Kanda and Moriizumi (2009), which is based on outdoor scale model experiment with the block size of 0.15m and 1.5m. It implies that the knowledge of the present experiment can be applied for understanding of scalar transfer process of real urban surfaces by considering the roughness Reynolds number.

CONCLUSION

A wind tunnel experiment on scalar concentration profiles and scalar transfer coefficients for urban-like cube arrays were performed for investigating scalar transfer process between urban surfaces and atmosphere, which is essential for accurate prediction of urban heat island. The scalar source was embedded on street surface of block arrays with a streamwise length of about 130 times of block height, hence, the measurement of profiles and transfer coefficient was done under the fully developed boundary layers of both scalar and momentum. The profiles measured at different distance from the leading edge indicate the convex increase of boundary layer depth against the distance. In addition, roughness length for scalar used in logarithmic similarity law was estimated based on log-law fitting. Moreover, the estimated values suggested that the present experiment with a length scale of 25mm is consistent with the universal relationship of roughness length for momentum and scalar expressed by roughness Reynolds number confirmed for both a smooth wall and block arrays with a length scale of 1.5m.

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