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Investigation of *Re*-independence of turbulent flow and pollutant dispersion in urban street canyon using numerical wind tunnel (NWT) models

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ABSTRACT

This paper numerically and experimentally studied the Reynolds number independence (*Re*-independence) of turbulent flow and pollutant dispersion in urban areas. The concept of numerical wind tunnel (NWT) is proposed and validated by prototype wind-tunnel experimental measurements. A new physical quantity: the ratio of relative change, *RRC*, is proposed to investigate the *Re*-independence quantitatively. For the given street canyon, numerically predicted variations of *RRC* vs. building Reynolds number (Re_H) from three k–ε turbulence models agree well with each other, and the variation trend shows that there exist two flow regimes in the range of Re_H studied: flow in low Re_H region is strongly affected by Re_H, while that in higher Re_H region is weakly affected by Re_H, giving a strong support to the concept of *Re*-independence of turbulent flow. A criterion of *RRC* less than 5% is suggested to determine the value of the critical Reynolds number. For the street canyon studied, such determined critical building Reynolds number ($Re_{H,\mathrm{crit}}$) is 3.3×10^4. Examinations of dimensionless velocity contours, local velocity vectors, and concentration contours demonstrate the feasibility of the suggested critical Reynolds number.

1. Introduction

The rapid increase in coal power plants in China has raised concerns on the effect of their exhaust on air quality in urban areas, especially at neighborhood (less than 5 km) and street scales (within 100–200 m). In addition, automobiles also emit such exhaust, which is released from relatively low heights (~10 m) within the city, and it can be captured in the wake of surrounding buildings. Therefore, it is necessary for comprehensive studies to understand the transport and dispersion characteristics of such pollutants in urban areas [1,2]. Many previous studies on the flow and pollutant dispersion in urban areas started from the urban street canyons. These studies cover the flow characteristics [3–6] and pollutant dispersion regimes [7–11], thermal stratification effects [12–15], etc. In this regard, reliable and operational modeling tools are highly required that can help estimate the effect of emitted hazardous airborne matter in an expeditious manner [16–19].

Traditional methods to investigate such subjects include the field measurements [20–22] and laboratory modeling in water channels and wind tunnels [1,23–25]. The measurement of flow field and dispersion distribution in street canyons under real atmospheric boundary-layer conditions is quite difficult [26]. In contrast, laboratory modeling in wind-tunnel experiments by artificially controlling the physical conditions provides an opportunity to examine the effects of individual or combined parameters. For an accurate modeling, several dimensionless parameters in the prototype must be duplicated in the wind-tunnel experiments. Starting with the conservation equations of mass, momentum, energy and concentration, five dimensionless parameters, Reynolds (*Re*), Rossby (*Ro*), Peclet (*Pe*), Froude (*Fr*) and Schmidt (*Sc*) numbers were obtained through nondimensionalization of the governing equations by Snyder [27]. The duplication of all the dimensionless parameters is impossible and impractical in wind-tunnel experiments. Snyder [27,28] pointed out that the Rossby number can be neglected when modeling prototype flows with a length scale less than about 5 km. The Reynolds number, Peclet number, and Schmidt number criteria may be neglected if the model flow is of sufficiently high *Re* with air as the modeling medium. Then in such a case *Fr* is the only one which should be matched between the prototype and the wind-tunnel tests. However, the Reynolds number is

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still an abused criterion in modeling flow in street canyon. The question is very simple: how large must the Reynolds number be to be "sufficiently high" or "large enough"?

For the similarity of flow fields, Reynolds number should be the same in the prototype and wind-tunnel tests [29,30]. In most engineering practices, such as energy and power engineering, refrigeration and air conditioning, etc., the satisfaction of this condition is not difficult. However, for the flow field in urban areas to implement this condition becomes rather difficult. Actually, the highest model Reynolds number obtained commonly in wind-tunnel tests with scale reductions from one hundredth to one thousandth, usually is several orders of magnitude smaller than that in the prototype [27].

Many previous wind-tunnel studies on the flow structure in urban areas mainly focused on finding the Reynolds number, beyond which flow goes into *Re*-independence regime. This special *Re* will be called critical *Re* in the following presentation. Similar to the complete roughness of turbulent flow in tubes [31], such situation for urban boundary-layer flow is called as aerodynamic roughness regime [27]. Aerodynamic roughness surface implies that the surface roughness heights are larger than the thickness of the viscous sub-layer. And an important fact is that most atmosphere flows are always in the aerodynamic roughness regime [27]. Thus, if wind-tunnel experiments are carried out in the aerodynamic roughness regime, the measured dimensionless results can be considered similar with that of the prototype. Such concept has been validated by comparing the field measurement with related water-channel or wind-tunnel modeling [20]. Therefore the search for the critical *Re* is of considerable importance for appropriately conducting wind-tunnel tests.

Snyder [27] proposed a roughness Reynolds number ($Re_r = u^* z_0/\nu$, where u^* is the friction velocity, z_0 is the roughness length and ν is the kinematic viscosity) as the evaluation criterion. Meroney [32] suggested that laboratory wind speed should be high enough, such that obstacle Reynolds numbers exceed 1.1×10^4 for sharp-edged objects or 10^5 for round objects. Uehara et al. [33] concluded that *Re*-independence could be expected for the whole flow field in the modeled urban areas as long as the critical roughness Reynolds number ($Re_{r,\mathrm{crit}}$) and dimensionless height ($z_+ = u^* z/\nu$, where z is the spatial coordinate in the vertical direction, m) were satisfied. Tominaga and Stathopoulos [34] found that the typical critical building Reynolds number of a 200-mm-high cubic model building is about 4000.

From above brief review on the *Re*-independence studies, it can be found that although a number of investigations have been conducted and more than 40 years have passed since the publication of the classical paper of Snyder [27], following three important problems yet have not been solved.

First, we still lack a physical quantity which can quantify the *Re*-independence of turbulent flow. So far, all the judgments for *Re*-independence are qualitative, and some inaccurate descriptions are used, such as "flow pattern will not be much affected by changing the Reynolds number", "the model flow will change very little with changes in the Reynolds number". One may ask how much is "not much"? How little is "very little"?

Second, if such a physical quantity is proposed what is the threshold beyond which the flow can be regarded as *Re*-independent; and if we want to improve the similarity degree between model and prototype, how to change this physical quantity? So far, the values of critical Reynolds number provided in the literature are obtained by some qualitative comparison, such as judging from the change in the shape of the separation bubbles [33].

Third, all the above mentioned results of *Re*-independence were obtained from wind-tunnel measurements. The weakness of physical modeling is its high cost, and the difficulty in obtaining the details of flow field and pollutant distribution. In addition, it is difficult to accurately measure the speed lower than 1 m/s and to reach velocity higher than 30 m/s. With the ever-increasing computer capacity and the improvement of numerical algorithms, CFD models have become a powerful tool to predict the detailed flow and pollutant dispersion processes occurring in urban street canyons. To our best knowledge, so far, all the previous related numerical works focused on studying some practical problems, not on searching for the critical Reynolds number.

In this paper, we propose a numerical wind tunnel (NWT) model to numerically investigate *Re*-independence of flow and pollutant dispersion in urban street canyon, aiming at solving the three problems mentioned above. The rest of the paper is organized as follows. Mathematical formulation and boundary conditions of the proposed NWT and experimental wind tunnel are described in Section 2. In Section 3, grid independence assessment and the NWT model validation by the wind-tunnel experimental results are conducted. Results of *Re*-independence of flow and pollutant dispersion are discussed in Section 4, and a physical quantity and a threshold for determining the critical Reynolds number are proposed. Finally, some conclusions are given in Section 5.

2. Methods

2.1. Numerical simulation

2.1.1. Prototype of the NWT model

The prototype of the NWT model is the TJ-1 boundary-layer wind tunnel in the State Key Laboratory of Civil Engineering for Disaster Prevention, Tongji University, China. Fig. 1 shows a picture of the interior of the TJ-1 wind tunnel and a three-dimensional (3-D) perspective view of the NWT configurations is presented in Fig. 2 with an amplified view of the street canyon model inserted in the upper right corner. The test section of this wind tunnel is H = 1.8 m, W = 1.8 m, and L = 12 m. For the NWT, the origin point is located at inlet (Fig. 2). The velocity profile of atmospheric boundary layers is generated by two spires located at x = 0.2 m, being used as vortex generations and the aligned array of roughness elements (12 rows of wooden cubes with 3 or 4 cubes per row). The dimensions of two kinds of roughness elements are shown in Fig. 2, and the entry roughness section is spread to x = 9 m, and the street canyon model is set at x = 9.5 m. The street canyon (Figs. 1 and 2) with a scale ratio 1:100 is composed of an upwind building and a downwind building with the same dimension of $h \times 3h/4 \times 3h$, where h is the height of the building given as h = 0.16 m. The pollution source located in the ground-level street with the dimension of $5h/8$ (width) $\times$ $3h$ (length) $\times$ $h/40$ (height) is placed between the two buildings.

2.1.2. Governing equations

The 3-D NWT model used here to predict turbulent air flow characteristics and pollutant dispersion, is based on Reynolds-averaged Navier–Stokes (RANS) equations, species transport equation together with turbulence model equations. The governing equations include: the continuity equation in incompressible form,

$$\frac{\partial u_j}{\partial x_j} = 0, \tag{1}$$

the RANS equation,

$$\frac{\partial u_j u_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\nu \frac{\partial u_i}{\partial x_j}\right) - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + g_i \tag{2}$$

and the transport equation for a passive pollutant,

$$\frac{\partial(\rho u_j c_i)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\frac{\partial c_i}{\partial x_j}\right) + S, \tag{3}$$