ARTICLE IN PRESS

International Journal of Heat and Mass Transfer xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Numerical investigations on *Re*-independence for the turbulent flow and pollutant dispersion under the urban boundary layer with some experimental validations

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ARTICLE INFO

Article history:
Received 9 March 2016
Received in revised form 2 August 2016
Accepted 12 August 2016
Available online xxxx

Keywords:
Numerical wind tunnel (NWT)
Flow similarity
Critical Reynolds number
Reynolds number independence
Turbulence model

ABSTRACT

This paper numerically studied the *Re*-independence of turbulent flow and pollutant dispersion around five scaled building models. The RANS-based CFD model, hereafter called numerical wind tunnel (NWT) model, was validated by wind-tunnel experiments and applied to investigate the flow-structure independence on building Reynolds number (Re_H) and roughness Reynolds number (Re_r). The ratio of relative change (*RRC*) was used to evaluate the *Re*-independence with 5% selected as the threshold. The results show that the critical Re_H ($Re_{H,crit}$) is strongly affected by the building structure, particularly the building height. However, the value of the critical Re_r ($Re_{r,crit}$) in the pedestrian level plane changes very little with the different building models, which is suggested to be 25 in terms of the *RRC* criterion. Distributions of dimensionless velocity and concentration in the pedestrian level planes validated this suggested value. For the RANS turbulence models tested in this paper (high Reynolds number model and low Reynolds number model) the predicted value of $Re_{r,crit}$ is independent on the model. This work improves the understanding of *Re*-independence in the investigation of the flow and pollutant dispersion by using wind-tunnel experiment.

1. Introduction

There has been particular concern on flow-structure investigations in urban areas over the last few decades which arises from the increased levels of air pollutants such as PM10 and PM2.5 in urban atmosphere in China [1–3]. The heavy fog haze and photochemical smog emerge out of the various interactions and deteriorate air quality seriously, affecting people's health, especially in large cities [4–7]. Many previous studies on the air pollutant dispersion within urban regions started from the investigations of the air flow characteristics because the flow structure determines the pollutant distribution [8–10].

Traditional methods to investigate flow characteristics include the field measurements [11,12] and laboratory modeling in wind tunnels or water channels [13–15]. However, there are many limitations and difficulties to measure flow field under real atmospheric boundary-layer conditions due to the uncertainty of the meteorological conditions and other measurement inconveniences [16] while these physical conditions can be artificially controlled by laboratory modeling. Snyder pointed out that for modeling a conventional fluid flow and pollutant dispersion the most important criteria are Reynolds number and Schmidt number [17,18].

It is well-known that for the flow similarity, Reynolds number should be the same in the wind-tunnel experiments [19,20]. Nevertheless, it's rather difficult to implement this criterion using the models with a small scale ratio ranging from 1:100 to 1:1000. Fortunately, when the Reynolds number is larger than a critical value the flow structure over a rough surface would be almost independent on the Reynolds number, and such flow is called aerodynamically rough turbulent boundary-layer flow [17,18,21]. Thus, searching for the critical Reynolds number is of considerable importance for appropriately conducting wind-tunnel experiments. However, there exist some disputes in previous studies when determining the critical value: Firstly, to the authors' knowledge there are at least five types of Reynolds number in this regard as shown in Table 1; Secondly, for the same type and building structure the proposed values of the relative critical Reynolds number are often quite different.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.08.038
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Please cite this article in press as: P.-Y. Cui et al., Numerical investigations on *Re*-independence for the turbulent flow and pollutant dispersion under the urban boundary layer with some experimental validations, Int. J. Heat Mass Transfer (2016), http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.08.038

Table 1
The types of Reynolds number for flow over a rough surface.

Author	Types of Reynolds number	Definitions of Reynolds number
Alessio et al. [22] Contini et al. [23]	Wind-tunnel-flow Reynolds number, Re_δ	$Re_\delta = U_0\delta/\nu$, U_0-wind-tunnel speed; δ-boundary-layer height; ν-kinematic viscosity of air
Uehara et al. [21]	Building Reynolds number, Re_H	$Re_H = U_H H/\nu$, H-characteristic height of the building; U_H-upstream undisturbed velocity at the height of H
Snyder [17] Uehara et al. [21]	Roughness Reynolds number, Re_r	$Re_r = u^* z_0/\nu$, u^*-fraction velocity; z_0-roughness height of the upstream roughness configurations
Saathoff et al. [24,25] Contini et al. [23]	Stack Reynolds number, Re_s	$Re_s = U_s D/\nu$, D-external diameter of stack; U_s-upstream undisturbed velocity at the height of stack
Obasaju and Robins [26] Contini et al. [23]	Emission Reynolds number, Re_e	$Re_e = U_e d/\nu$, d-internal diameter of stack; U_e-average exit velocity of the emission

The existing results of $Re_{H,crit}$ and $Re_{r,crit}$ are summarized in Table 2. Most results were obtained by wind-tunnel measurements. From this table, only two values of $Re_{r,crit}$ are proposed with 2.5 and 5.4, respectively, and most other values are for $Re_{H,crit}$ with a wide range from 2.0×10^3 to 1×10^5. The diversity of $Re_{H,crit}$ may come from the following aspects: (i) lack of an accurate definition of *Re*-independence, for example, Uehara et al. [21] determined the value of $Re_{H,crit}$ by observing the qualitative variations of the dimensionless velocity distribution and the recirculating zone; (ii) difference in building configurations, for example, the critical Reynolds number of Hoydysh et al. [27] and Cui et al. [37] was for the urban street canyons, while that of Uehara et al. [21] was for the single building and building groups; (iii) different selection of the characteristic length used for defining the Reynolds number, for instance, according to the selection of Uehara et al. [21] the characteristic lengths were 0.1 m and 0.2 m while 0.16 m was applied according to Cui et al. [37]; (iv) uncertainty of velocity field measurement.

These disadvantages of the wind-tunnel experiments of their high cost and inconvenient operation however can be overcome by CFD predictions based on a RANS (Reynolds Averaged Navier–Stokes) model or LES (Large Eddy Simulation) model for flow and dispersion around buildings [38–41]. It is well known that LES which resolves large-scale unsteady motions and requires modeling only of the small-scale can perform better than RANS in modeling the distributions of mean velocity and turbulence energy around a simple building, which is because the momentum diffusion due to vortex shedding around the building is not reproduced in steady-state RANS computation [42]. However, LES requires larger computation resources than the widely used RANS model. Furthermore, for flow over the building group and pollutant dispersion in downtown Montreal Gousseau et al. [43] adopted both LES and RANS and obtained very similar average velocity distributions. Based on the above facts, in this paper the RANS model is adopted, including the high-Reynolds-number models and low-Reynolds-number model. Stimulated by the afore-mentioned situation, Cui et al. [37] firstly searched for the $Re_{H,crit}$ (=3.3×10^4) through CFD method (RANS-based CFD model) and found the $Re_{H,crit}$ is independent on the three RANS models adopted.

Based on the above reviews on *Re*-independence studies, one conclusion can be made that the $Re_{H,crit}$ is case-dependent (such as building shape, height, single or multiple, etc.). Of course this is not convenient for practical application. To the authors' understanding, for studying the *Re*-independence, the following questions need to be further clarified: (i) Is there a general critical Reynolds number which is not affected by the downstream specific buildings for a given oncoming flow condition? If the answer is positive, then (ii) What are the definition and the correspondent value? (iii) Should we take the value of *RRC* (=5%) as indicated by Cui et al. [37] to evaluate the *Re*-independence for the entire flow field or just focusing on some local part we are interested in? (iv) Whether the dimensionless distribution of the pollutant can also be *Re*-independent under the condition of $Re_r \geqslant Re_{r,crit}$?

2. Methods

2.1. Numerical simulation

2.1.1. Physical prototype of the NWT model

The prototype of the NWT model is TJ-1 boundary-layer wind tunnel. Fig. 1 shows the picture of TJ-1 wind tunnel inner side and the test configurations. With an amplified view of five building models with scale ratio of 1:100 inserted in the upper right corner, Fig. 2 shows a three-dimensional (3-D) perspective view of the NWT configurations, in which the dimensions, configurations and positions of roughness elements, spires, baffles and building

Table 2
The critical Reynolds number existing in literature.

Author	The type of Reynolds number	The value of Re_{crit}
Snyder [17,18]	Re_H (building Reynolds number)	4.0×10^3
	Re_r (roughness Reynolds number)	2.5
Hoydysh et al. [27]	Re_H (building Reynolds number)	3.4×10^3
Castro and Robins [28]	Re_H (building Reynolds number)	4.0×10^3
Cherry et al.[29]	Re_H (building Reynolds number)	3.0×10^4
Meroney [30]	Re_H (building Reynolds number)	$1.1 \times 10^4 \sim 1.0 \times 10^5$
Ohba [31]	Re_H (building Reynolds number)	2.1×10^3
Djilali and Gartshore [32]	Re_H (building Reynolds number)	2.5×10^4
Mochida et al. [33]	Re_H (building Reynolds number)	7.5×10^3
Saathoff et al. [24,25]	Re_b (building Reynolds number)	1.1×10^4
Uehara et al. [21]	Re_H (building Reynolds number)	$3.5 \times 10^3 \sim 8.0 \times 10^3$
	Re_r (roughness Reynolds number)	5.4
Yee et al. [34]	Re_H (building Reynolds number)	4.0×10^3
Lim et al. [35]	Re_H (building Reynolds number)	$(2.0 \sim 3.0) \times 10^4$
Gupta et al. [36]	Re_b (building Reynolds number)	1.1×10^4
Cui et al. [37]	Re_H (building Reynolds number)	3.4×10^4

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