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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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 ($Re_{H, \text{crit}}$) is strongly affected by the building structure, particularly the building height. However, the value of the critical Re_r ($Re_{r, \text{crit}}$) 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 $Re_{r, \text{crit}}$ 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.

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

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 PM_{2.5} 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 climate 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 pollution 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.

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 for 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 buildings, 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 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 $Re_{H,crit}$ ($=3.3 \times 10^4$) through CFD method (RANS-based CFD model) and found the $Re_{H,crit}$ is case-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) Is the dimensionless distributions of the pollutant can also be Re -independent under the condition of $Re_r \geq Re_{r,crit}$?

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. Figure 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, Figure 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 models are depicted in details. It should be noted that the inlet plane of the computational domain is 0.2 m ahead of the physical wind tunnel inlet plane in order to adopt the uniform inlet velocity condition. The test section of this wind tunnel has the dimensions of $H = 1.8$ m, $W = 1.8$ m, and $L = 12$ m.

2.1.2. Governing equations for the air flow and pollutant dispersion

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

$$\frac{\partial u_j}{\partial x_j} = 0 \quad (1)$$

the RANS equation

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

and a transport equation for a passive dispersion

$$\frac{\partial(\rho u_j c_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\left(\rho D_{i,m} + \frac{\eta_t}{Sc_t} \right) \frac{\partial c_i}{\partial x_j} \right) + S_i \quad (3)$$

where, u_i is the time-averaged velocity, ρ is the density, η and η_t are molecular and turbulent viscosity, respectively. p is the pressure, g_i is the gravitational body force, c_i is the local mass fraction of each species, $D_{i,m}$ is the diffusion coefficient for species i in the mixture, Sc_t is the turbulent Schmidt number given as $Sc_t = 0.7$ [44], and S_i denotes the pollution source term.

Three turbulence closure models, for the turbulent kinetic energy k and the dissipation rate of turbulent kinetic energy ε , including standard k - ε [45], RNG k - ε [46] and realizable k - ε models [47] were adopted and their results were compared to determine the appropriate turbulence model for this study. More detailed definitions of the three models are summarized in Table 3.

2.1.3. Boundary conditions

Apart from the governing equations, boundary conditions are needed to complete the numerical model. They are set as follows:

(1) Inlet: a uniform inlet air velocity in the range of 0.1 m/s - 4 m/s is imposed in the inlet plane with the pollutant mass fraction $c_p = 0$. The initial condition for wind turbulent kinetic energy k is

$$k = \frac{3}{2} (\bar{u} I)^2 \quad (4)$$

where

$$I = 0.16 (Re_D)^{\frac{1}{8}} \quad (5)$$

where $\bar{u}$ is the mean velocity, I is the turbulent intensity, Re_D is the Reynolds number of the inlet plane based on the hydraulic diameter of the wind-tunnel cross section. The dissipation rate ε is specified as

$$\varepsilon = c_{\mu}^{\frac{3}{4}} \frac{k^{\frac{3}{2}}}{l} \quad (6)$$

where l is the turbulence length scale, equals to $0.07L$, L is the hydraulic diameter of inlet plane ($L = 1.8$ m), $c_{\mu} \approx 0.085$ [48].

(2) Walls: all the building and roughness element facets, the ground, side and top of the wind tunnel were set as walls, for which a no-slip condition is imposed (i.e. $u = v = w = 0.0$ m/s). The standard wall functions of Launder and Spalding [49] (also see Tao [50]) was used to deal with the solid surfaces of the NWT for the RNG k - ε models.

(3) Outlet: at the exit plane an outflow boundary condition is imposed where the first derivatives for all flow variables along flow direction equal zero.

(4) Pollution source intensity: the pollutant source is only configured in Model 4 (street canyon model) for numerical validation. The release rate (Q_e , surface source) of the pollution source (the mixture of SF₆ and nitrogen with the mass fraction of SF₆ being 0.25) is 0.025 g/(m²·s), imposed in the ground-level street within a volume of 0.48 m× 0.1 m× 0.004 m to simulate the exhaust of automobile (shown in Fig 1(b)) .

2.1.4. Numerical techniques

The model equations were discretized with the finite volume method (FVM), and solved by the commercial computational fluid dynamics software, FLUENT 14.0. The SIMPLE algorithm was adopted to handle the velocity-pressure coupling and second order upwind scheme was applied to discretize the convective term for a reasonable numerical precision [50, 51]. The convergence criterion of the iteration is the relative residuals of all dependent variable being less

than 10^{-5} . This is a general practice for examining convergence and well-accepted in similar simulations [52, 53].

The mesh of the NWT model was generated by the software GAMBIT 2.4.6. The computational domain near the spires was discretized by unstructured elements. Except that, the other domain was discretized by hexahedral grids with variable sizes: close to the building wall the mesh is the finest with the cells magnitude of 1-5 mm, a coarser resolution near the ground and roughness elements with the magnitude of 0.5-4 cm, and a fairly coarse resolution (5-12 cm) in the regions near the upper boundaries of the domain. The mesh around the Model 2 is shown in Fig. 3, for example.

2.2. Experimental validation setups

The experiments for validating the NWT model were performed in TJ-1 boundary-layer wind tunnel. According to ASHRAE [54], to simulate an urban atmospheric boundary layer, the velocity $u(z)$ profile (Eq. 7) and the turbulence intensity $I_u(z)$ profile (Eq. 8) ahead of the test section should be reasonably simulated by the power law with an profile exponent α ($\alpha = 0.30$).

$$\frac{u(z)}{u(z_{ref})} = \left(\frac{z}{z_{ref}} \right)^\alpha \quad (7)$$

and

$$\frac{u(z)}{u(z_{ref})} = \left(\frac{z}{z_{ref}} \right)^\alpha \quad (8)$$

where $u(z_{ref} = 0.5 \text{ m}) = 4.0 \text{ m/s}$, $I_u(z_{ref} = 0.5 \text{ m}) = 22 \%$. It is noted that the position at $z_{ref} = 0.5 \text{ m}$ is chosen for mimicking the atmospheric boundary layer of urban terrain according to ASHRAE [54]. In fact, z_{ref} can be changed to the other height, but it should be ensured that both z_{ref} and

$u(z_{ref})$ are on the curve of the fitted power law. The velocity profiles and turbulence intensities ahead of the test section were measured by 3-D Cobra probes [55]. DB-600 SF₆ quantitative detector with accuracy of 0.01 ppm was applied to measure the SF₆ concentration, which was collected into different air sample bags using sampling pumps (sampling flow rate: 150 ml/min; sampling time: 2 min) via receptor tubes that is located in the street center and can move up and down along the height (seen in Fig. 1(b)).

3. Grid-independence examination and validations for NWT model

3.1. Grid-independence examination

To reduce the computational cost, a non-uniform structured grid system is used to discretize the computational domain. The grid with a finest resolution of the cell scale of 0.001 – 0.002 m is used to discretize the building model surface and ground surface. On the roughness surface the finer grid resolution of 0.004 – 0.01 m is used, and the farther the distance from the building model and the roughness, the coarser the grid is applied to discretize the other domain, where the length ratio of two neighborhood cells is kept from 1.04 – 1.18. The grid-independence examinations of the five numerical models were examined to ensure the accuracy of the numerical results. Take Model 1 for instance, four grid systems with 6.26×10^5 cells (Case-1), 3.88×10^6 cells (Case-2), 7.82×10^6 (Case-3) and 1.48×10^7 cells (Case-4) were generated by varying the grid scale and scale ratio of adjacent grids. The results of velocity magnitude against the height in the building wake ($x = 10.94$ m, $y = 0$ m) at the wind-tunnel speed $U_0 = 1$ m/s are compared in Fig. 4. Obviously, the data of Case-1 deviate from that of Cases 2 and 3, but the results of Case-2, Case-3 and Case-4 are fairly close to each other. This indicates that the resolution of the finer grid of Case-2 is adequate to guarantee the computational precision.

Therefore, the final cell number used for all simulations of Model 1 is 3.88×10^6 . The grid-independence examinations of the other four models were also analyzed, and the grid numbers of 3.46×10^6 , 3.22×10^6 , 3.04×10^6 and 2.95×10^6 were found to be appropriate for Models 2-5, respectively. In addition, for other two turbulence models and other inlet velocities our simulation results also show that the aforementioned grid numbers can obtain grid-independent solutions. For the simplicity of presentation, such comparison results are not presented here.

3.2. Validations for NWT model

To validate the numerical results, wind tunnel measurements were conducted for five models in TJ-1 wind tunnel. Take Model 4 for example, the dimensionless velocity distributions predicted from three turbulence models are compared with the experimental results at two positions: dimensionless stream-wise velocity (u/U_0) on the building roof (A: $x = 10.84$ m, $y = 0$ m) (Fig. 5(a)) and dimensionless mean velocity (U/U_0) at the street canyon center (B: $x = 11.0$ m, $y = 0$ m) (Fig. 5(b)). The following features may be noted from Fig. 5(a-b). First, In Fig. 5(b) the numerical results from RNG model agree better with the experimental data, with the RNG results being 4.52% deviation with experimental results less than the standard $k-\varepsilon$ model of -8.47 % deviation (shown in Table 4). Second, some negative values of u/U_0 in a very narrow region attached on the building roof are detected in both experimental and computational results at position A, which could be the consequence of flow separated at the top edge of a cuboid building and reattached very similar to the results of Uehara et al. [21]. The results of Tominaga and Stathopoulos [56] showed that the standard $k-\varepsilon$ model could not reproduce the reverse flow on the roof. In our work, however, a small reverse flow is produced by the standard $k-\varepsilon$ model with $U_0 = 4$ m/s, which might be resulted from the finer mesh on the building roof. It is noted

that different scaled velocities are used for locations A and B from measurement considerations: at location A an accurate measurement is easier than that at location B. Thus for A u/U_0 is adopted where u includes both direction and magnitude, while at B it is replaced by magnitude U . Table 4 lists the quantitative comparison of U/U_0 between the experimental and numerical results for Models 1 and 4 under two Re_r numbers, which shows that the mean deviation from the RNG $k-\varepsilon$ model is 4.4%, less than the standard (7.2%) and realizable (6.4%) $k-\varepsilon$ models. The quantitative analysis is consistent with the above qualitative discussion in Fig. 5(a-b), which further proves the RNG model can perform better for flow simulation in the NWT model. The comparisons of concentration (c) obtained from three turbulent models and wind tunnel measurements at $U_0 = 4$ m/s against height at position B ($x = 11$ m, $y = 0$ m) are shown in Fig. 6, which further confirm that the RNG $k-\varepsilon$ model is much better for predicting the pollutant dispersion.

Figures 7(a) and (b) show the comparisons of dimensionless velocity and turbulent intensity profiles, respectively, which are obtained by the RNG $k-\varepsilon$ model, experiment and the power law fitting from experimental data (Eqs. 7 and 8, where $a = 0.3$, $u(z_{ref} = 0.5 \text{ m}) = 4.0$ m/s, $I_u(z_{ref} = 0.5 \text{ m}) = 22 \%$.) at position C ($x = 10.5$ m, $y = 0$ m) without building models. The deviations of measured and predicted profile distributions with the power law fitting are both less than 5%, which indicates that the air flowing through the element configurations shown in Fig. 2 could well perform and simulate the flow characteristics of the urban atmospheric boundary layer experimentally and numerically.

In addition, to examine whether different turbulence models would affect the values of RRC , apart from the RNG $k-\varepsilon$ model, a low-Reynolds-number turbulence model [57] was also adopted for Model 1 whose numerical grids was refined in the thickness of the wall boundary-

layer (at least ten nodes in the viscous sub-layer). Numerical simulations of the low Reynolds number model were performed for the cases of U_0 from 0.1 m/s to 4.0 m/s (the Re_D from 1.2×10^3 to 4.9×10^5) to investigate the relative change of the dimensionless velocity distributions. Figure 7(c) compares the dimensionless velocity distributions between the RNG $k-\varepsilon$ model and the low $k-\varepsilon$ model with $U_0 = 0.1$ m/s. Although due to considering the effects of molecular viscosity by the low Re $k-\varepsilon$ model, there exists about 5% ~ 10% discrepancies in the building-wake regions where the local $Re_t < 150$ for this two turbulent models, the velocity distributions get a good agreement above the building model where the local $Re_t > 150$. Moreover, with the Re_D increase, the discrepancies in the velocity distributions get smaller and smaller for this two models. Our previous work illustrated that the critical Re number was independent on the three high-Reynolds-number models (standard, RNG and realizable $k-\varepsilon$ models) [37]. In this study, we can expect that the predicted critical Re number is independent on the turbulence model adopted, at least in the range of standard $k-\varepsilon$ model and the low Re $k-\varepsilon$ model (details will be given later). In consideration of the time consuming and the difficulties in mesh generation for the low Reynolds number $k-\varepsilon$ model, the RNG $k-\varepsilon$ model with the standard wall function is adopted to simulate the turbulent flow for the following study.

4. Results and discussion

4.1. Change in the Re_r and Re_H with the wind-tunnel speeds

The velocity profiles of a turbulent boundary layer can be well established by wind tunnel experiment and numerical simulations (seen in Fig. 7(a)). According to the boundary-layer theory, the region closest to the boundary is called the laminar sub-layer, because within the region turbulence is suppressed by viscosity. In this region, the velocity profile is defined by the

stress-relation and proportional to the height z (Eq. 9) [21, 58, 59]. Above the laminar sub-layer, it is defined as logarithmic layer, where the velocity profile is logarithmic. The profile shape is dependent on both the ground stress (through u^*) and the ground texture (roughness), described by the characteristics roughness length (z_0). Figure 8 shows the dimensionless velocity distributions against the height at position C without building models with the wind-tunnel speeds changing from 0.1 to 4.0 m/s. It is interesting to note that the velocity profiles shown in Figs. 7 and 8 conform well to the atmospheric boundary-layer profiles according to ASHRAE [54] (5% deviation). From Fig. 8 it is noted that below about 0.01 m several points closest to the boundary could be confirmed to lie inside the laminar sub-layer. The logarithmic layer may begin from 0.04 to 0.8 m, so the simulated height of the atmospheric boundary-layer is at least 80 m (scale ratio 1:100). In the logarithmic layer, the dimensionless velocities reach an agreement more easily than that in the laminar sub-layer due to the effect of viscous forces from the ground. The predicted roughness length (z_0) is 4.7 mm, deduced from the line fitted to the mean velocity distribution within the range of $0.05 \text{ m} \leq z \leq 0.8 \text{ m}$. The friction velocity (u^*) can be estimated by fitting the logarithmic profiles (Eq. 10) corresponding to different wind-tunnel speeds. The values of Re_r and Re_H are summarized in Table 5.

With the above discussion the velocity profile in laminar sub-layer and in the logarithmic layer are shown as follows:

Laminar sub-layer:

$$u(z) = \frac{u^{*2} z}{\nu} \quad (9)$$

Logarithmic layer:

$$u(z) = \frac{2.3u^*}{\kappa} \lg(z / z_0) \quad (10)$$

where $\kappa = 0.4$ is an empirical constant, known as von Karman's constant.

4.2. Variations of velocity distribution with U_0 around different building models

The dimensionless distributions of mean velocity (U/U_0) around building Models 1, 3, and 5 predicted by the RNG $k-\varepsilon$ turbulence models are shown in Figs. 9 (a), (b) and (c) respectively, with the wind-tunnel speeds (U_0) varying from 0.1 to 4.0 m/s. The values of Re_r corresponding to the wind-tunnel speeds are given in Table 5.

On the whole, Figs. 9(a-c) show that the velocity distributions vary with U_0 and the variation gradually becomes less significant with the increase of U_0 . This implies that with increasing U_0 (hence Re_r) the difference in flow structures gradually diminishes. Such variation trends are the same for the five models. Another notable feature is that the local diminishing rate of difference in velocity distributions varies with the detective location. Generally speaking, for the locations far away from the solid wall, the dimensionless local velocity distribution is easy to be close to each other, while for locations close to solid wall the diminishing rate of difference in local velocity distribution is much slower than that of far from the wall. Thus we suggest that when the critical Reynolds number for the flow-independence is mentioned, it is vital to indicate the studied region is for the entire flow or for some special region where our research interest is focused on.

According to the discussions, there should exist the most difficult regions where the value of the $Re_{r,crit}$ is the largest. That is to say it requires a very high wind-tunnel speed to reach Re -independent regime for these regions, and under this circumstance other regions can satisfy the local flow structure similarity. Snyder [17] and Uehara et al. [21] suggested the values of the

$Re_{r,crit}$ are 2.5 and 5.4, respectively. However, these critical values were obtained by qualitative analysis. And from the analysis of Figs. 9(a-c), we can conclude that the values of the $Re_{r,crit}$ will change with the different regions we are interested in for the given configuration of the roughness elements.

4.3. The physical quantity for determining $Re_{r, crit}$

The above discussions on the Re -independence of flow structure around the different building models are all qualitative. To investigate the Re -independence quantitatively and determine the specific value of the $Re_{r,crit}$, for a given flow condition a more precisely physical quantity is highly needed. We proposed the following quantity (RRC) given in Eq. 11 for judging whether the flow can be regarded into the Re -independence regime [37]

$$RRC = \frac{\Delta V/V}{\Delta Re_r/Re_r} \quad (11)$$

where V is the dimensionless characteristic velocity and ΔV is its change corresponding to the change in Re_r , ΔRe_r . When RRC is less than a value, the flow structure can be regarded as Re -independent. According to conventional engineering practices, variation less than 5% can often be neglected [37]. In this study, we hence adopt this threshold. Due to the differences of the relative strength of Reynolds stress and viscous stress, the curves of RRC against Re_r vary with locations. Figures 10 (a-e) exhibit the values of RRC for different locations varying against Re_r and Re_H around the five building models predicted by the RNG k - ε turbulence models. In Fig.10, V refers to the average values of dimensionless velocities along the lines in different planes, such as the pedestrian level plan ($z = 0.015$ m), the planes closest to the ground ($z = 0.002$ m) and to

the building roof (0.002 m from the roof), far away from the building models (0.04 m far away from the roof), and vertical planes between the two buildings.

Figures 10 (a) and (b) show the curves of RRC varying against Re_r and Re_H around Models 1 and 2 with the similar detective regions. Despite the difference of the two models, the variation trends of the three curves corresponding to the same detective regions are quite similar. The flow structure in the regions far away from the models ($RRC-2$) can get into Re -independence easily due to the negligible viscous stress, where the $Re_{r,crit}$ equals to 2.5. On the contrary, the flow structure closest to the ground behind the building models ($RRC-3$) need a larger $Re_{r,crit}$ (about 42) to get into Re -independence regime. The values of $Re_{r,crit}$ in the interesting pedestrian level plane ($RRC-3$) are the same ranging from 20 to 25 for the two single models. In addition, $Re_{H,crit}$ is affected by the building height strongly. Specifically, the values of $Re_{H,crit}$ are quite different with 3.6×10^3 and 1×10^4 in the pedestrian level planes for the two models ($H_1 = 0.1\text{m}$ and $H_2 = 0.2\text{ m}$), respectively. The same conclusions can be obtained from the other planes studied. In our previous study [37] it has been shown that the numerically determined critical Reynolds number is not sensitive to the three turbulence models. In order to further examine whether such insensitivity of the critical Reynolds number determination is still kept when the low-Reynolds number model is used, for which no any wall function is needed, the comparison between the results from RNG and one low Reynolds number model is conducted. The $RRC-1-1$ curve in Fig. 10(a) is obtained from low Reynolds number model, which is in good agreement with RRC curves from RNG high Reynolds number (Fig. 10(a)). This comparison indicates that the values of $Re_{r,crit}$ in the pedestrian level planes are independent on the turbulent models, regardless of the high Reynolds model or the low Re $k-\varepsilon$ model.

Figures 10(c-d) show the RRC varying against Re_r and Re_H around the street canyon models with two different configuration buildings, which belong to the step down canyon (Model 3) and regular canyon (Model 4), respectively. The type of flow regime is known as “skimming flow regime” [13]. For the pedestrian level planes ($z = 0.015$ m) of the two models, the values of the $Re_{r,crit}$ are almost the same, which is suggested to be 25. The curves of $RRC-2$ in Figs. 10(c-e) give the values of the mean $Re_{r,crit}$ around Models 3, 4 and 5 are from 60 to 75, which means the geometric regions denoted in $RRC-2$ are the most difficult areas that need higher wind-tunnel speed to get into Re -independence.

Figure 10(e) shows the curves of RRC against Re_r and Re_H in the vertical center planes of Model 5 along the x axis direction. Comparing $RRC-2$ to $RRC-4$, it needs a higher wind-tunnel speed for the flow in the vertical center line between the first two building models ($RRC-2$) to reach Re -independence regime than that in the last two building models ($RRC-4$). The quantitative results agree well with the qualitative analysis of the dimensionless velocity distributions in Figs. 9 (c1) and (c2), due to the different building configurations resulting in the different flow structures and the discrepancies among the relative viscous stress.

From Figs. 10(a-e), two important findings can be noted. First, the curves of RRC vs. Re_r have a sharp decrease with increasing Re_r in the low Re_r region, while when Re_r is larger than a certain value RRC becomes quite small and its decreasing trend is quite mild. Such variation patterns of RRC vs. Re_r actually reflect that there exist two flow regimes: one is a strong Re -dependent regime and the other is a weak Re -dependent regime. This discovery gives a strong support to the existence of Re -independent regime for boundary-layer flow over a rough surface. Second, there exist appreciable differences among the values of $Re_{r,crit}$ at different locations due to the discrepancy between the relative strength of Reynolds stress and viscous stress. However,

all the mean values of the $Re_{r,crit}$ in the interested pedestrian level planes ($z = 0.015$ m) are in the range of 20 to 25 for the five models studied, therefore we suggest that the $Re_{r,crit}$ is 25. The values of the $Re_{H,crit}$ for the most difficult regions around the five models are in the range of 60-75, we thus suggest that the $Re_{r,crit}$ of the most difficult regime is 75. For the study of pollutant transport and their effects on human health, it is reasonable to select the local critical Reynolds number in the pedestrian level plane as the criterion of flow-independence to economically conduct wind-tunnel experiments.

4.4. Further confirmation of $Re_{r,crit}$ in the pedestrian level plane

To further examine the flow structure similarity, the dimensionless velocity contours in the pedestrian level plane ($z = 0.0015$ m) around Model 4 at different Re_r predicted by the RNG $k-\epsilon$ turbulent models are shown in Fig. 11, where the color labels represent the velocity magnitude. The flow contours alter appreciably with increasing Re_r in the low Re_r range (Figs. 11(a-c)) while when Re_r is larger than 25 the contours are almost identical (Figs. 11(d-f)). This further confirms that the value of 25 could be taken as the critical Reynolds number when focus is put in the pedestrian level plane. Moreover, the dimensionless velocity contours of the other four building models show the same results.

Figure 12 describes the variations of the dimensionless mean concentration, K , in the pedestrian level planes ($z = 0.015$ m) between the two building models of Model 4 against the various Re_r . K is specified as

$$K = cu_h h / (Q_e / l) \quad (12)$$

where c is the measured mass concentration of SF_6 , u_h is the mean wind speed at the height (h) in the undisturbed approaching flow and Q_e / l (line source) is the tracer gas source strength per unit

length. To indicate the change degree of the dimensionless mean concentration, a parameter of relative difference (RD) is defined as

$$RD = \frac{K^* - K}{K} \quad (13)$$

where K^* presents the previous concentration value, K presents the present concentration value, both are related to Re_r . Figure 12 presents that the value of K has a sharp decrease with increasing Re_r in the low Re_r range, while the alteration becomes mild as Re_r over a certain value, which shows a similar variation tendency with the curves of $RRC-Re_r$ in Fig.10. This reveals that there exists a critical Re_r over which the dimensionless distribution of the pollutant concentration will change very little with Reynolds number. It deserves to note that the critical Reynolds number is about 25 as the value of RD less than 0.05, which can be regarded as the dispersion independence in the engineering practice. To further confirm the Re -independence of pollutant dispersion, the variations of dimensionless pollutant concentration in the pedestrian level plane with various Re_r (from 2.86- to 92.67) for Model 4 are presented in Fig. 13. It is noted that when Re_r is larger than 25, the distribution patterns of the dimensionless concentration, K , remain almost unchanged in the pedestrian level plane. These results once again show the feasibility of the proposed $Re_{r,crit}$ for passive dispersion studied. The agreement of Re -independence between flow structure and pollutant concentration distribution further demonstrates that the criterion of Re -independence of flow structures can be used for guiding the pollutant dispersion in wind-tunnel study.

5. Conclusions

This paper is devoted to the Re -independence of air flow and pollutant dispersion under the

urban boundary layer. The NWT model with RNG $k-\varepsilon$ turbulence model was applied to search for the critical Reynolds number. The following conclusions can be obtained under the simulated atmospheric boundary layer.

(1) There exist discrepancies in the values of $Re_{r,crit}$ at different locations due to the differences in the relative strengths between Reynolds and viscous stress. Thus it is suggested that when the $Re_{r,crit}$ for the flow-independence is mentioned, it is necessary to indicate which region it is referred to.

(2) For a given flow condition (the same urban atmosphere boundary layer ahead of the buildings), the predicted $Re_{r,crit}$ by the RNG and low Reynolds number $k-\varepsilon$ model, respectively, are the same, which implies that by our RRC criterion the numerically predicted critical Reynolds number is independent at least on the turbulence models adopted in this paper.

(3) According to the 5% threshold of the RRC , the mean $Re_{r,crit}$ is suggested to be 25 in the pedestrian level planes for the flow passing the five different scaled building models, which is further verified by the dimensionless velocity contours in the pedestrian level plane. The mean $Re_{r,crit}$ can be considered to be independent on the building model structures (such as sizes, shapes, single or multiple). However, the $Re_{H,crit}$ is strongly influenced by the building structures, especially the building height, hence it is a case-dependent quantity and not suitable to be regarded as a general criterion to identify the Re -independence of flow structure.

(4) The variations of the dimensionless concentration K vs. Re_r and its relative difference RD vs. Re_r indicate that for the wind-tunnel study of air flow and pollutant passive dispersion, for the configurations tested the flow structure independence can guarantee the variation of the dimensionless concentration being Re -independent in the pedestrian level plane.

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Captions

Fig. 1. Photographs of TJ-1 boundary-layer wind tunnel and test configurations.

Fig. 2. Computational domain and five scaled models.

Fig. 3. Grid view of Model 2.

Fig. 4. Grid independence assessment by Model 1.

Fig. 5. Comparisons of dimensionless velocities between numerical simulation and experiments at $U_0 = 4$ m/s.

Fig. 6. Comparisons of concentration (c), between numerical simulations with three turbulent models and experiments at $U_0 = 4$ m/s against height at the center of the Model 4.

Fig. 7. Comparisons of dimensionless mean velocity and turbulent intensity against height with power law, numerical simulation and experiments.

Fig. 8. Changes in dimensionless mean velocity (U/U_0) profiles with wind-tunnel speeds from 0.1 m/s to 4.0 m/s at the position C (from NWT model).

Fig. 9. Variations of dimensionless mean velocity (U/U_0) distributions of different models obtained from the RNG $k-\varepsilon$ model.

Fig.10. RRC against Re_r/Re_H at different positions around five scaled models.

Fig. 11. Variations of dimensionless velocity contours in the pedestrian level plane with various Re_r for Model 4.

Fig. 12. Variations of the dimensionless mean concentration K and its relative difference RD with various Re_r in the pedestrian level plane around Model 4.

Fig. 13. Variations of dimensionless pollutant concentration in the pedestrian level plane with various Re_r for Model 4.

(a) Inner side of TJ-1 boundary-layer wind tunnel

(b) Street canyon model (Model 4)

Fig. 1. Photographs of TJ-1 boundary-layer wind tunnel and test configurations.

(a)

(b)

Fig. 3. Grid view of Model 2 (a) in x - z plane at $y = 0$ m; (b) in x - y plane at $z = 0.08$ m.

Fig. 4. Grid independence assessment by Model 1.

(a) At location A

(b) At location B

Fig. 5. Comparisons of dimensionless velocities between numerical simulation and experiments at $U_0 = 4$ m/s.

Fig. 6. Comparisons of concentration (c), between numerical simulations with three turbulent models and experiments at $U_0 = 4$ m/s against height at the center of the Model 4.

(a)

(b)

Fig. 7. Comparisons of dimensionless mean velocity (a) U/U_{ref} , and turbulent intensity (b) Iu/Iu_{ref} against height with wind tunnel measurement, CFD, and fitting power law curve at position C ($x = 10.5$ m, $y = 0$ m) without building models. (c) Comparisons of velocity distributions for the RNG and low Re $k-\varepsilon$ model with Model 1.

Fig. 8. Changes in dimensionless mean velocity (U/U_0) profiles with wind-tunnel speeds from 0.1 m/s to 4.0 m/s at the position C (from NWT model).

(a1) Model 1: on the roof ($x = 10.84$ m, $y = 0$ m)

(a2) Model 1: in the building wake flow ($x = 10.94$ m, $y = 0$ m)

(b) Model 3: between the two buildings ($x = 10.95$ m, $y = 0$ m)

(c1) Model 5: between the first two buildings ($x = 10.95$ m, $y = 0$ m)

(c2) Model 5: between the last two buildings ($x = 11.15$ m, $y = 0$ m)

Fig. 9. Variations of dimensionless mean velocity (U/U_0) distributions of different models

obtained from the RNG $k-\varepsilon$ model.

(a) *RRC* around Model 1

- ① Region for *RRC*-1 and *RRC*-1-1 ($10.92 \text{ m} \leq x \leq 11.0 \text{ m}$, $z = 0.015 \text{ m}$, $y = 0 \text{ m}$)
- ② Region for *RRC*-2 ($10.84 \text{ m} \leq x \leq 10.88 \text{ m}$, $z = 0.14 \text{ m}$, $y = 0 \text{ m}$)
- ③ Region for *RRC*-3 ($10.92 \text{ m} \leq x \leq 11.0 \text{ m}$, $z = 0.002 \text{ m}$, $y = 0 \text{ m}$)

(b) RRC around Model 2

- ① Region for $RRC-1$ ($10.92 \text{ m} \leq x \leq 11.10 \text{ m}$, $z = 0.015 \text{ m}$, $y = 0 \text{ m}$)
- ② Region for $RRC-2$ ($10.84 \text{ m} \leq x \leq 10.88 \text{ m}$, $z = 0.24 \text{ m}$, $y = 0 \text{ m}$)
- ③ Region for $RRC-3$ ($10.92 \text{ m} \leq x \leq 11.10 \text{ m}$, $z = 0.002 \text{ m}$, $y = 0 \text{ m}$)

(c) RRC around Model 3

- ① Region for $RRC-1$ ($10.92 \text{ m} \leq x \leq 10.98 \text{ m}$, $z = 0.015 \text{ m}$, $y = 0 \text{ m}$)
- ② Region for $RRC-2$ ($10.92 \text{ m} \leq x \leq 10.98 \text{ m}$, $z = 0.002 \text{ m}$, $y = 0 \text{ m}$)
- ③ Region for $RRC-3$ ($11.12 \text{ m} \leq x \leq 11.20 \text{ m}$, $z = 0.002 \text{ m}$, $y = 0 \text{ m}$)

(d) RRC around Model 4

- ① Region for $RRC-1$ ($10.94 \text{ m} \leq x \leq 11.06 \text{ m}$, $z = 0.015 \text{ m}$, $y = 0 \text{ m}$)
- ② Region for $RRC-2$ ($x = 11.00 \text{ m}$, $0.02 \text{ m} \leq z \leq 0.14 \text{ m}$, $y = 0 \text{ m}$)
- ③ Region for $RRC-3$ ($11.24 \text{ m} \leq x \leq 11.6 \text{ m}$, $z = 0.015 \text{ m}$, $y = 0 \text{ m}$)
- ④ Region for $RRC-4$ ($10.94 \text{ m} \leq x \leq 11.06 \text{ m}$, $z = 0.002 \text{ m}$, $y = 0 \text{ m}$)

(e) RRC around Model 5

- ① Region for RRC-1 ($10.92 \text{ m} \leq x \leq 10.98 \text{ m}$, $z = 0.015 \text{ m}$, $y = 0 \text{ m}$)
- ② Region for RRC-2 ($x = 10.95 \text{ m}$, $0.02 \text{ m} \leq z \leq 0.08 \text{ m}$, $y = 0 \text{ m}$)
- ③ Region for RRC-3 ($11.12 \text{ m} \leq x \leq 11.18 \text{ m}$, $z = 0.015 \text{ m}$, $y = 0 \text{ m}$)
- ④ Region for RRC-4 ($x = 11.15 \text{ m}$, $0.02 \text{ m} \leq z \leq 0.08 \text{ m}$, $y = 0 \text{ m}$)
- ⑤ Region for RRC-5 ($11.32 \text{ m} \leq x \leq 11.4 \text{ m}$, $z = 0.015 \text{ m}$, $y = 0 \text{ m}$)

Fig. 10. RRC against Re_r/Re_H at different positions around five scaled models.

Fig. 11. Variations of dimensionless velocity contours in the pedestrian level plane with various Re_r for Model 4.

Fig. 12. Variations of the dimensionless mean concentration K and its relative difference RD

with various Re_r in the pedestrian level plane around Model 4.

Fig. 13. Variations of dimensionless pollutant concentration in the pedestrian level plane with various Re_r for Model 4.

Table Captions

Table 1 The types of Reynolds number

Table 2 The critical Reynolds number

Table 3 The governing equations for the three k - ε turbulence models

Table 4 Quantitative comparisons of wind tunnel measurements and three turbulence models

Table 5 Reynolds numbers corresponding to wind-tunnel speeds

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 -the 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 -the 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^* -friction 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 - the external diameter of stack; U_s -the 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 - the internal diameter of stack; U_e -the average exit velocity of the emission.

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

Table 3The governing equations for the three k - ε turbulence models

	Eddy viscosity η_t	Transport equation of k	Transport equation of ε
Standard k - ε model	$\eta_t = \rho C_\mu \frac{k^2}{\varepsilon},$ $C_\mu = 0.09$	$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] +$ $G_k - \rho \varepsilon$ $G_k = \eta_t \frac{\partial u_i}{\partial x_j} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad \sigma_k = 1.0$	$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] +$ $\frac{\varepsilon}{k} (C_{\varepsilon 1} G_k - C_{\varepsilon 2} \rho \varepsilon)$ $C_{\varepsilon 1} = 1.44, C_{\varepsilon 2} = 1.92, \sigma_\varepsilon = 1.3$
RNG k - ε model	$\eta_t = \rho C_\mu \frac{k^2}{\varepsilon},$ $C_\mu = 0.085$	$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] +$ $G_k - \rho \varepsilon$ $\sigma_k = 0.7179$	$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] +$ $\frac{\varepsilon}{k} (C_{\varepsilon 1} G_k - C_{\varepsilon 2} \rho \varepsilon)$ $C_{\varepsilon 1} = 1.42 - \frac{\tilde{\eta}(1 - \tilde{\eta}/4.38)}{1 + 0.012\tilde{\eta}^3}, \quad \tilde{\eta} = S \frac{k}{\varepsilon},$ $C_{\varepsilon 2} = 1.68, \quad \sigma_\varepsilon = 0.7179$
Realizable k - ε model	$\eta_t = \rho C_\mu \frac{k^2}{\varepsilon}, C_\mu = \frac{1}{4.04 + A_S k u^* / \varepsilon}$ $u^* = \sqrt{S_{ij} S_{ij} + \tilde{\Omega}_{ij} \tilde{\Omega}_{ij}}, \tilde{\Omega}_{ij} = \Omega_{ij} - 2\varepsilon_{ijk} \omega_k$ $A_S = \sqrt{6} \cos \phi, \phi = \frac{1}{3} \arccos(\sqrt{6} W)$ $W = \frac{S_{ij} S_{jk} S_{jk}}{\tilde{S}^3}, \tilde{S} = \sqrt{S_{ij} S_{ij}}$	$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] +$ $G_k - \varepsilon, \quad \sigma_k = 1.0$	$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\eta + \frac{\eta_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] +$ $C_1 \rho S_\varepsilon - C_2 \rho \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}}$ $C_1 = \max \left[0.43, \frac{\tilde{\eta}}{\tilde{\eta} + 5} \right], C_2 = 1.9, \sigma_\varepsilon = 1.2$

Table 4

Quantitative comparisons of wind tunnel measurements and three turbulence models

$RD = \frac{(U/U_0)_{NWT} - (U/U_0)_{EXP}}{(U/U_0)_{EXP}} \times 100\%$
Re_τ		37	113	37	113	37	113	37	113
Wind tunnel measurement	U/U_0	0.79	0.788	0.146	0.149	0.92	0.901	0.166	0.177
Standard k - ε model	U/U_0	0.729	0.726	0.137	0.139	0.86	0.848	0.152	0.162
	$RD(\%)$	-7.72	-7.87	-6.16	-6.71	-6.52	-5.88	-8.43	-8.47
RNG k - ε model	U/U_0	0.762	0.755	0.139	0.155	0.958	0.95	0.159	0.185
	$RD(\%)$	-3.54	-4.19	-4.79	4.03	4.13	5.44	-4.22	4.52
Realizable k - ε model	U/U_0	0.84	0.84	0.154	0.158	0.972	0.952	0.178	0.191
	$RD(\%)$	6.33	6.60	5.48	6.04	5.65	5.66	7.23	7.91

Table 5

Reynolds numbers corresponding to wind-tunnel speeds

U_0 m/s	u^* m/s	$Re_r = u^* z_0 / \nu$ ($z_0 = 4.7$ mm)	U_{H1} ($H_1 = 0.1$ m)	U_{H2} ($H_2 = 0.2$ m)	$Re_H = U_{H1} H_1 / \nu$ ($H_1 = 0.1$ m)	$Re_H = U_{H2} H_2 / \nu$ ($H_2 = 0.2$ m)
0.01	0.010	2.86	0.07	0.092	473	1243
0.02	0.019	6.29	0.138	0.178	932	2405
0.04	0.038	12.83	0.274	0.351	1851	4743
0.06	0.057	19.04	0.525	0.411	3547	5554
0.08	0.076	25.39	0.547	0.698	3696	9432
0.12	0.113	37.13	0.819	1.045	5534	14122
0.16	0.150	48.70	1.092	1.39	7378	18784
0.20	0.186	59.94	1.366	1.736	9230	23459
0.24	0.222	70.94	1.639	2.081	11074	28122
0.28	0.269	84.95	1.859	2.4	12561	32432
0.32	0.295	92.67	2.186	2.772	14770	37459
0.36	0.331	103.02	2.46	3.118	16622	42135
0.40	0.368	113.82	2.734	3.463	18473	46797

 H_1 -the height of Model 1; H_2 -the height of Model 2.