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Large eddy simulation of fire smoke re-circulation in urban street canyons of different aspect ratios

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Abstract

Critical re-circulation phenomenon happens when a fire occurs in an urban street canyon, in which the uprising smoke plume is re-circulated back into the base of the street canyon by the wind-induced flow. This happens when the inertia of the wind flow with a certain so-called critical re-circulation velocity balances the buoyancy force of the fire smoke. The fire smoke dispersion and critical re-circulation wind velocity have been revealed in previous works for urban street canyons with aspect ratio (W/H) of unity. This paper presents an investigation of the effect of street canyon aspect ratio on the above behaviour. Large Eddy Simulation (LES) was performed by Fire Dynamics Simulation (FDS) for a 5 MW fire corresponding to the Heat Release Rate of a burning car. The simulated street canyon has height of 18 m and different width of 9 m, 12 m, 15 m, 18 m, 21 m, 24 m, 27 m, 30 m and 36 m respectively, with aspect ratios varied from 0.5 to 2.0. The smoke soot and CO concentration distribution were presented for different street canyon aspect ratios. It was found that the variation of critical re-circulation wind velocity with street canyon aspect ratio can be divided into three zones. The critical re-circulation wind velocity firstly increases at the first zone, then remains constant at the second zone, and finally increases again at the third zone with the increasing of the street canyon aspect ratio. This special behaviour was explained based on the flow characteristics in the street canyon.

Keywords: Street canyon; Large eddy simulation; Critical re-circulation wind velocity; Smoke; Aspect ratio

Nomenclature

u	wind velocity (m/s)
F_r	Froude number
H	the height of street canyon (m)
W	the width of street canyon (m)
Greek symbols	
u_{ijk}	velocity components in x-direction (m/s)
υ_{ijk}	velocity components in y-direction (m/s)
ω_{ijk}	velocity components in z-direction (m/s)
δt	time step (s)
δx	grid size in x-direction (m)
δy	grid size in y-direction (m)
δz	grid size in z-direction (m)
Subscripts	
c	critical

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i	the position of the cell in *x*-direction
j	the position of the cell in *y*-direction
k	the position of the cell in *z*-direction

1. Introduction

Street canyon is an important part of modern cities and the terminology was first suggested by Vardoulakis et al. [1], as shown schematically in Fig. 1. Because of concerns for the air quality at the street level and its health impacts to the people, street canyon pollution problems have been studied extensively by both experimental and numerical approaches [2-11].

Existing researches show that the buoyancy factors considered by most of the researchers were only limited to buoyancy induced by natural heat source such as solar heating [6, 12-14]. Sini et al. [6] investigated the effects of the wall heat flux due to the solar heating of ground or building walls on the flow structure within the street canyon. Dimitrova et al. [12] studied the thermal effects on the wind field characteristics within the urban environment. Kim and Baik reached the flow characteristics with bottom [13] or bottom and roof heating [14] within the street canyon. All of these former studies considered the weak buoyancy effect only.

However, it should be noted that a strong buoyancy effect will appear if a fire accident occurs in the street canyon. In the real world, a burning vehicle in the street canyon or a fire occurred in each side building of the street canyon not only generates harmful smoke plume but also can arouse strong buoyancy effect. The current research of such buoyancy effect on the transportation of these hazardous combustion products in urban elements is still very few. Since the main cause of the death during urban fires is the toxicity and asphyxiating action of the harmful smoke [15, 16], the street canyon's smoke dispersion characteristic with such strong buoyancy effect should be given considerable attention.

Hu et al. [17] investigated the flow pattern within urban street canyon in presence of strong buoyant contamination sources at the street floor center. This research pointed out that the plume dispersion pattern fell into four regimes with the increase of the wind flow velocity and there was a critical turning point of wind velocity u_c that the plume dispersion pattern changed from regime Ⅱ to regime Ⅲ. Later, Hu et al. [2] studied the pollutant gas dispersion with buoyancy ejected from the adjacent building into an urban street canyon. It was found that the plume ejected from the adjacent building into an urban street canyon under a perpendicular wind flow can also be divided into four regimes with a turning point.

If the perpendicular wind velocity exceeded the turning point which was defined as the critical re-circulation velocity [17], the initially uprising pollutant smoke which would have been vented out of the street canyon by the air of its own buoyancy will be re-circulated back into the street canyon along the wall of the leeward building and diffuses in the entire street canyon. This is a serious situation as the re-circulated smoke will be harmful and toxic to the pedestrian in the street canyon and it may cause traffic accident more easily because that the smoke caused path's visibility to reduce greatly. So, the critical re-circulation wind velocity is a very significant parameter.

The critical re-circulation wind velocity was involved in both of the former work conducted by Hu [2, 17]. The smoke dispersion pattern and the relation between the critical re-circulation wind velocity and buoyancy strength of the fire source which is characterized by Froude number F_r is revealed. In these works, the aspect ratio (W/H) of the street canyon is maintained at unity and the influence of the aspect ratio on critical re-circulation wind velocity was never researched. So, this paper presents a continuous effort to investigate the effect of street canyon aspect ratio on the smoke dispersion and the critical re-circulation wind velocity.

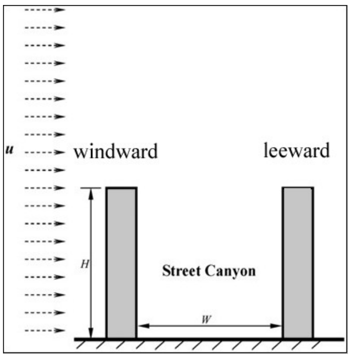

Fig. 1. Schematic of street canyon with perpendicular wind flow.

2. Numerical method and model configuration

2.1. Numerical methodology

Turbulence methods used in CFD generally include Reynolds Averaging Navier-Stokes equation (RANS) method, Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS) [18-20]. DNS directly solves the Navier–Stokes equations without any turbulence model. The smallest dissipative scale known as Kolmogoroff scale is resolved. So DNS can give the most detailed characteristics of the flow [21, 22]. However, it needs so many computer resources that it can hardly be used in majority of the research, particularly the large Reynolds number case such as the simulation in this article [23]. RANS k-ε turbulence model is used to solve the time-averaged equations. It is clear that there is a fatal disadvantage in the RANS k-ε turbulence model that it can't predict the unsteadiness and intermittency of the turbulence flow accurately. So, it is not very suitable to simulate the transient flow characters in and above the street canyon [2]. Large Eddy Simulation (LES) is able to predict the unsteadiness and intermittency which is the most important feature of a strong turbulent buoyancy-driven flow. It has been recently widely applied to simulate the turbulent pollutant transport in street canyons and fire-induced flow in fire scenarios. In LES, the large eddy turbulence is directly computed while the small turbulent motions are modeled by Sub-Grid Models (SGM).Walton et al. [24, 25] demonstrated that the LES predictions could exhibit agreement with the experimental results very well in the street canyon.

Fire Dynamics Simulator (FDS) [26, 27] which was developed by National Institute of Standards and Technology (NIST), solves numerically a form of the Navier-Stokes equations for thermally driven flow. It is now a popular CFD tool in fire related research, as well as used to simulate the concentration and flow distribution in urban street canyons (*e.g.* [2, 17, 28]).

The governing equations which consist of conservation of mass, momentum and the transport of sensible enthalpy for LES simulation can be found from [2, 17, 26, 27].

In FDS, the Courant-Friedrichs-Lewy (CFL) criterion is used along with a self-varying time step [27] for justifying the computational convergence. The physical meaning of such a convergence criteria is that when computing a wave crossing a discrete grid, the time step must be less than the time for the wave to travel adjacent grid points. This criterion is more important for large-scale calculations where convective transport dominates the diffusive one. In FDS, the estimated velocities are tested at each time step to ensure that the following CFL criterion is satisfied [27]:

$$\delta t \cdot \max\left(\frac{|u_{ijk}|}{\delta x}, \frac{|v_{ijk}|}{\delta y}, \frac{|\omega_{ijk}|}{\delta z}\right) < 1 \tag{1}$$

During the calculation, the time step is varying and constrained by the convective and diffusive transport speeds to ensure that the CFL condition is satisfied at each time step [27].

2.2. Physical model setup

In our simulations we changed the street canyon width based on the model used by Baker et al. which were 18 m wide, 18 m high and 40 m long [29]. Nine different aspect ratios were simulated while the building thickness was remained 3 m and the width of the street canyons were 9 m, 12 m, 15 m, 18 m, 21 m, 24 m, 27 m, 30 m and 36 m respectively *i.e.* the aspect ratio varied from 0.5 to 2.0. For the reason of daylighting demand of residents within the buildings on both sides of the street canyon, the aspect ratio should not less than 0.5. On the other hand, in view of saving occupied area, seldom street canyons aspect ratio is larger than 2.0. The simulation cases are summarized in Table 1.

A uniform inlet velocity boundary condition was set at the left side of the simulation domain and the solid surface boundary condition is non-slip. The top and the other three sides of the domain were all set to be naturally opened with no initial velocity boundary condition specified for these openings. The fire source is located at the centre of the street canyon base to produce buoyancy driven plume flow. The heat release rate (HRR) of the fire source considered here was 5 MW, typically a burning car's HRR.

In LES simulation, the grid size is an important factor to be considered. It should be fine enough to include the turbulence scales associated with the largest eddy motions. For the simulation of this paper, the grid size is uniformly 0.25 m in the three spatial directions. All of the simulated cases were summarized in Table 1. The validation of the numerical model had been reported in the former works [2, 30, 31], in which the simulation results from the proposed numerical scheme can give prediction agree well with experimental data.

A typical time-evolution of the time step and the corresponding maximum CFL number for the LES simulation in this paper is shown in Fig. 2. The sudden drop of the time step value takes place when the fire starts. The smaller time steps are required for the equation solver to resolve the fire enhanced turbulent flows. It is shown that the CFL number never exceeds 1. So, the CFL criterion was satisfied during the simulations.

Table 1. Summary of the simulation cases

W:*H*	Wind velocity (m/s)						
9:18	2.0	2.3	2.4	2.5	2.6	2.7	3.0
12:18	2.4	2.5	2.6	2.7	2.8	2.9	3.0
15:18	2.0	2.3	2.5	2.7	2.8	2.9	3.0
18:18	2.8	2.9	3.0	/	/	/	
21:18	2.3	2.4	2.5	2.7	2.8	2.9	3.0
24:18	2.9	3.0	/	/	/	/	/
27:18	2.9	3.0	/	/	/	/	/
30:18	3.0	3.1	3.2	/	/	/	/
36:18	3.0	3.2	3.3	3.4	3.5	3.6	3.7

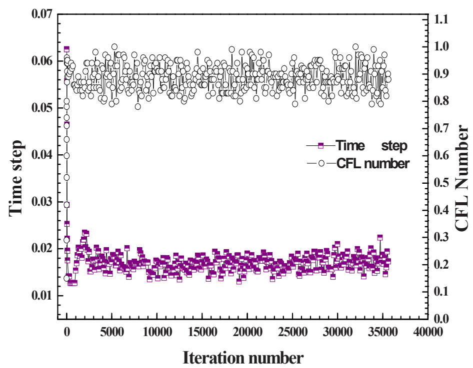

Fig. 2. Typical time step and CFL convergence of the simulation.

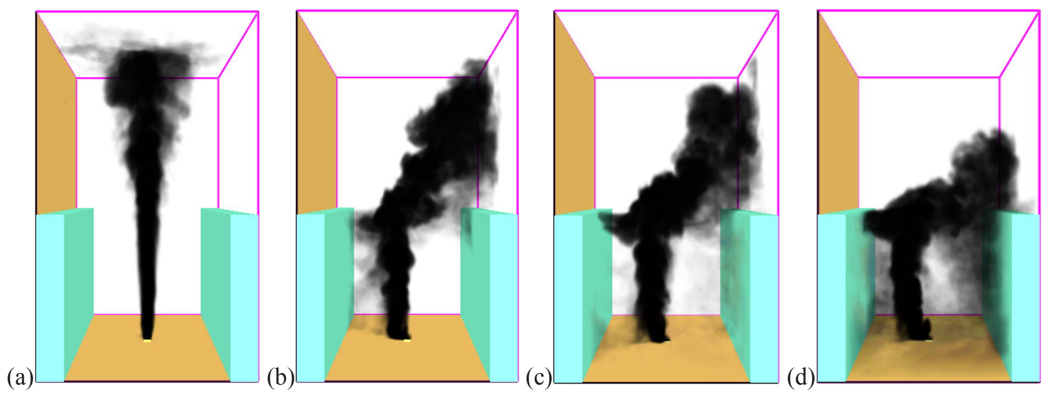

Fig. 3. Smoke plume flow pattern under different wind velocities while *W*=18 m. (a) *u*=0 m/s; (b) *u*=2.8 m/s; (c) *u*=3.0 m/s; (d) *u*=5.0 m/s.

3. Results and discussion

3.1. Smoke soot and CO concentration field

Four distinct regimes were identified to categorize the plume dispersion pattern characteristics under different levels of wind velocities in the former work [17]. Take W=18 m for an example, as shown in Fig. 3, the smoke plume tilt angle increased along with the increasing of the wind velocity. In the first regime, the smoke rose straight until it reached the top of street canyon and then it was blown to the leeward building of street canyon by the wind, but still not touching the building in the leeward direction when the wind velocity smaller than 2.8 m/s. In the second regime, the lower edge of smoke plume begins to touch the leeward side wall when the wind velocity reaches 2.8 m/s. However, the smoke soot cannot get to bottom of the street canyon because of the buoyancy of the fire. In the third regime, when the wind velocity increased to 3.0 m/s, the smoke soot begin to go downstream along the leeward side wall until it arrived to the bottom of the street canyon and starting going horizontally along the floor to the windward building. In the fourth regime, when the wind velocity reached high levels, for example, 5 m/s in Fig. 3, the smoke was easily and heavily re-circulated back into street canyon.

The critical re-circulation phenomena is defined as the attaching leeward wall smoke finally reaches the base of the street canyon and then begins to go horizontally along the floor to the wind ward building. The critical re-circulation wind velocity was determined based on the observation of the smoke flow behaviour along the leeward building side wall. When the wind velocity exceeded this critical re-circulation velocity, here as 3.0 m/s, the smoke soot was re-circulated back into the street canyon and accumulated in the street canyon. If the wind velocity reached higher levels, for example, 5.0 m/s in Fig. 3, the smoke in the ground level in the leeward direction started to extend to the windward part of the street canyon. The entire street canyon was full of smoke.

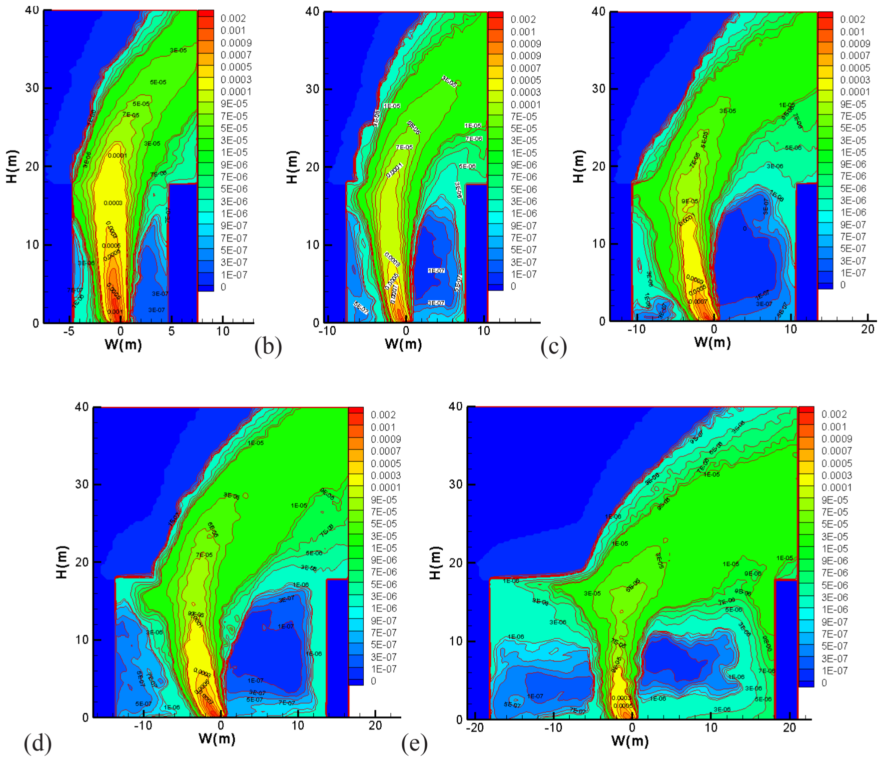

Fig. 4. Typical CO concentration contours of the simulated cases when critical re-circulation phenomena occurred: (a) W=9 m, u=2.4 m/s; (b) W=15 m, u=2.8 m/s; (c) W=21 m, u=3.0 m/s; (d) W=27 m, u=3.0 m/s; (e) W=36 m, u=3.7 m/s.

Figure 4 presents the typical CO concentration contours of the simulated cases. The unit of the CO concentration presented in Fig. 4 is mol/mol which can be converted into a well-known unit ppm by multiplying 10^6. It is obvious that all of them formed large scale vortex except Fig. 4 (a) and it is apparently because the width of the street canyon was too narrow to form large scale vortex as formed in Fig. 4 (b~e). When the wind velocity exceeds the critical re-circulation wind velocity, the CO concentration will suddenly rise in the street canyon. Thus, we paid close attention to the variations of CO concentration distribution along with the change of the aspect ratio when critical re-circulation phenomena occurred.

The pollutant was mainly contained in three regions: rising plume region, windward region and leeward region as shown in Fig. 4. The differences of CO concentration value between windward region and leeward region diminishes as the increasing of the aspect ratio. The pollutant distributed more evenly for a wider street canyon. Another interesting characteristic is that the pollutant is re-circulated to the bottom of the street canyon to form the vortex and then the vortex would carry the pollutant into street canyon in return. But, the interior of the vortex almost has no contaminant nevertheless.

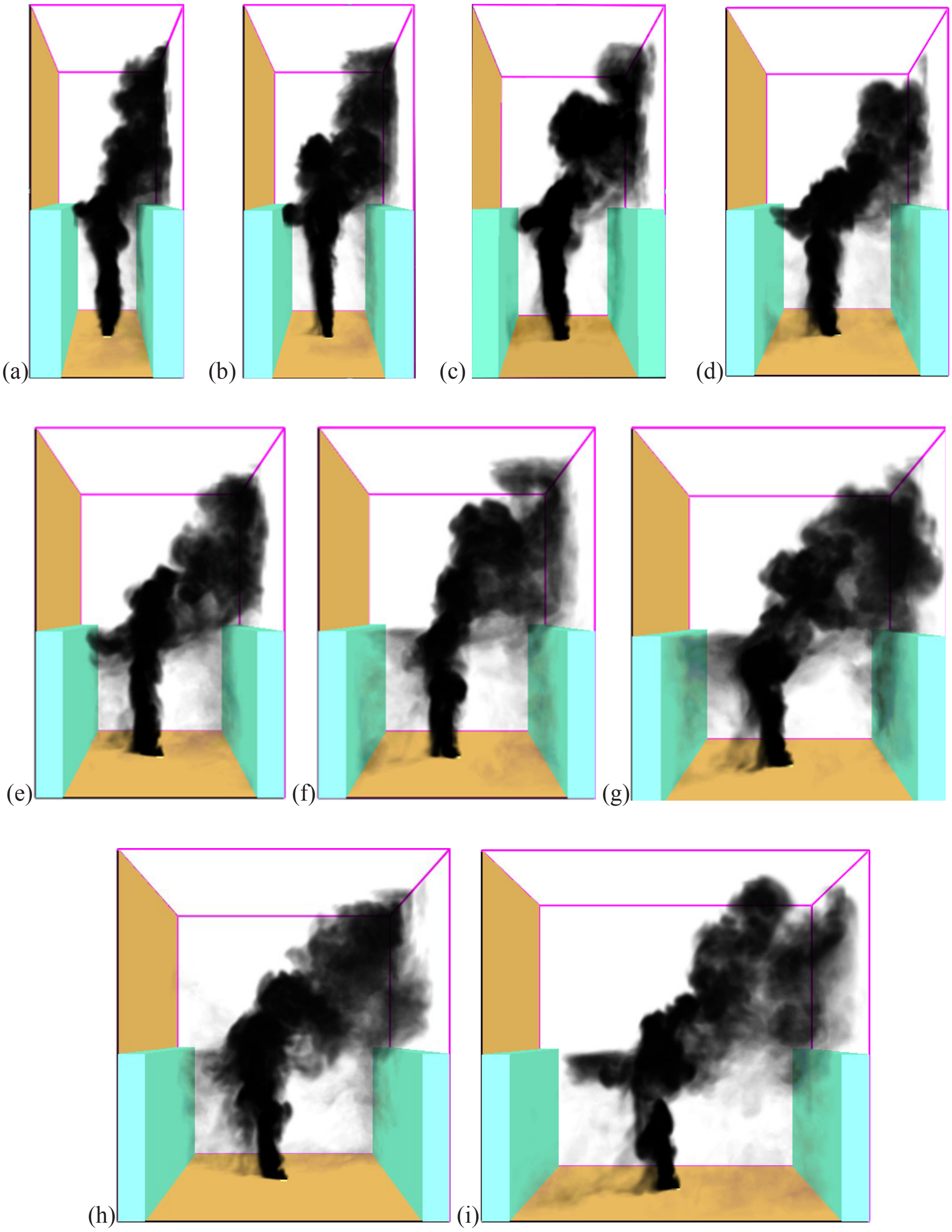

Fig. 5. Critical re-circulation phenomenon at different aspect ratios: (a) W=9 m, u=2.4 m/s; (b) W=12 m, u=2.6 m/s; (c) W=15 m, u=2.8 m/s; (d) W=18 m, u=3.0 m/s; (e) W=21 m, u=3.0 m/s; (f) W=24 m, u=3.0 m/s; (g) W=27 m, u=3.0 m/s; (h) W=30 m, u=3.1 m/s; (i) W=36 m, u=3.7 m/s.

3.2. Change of critical re-circulation wind velocity with aspect ratio

Figure 5 presents the critical re-circulation condition of the whole simulated aspect ratios. From the Figs. 5 (a~c), it can be observed that the critical re-circulation velocity increases with the aspect ratio when the aspect ratio isn't greater than 1. The plume flow format in and above the canyon with three different aspect ratios which are greater than 1 are shown in Figs. 5 (e~i). However, the most striking feature was that Fig. 5 (e~g) indicated that the critical re-circulation wind velocity was a constant i.e. it would remain invariant in a range provide that the aspect ratio exceeded 1 and then the critical re-circulation wind velocity would increase again when the aspect ratio is greater than a value 1.5 as shown in Fig. 5 (h~i).

The wind flow pattern inside street canyons without fire depends on their geometry, in particular, the street canyon aspect ratio. Based on field measurements and mathematical modeling results, Oke [32] identified three flow regimes. For aspect ratio greater than 3.33, the flow fields associated with the buildings do not interact, which results in the isolated roughness flow (IRF) regime. At closer spacing whose aspect ratio between 1.43 and 3.33 the wake behind the windward building is disturbed by the recirculation created in front of the windward building. This is the wake interference flow (WIF) regime. Further reducing the building spacing with aspect ratio less than 1.43 results in the skimming flow (SF) regime [32].

The critical re-circulation wind velocities for different aspect ratios were summarized in Fig. 6. Obviously, it can be divided into three zones according to the aspect ratio. The critical re-circulation wind velocity grows linearly at the initial stage, then maintained at the constant and finally it continued to increase with the increasing of the aspect ratio. The transition between the second and the third zone in Fig. 6 is identical to that of the turning point between skimming flow regime and the wake flow regime. However, even within the skimming flow regime, it is revealed in this paper that there exists another turning point (W:H=1:1). Before this turning point in the skimming flow regime, the critical re-circulation wind velocity increases with aspect ratio of the street canyon but after that it remains constant independent of the aspect ratio.

4. Conclusions

This paper investigates the effect of aspect ratio of the street canyon on the fire smoke dispersion and critical re-circulation wind velocity for the scenario of a fire occurred in an urban street canyon. It is revealed that the change of critical re-circulation wind velocity with aspect ratio of the street canyon can be divided into three zones with two turning points in a u_c *vs* W/H plot as shown in Fig. 6. The first turning point is found at the aspect ratio of unity. The second turning point is at aspect ratio of 1.43 which is identical to the transitional point for the flow pattern in the street canyon from skimming flow regime to wake interference flow regime.

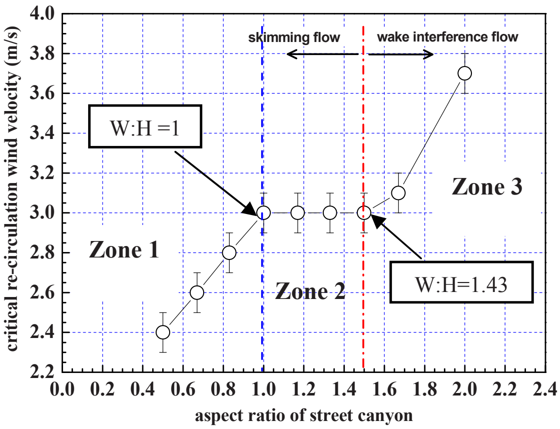

Fig. 6. Critical re-circulation wind velocities *vs.* aspect ratios of street canyons.

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