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The Effect of Locating High-Rise Buildings On the Wind Flow Using CFD Simulation, Case Study Chitgar Towers in Tehran

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ABSTRACT

Nowadays, concentration or dispersion of air pollutants is the main issues of cities and especially metropolitan areas. One of the most important factors in reducing emissions and air conditioning in urban areas is proper wind flow, especially on the pedestrians. The result of the interaction of large-scale flow, the medium-scale and micro-scale form wind flow on the pedestrians. The wind flow on the pedestrians is under the influence of texture, shape and also structure of urban areas. Therefore, we can manage wind flow on the pedestrians and thus improve air quality in the cities with making changes in the size, shape, and layout of the buildings. In this study wind flow in the parts of Chitgar district in Tehran around 80 towers simulated and influence of tall buildings in wind field in the range of approximately 4/8 square kilometers had reviewed. This study is done by using numerical solution of Reynolds average time, Naiver-Stokes equation, and approximate solution of $k-\varepsilon$ *two-equation model of wind flow. In this study wind flow is stimulated in two condition: The First one is the actual pose of the towers and the second is proposed location for the towers. The results show that the displacement and removal of some towers can significantly improve air conditioning around the towers and also so far from the towers.*

Keywords*: Air quality, CFD, buildings, Navier-Stokes equation*

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INTRODUCTION

In the today's world, high rise building is one of the phenomena that large cities have faced. In recent years, the vertical development of cities rightly or wrongly has been one of the important programs of urban development and high-rise building especially in big cities like Tehran has happened. Research shows a close relationship between the rise in high-rise buildings in the metropolitan areas and large reduction in wind speed. for instance Ranjbar et al. studied the effects of wind flow in Tehran (Ranjbar, F., Najafi, H and Minooei.R,2010) Wind data from Doshan tape, Geophysics,Mehrabad Airport and Chitgar meteorological stations collected and studied. The conclusions show that wind speed in Tehran in recent decades has decreased. These changes are more visible, especially in Chitgar station that can be caused by the expansion of the city in West of Tehran.

Baik et al. simulated flow and pollutant dispersion in a densely built-up area of Seoul, Korea (Harlow, F. H, and Nakayama, P. I ,1968). In this study, flow and pollutant dispersion are numerically examined using a computational fluid dynamics (CFD) model coupled to a mesoscale model [fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5)]. The CFD model used is a Reynolds-averaged Navier–Stokes equations model with the renormalization group $k-\varepsilon$ turbulence model. Results from the coupled CFD–MM5 model simulation show that the flow in the presence of real building clusters can change significantly as the ambient wind speed and direction change. Diurnally varying local circulations mainly cause changes in ambient wind speed and direction in the present simulation. Some characteristic flows—such as the double-eddy circulation, channeling flow, and vertical recirculation vortex—are simulated. Pollutant dispersion pattern and the degree of lateral pollutant dispersion are shown to be complicated in the presence of real building clusters and under varying ambient wind speed and direction. This study suggests that because of the sensitive dependency of urban flow and pollutant dispersion on variations in ambient wind, time-dependent boundary conditions should be used to better simulate or predict them when the ambient wind varies over the period of CFD model simulation.

Building configurations in previous CFD modeling studies are diverse with specific research objectives, ranging from an idealized street canyon to a real urban setting. For example, Flaherty et al. numerically investigated flow and plume dispersion in Oklahoma City, Oklahoma, and showed that the many short buildings have a relatively small effect on the flow field, whereas the few tall buildings considerably influence the transport and diffusion of tracer gas (Harlow, F. H, and Nakayama, P. I;1968). (Fig. 1)

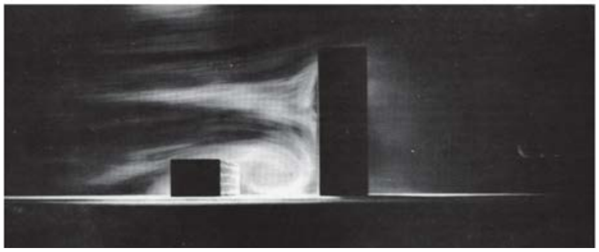

Figure1: Cutting of vertical wind flow around the building short and long.

The complex interactions between urban microclimates and morphologies determine the comfort of pedestrians within cities. In studies carried out by Amorim et al. the wind comfort was measured in the main avenue of the Portuguese city of Aveiro based on international criteria (Launder, B. E. and Sharma, B. I,1974). To this effect, the CFD model Fluent was applied to a 3D virtual domain, constructed from GIS information using a CAD tool, while taking into account the meteorological data measured at a local weather station. Results indicated a highly complex wind flow within the urban canyon, consequence of the existing architectural characteristics and the wind direction. Additionally the canyon orientation, its aspect ratio (with tall buildings at its edge) and the lack of trees combine to induce a swirling flow with velocity intensification along the length of the avenue.In this study, wind speed and pressure field around some isolated towers are simulated. Then, with the change in the layout of the towers, the optimal conditions for increasing wind speed at crossings and reducing the pressure gradient can be simulated around the towers.

2 MATERIALS AND METHODS

In this study, 80 towers in some parts of District 22 around Chitgar Lake in Tehran have been simulated based on the numerical solution of RANS equations and approximate solution model. In this study wind flow is simulated in the actual and the proposed situation around the selected towers of the study area. This study on a range of 3 km by 1.6 km in the north of Chitgar Lake and downstream of northern Tehran has been done. In Figure 2, regions and also included towers are marked.

Figure2: The area under review with 80 towers located in the northwest and downstream of Can River.

In Figures 3a and 3b, perspective and schematic view of the study area determined respectively.

Figure 3a: Schematic view of the towers.

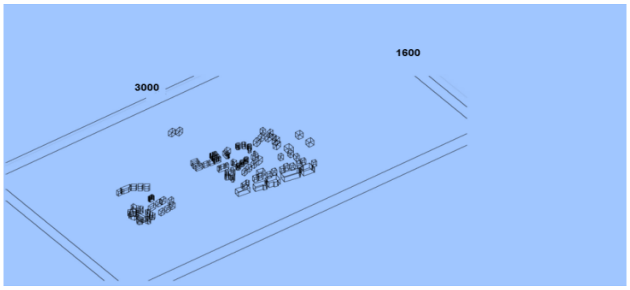

Figure 3 b: Three-dimensional view of the towers

Hussein Golbabai and et al. showed that in Tehran in a period of 50 years, the average prevailing winds are in the west direction and the average annual wind speed is about 5 meters per second (Baik, J.-J., Park, S.-B. and Kim, J.-J;2009). In this study, to run the model, the average speed of the wind is considered 5 meters per second in the west.

2.1 Introductionof $k-\varepsilon$ model, Reynolds average time and Navier- Stokes equation

The ability of CFD models as a promising tool for the study and simulation of turbulent flow in the boundary layer, caused by due to the development of software computing and computer hardware. In fact, the simulation of turbulent flow models, are based on equations of conservation of mass, momentum and energy flow. By the early 1950's, four main categories of turbulence models had evolved, viz.

1. Algebraic (Zero-Equation) Models
2. One-Equation Models
3. Two-Equation Models
4. Second-Order Closure Models

In modern terminology, we refer to a mixing-length model as an algebraic model or a zero-equation model of turbulence. By definition, an n-equation model signifies a model that requires solution of n additional differential transport equations in addition to those expressing conservation of mass, momentum and energy.

Kolmogorov introduced complete model of turbulence (Flaherty, J. E., Stock, D. and Lamb, B;2007). In addition to having a modeled equation for K, he introduced a second parameter ω that he referred to as" the rate of dissipation of energy in unit volume and time." In this model, known as a $k-\omega$ model, ω satisfies a differential equation similar to the equation for k. The model is thus termed a two-equation model of turbulence.

By far, the most extensive work on two-equation models has been done by Launder and Spalding and a continuing succession of students and colleagues. Launder' $k-\varepsilon$ model (Amorim, J. H., Valente, J., Pimentel, C. and Freitas, D. S.;2014). where ε is proportional to the product of k and ω, is as well-known as the

mixing-length model and is the most widely used two-equation model. Chouand Rotta laid the foundation for turbulence models that obviate use of the Boussinesqapproximation(Golbabaei, H., Mahdavivafa, H., Rodgamy, P. and Khalil Poor, A;2010; Kolmogorov, A. N;1942). He devised a plausible model for the differential equation governing evolution of the tensor that represents the turbulent stresses, i.e., the Reynolds-stress tensor. This approach is called second-order or second-moment closure. The most common model for the study of turbulent flows around buildings and in urban areas-is a $\mathrm{k}-\varepsilon$ model.
The earliest development efforts based on this model were those of Chou, Harlow and Nakayam [8, 10]. The central paper however, is that by Jones and Launder that, in the turbulence modeling community, has nearly reached the status of the Boussinesq and Reynolds papers. That is, the model is so well known that it is often referred to as the Standard $\mathrm{k}-\varepsilon$ model. Actually,Launder and Sharma "retuned" the model's closure coefficients and most researchers use the form of the model presented in the 1974 paper (Rotta, J. C;1951). The Standard $\mathrm{k}-\varepsilon$ model is as follows.

Eddy Viscosity

$$\nu_T = C_\mu k^2 / \varepsilon \quad (1)$$

Turbulence Kinetic Energy

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij}\frac{\partial U_i}{\partial x_j} - \varepsilon + \frac{\partial}{\partial x_j}\left[\left(\nu + \nu_T/\sigma_k\right)\frac{\partial k}{\partial x_j}\right]$$

(2)

Dissipation Rate

$$\frac{\partial \varepsilon}{\partial t} + U_j \frac{\partial \varepsilon}{\partial x_j} = C_{\varepsilon 1}\frac{\varepsilon}{k}\tau_{ij}\frac{\partial U_i}{\partial x_j} - C_{\varepsilon 2}\frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j}\left[\left(\nu + \nu_T/\sigma_\varepsilon\right)\frac{\partial \varepsilon}{\partial x_j}\right]$$

(3)

τ_{ij} In these two equations is Reynolds stress tensor, U_i is the mean flow velocity in the direction X. Closure coefficient and auxiliary relations is as follows:

$$C_{\varepsilon 1} = 1.44, \quad C_{\varepsilon 2} = 1.92, \quad C_\mu = 0.09, \quad \sigma_\mathrm{k} = 1.0, \quad \sigma_\varepsilon = 1.3$$

(4)

$$\omega = \frac{\varepsilon}{(C_\mu k)}, \qquad l = C_\mu k^{3/2}/\varepsilon \quad (5)$$

In the modeling of wind flows around the tower, Reynolds-averaged equations of motion and pressure equation arerequiring in the form of conservation. These equations can be expressed as follows:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (6)$$

$$\rho\frac{\partial U_i}{\partial t} + \rho\frac{\partial}{\partial x_j}\left(U_j U_i + \overline{u'_j u'_i}\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\mu S_{ji}\right)$$

(7)

$$a_p \vec{U}_p = H(\vec{U}) - \nabla p \Leftrightarrow \vec{U}_p = \frac{H(\vec{U}) - \nabla p}{a_p}$$

(8)

S_{ji} is the strain-rate tensor. Equations (6) and (7) generally are called, Reynolds -averaged Navier-Stokes (RANS) equation. In Equation (8),the first term of $H(\vec{U})$ represents the matrix coefficients of the neighboring cells multiplied by their velocity, while the second part contains the unsteady term and all the sources except the pressure gradient. The continuity equation is discretized as:

$$\nabla \cdot \vec{U} = \sum_f \vec{S} \cdot \vec{U}_f = \circ$$

(9)

where $\vec{S}$ is outward-pointing face area vector and $\vec{U}_f$ the velocity on the face.
The velocity on the face is obtained by interpolating the semi discretized form of the momentum equation as follows:

$$\vec{U}_f = \left(\frac{H(\vec{U})}{a_p}\right)_f - \frac{(\nabla_p)_f}{(a_p)_f} \quad (10)$$

By substituting this equation into the discretized continuity equation obtained above, we obtain the pressure equation:

$$\nabla \cdot \left(\frac{1}{a_p}\nabla p\right) = \nabla \cdot \left(\frac{H(\vec{U})}{a_p}\right) = \sum_f \vec{S} \cdot \left(\frac{H(\vec{U})}{a_p}\right) \quad (11)$$

This model, in OpenFoAM the software with using SimpleFoAM solver implemented. This solver for incompressible turbulence flow is used. This type of solution for modeling around buildings and for urban areas was recommended by software. This procedure can be expressed as follows:
SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) allows coupling the Navier-Stokes equations with an iterative procedure, which can be summed up as follows:

A) Define the boundary conditions
B) Discrete momentum equation to calculate the average speed values
D) Calculating the mass flux in the cell means (component)
E) Apply pressure and under-relaxation equation
F) Modifying the way cells in the fluid mass
G) Modification of the speed based on the new values of pressure
H) Review of the boundary conditions
I) Repeat steps to achieve convergence

3 Results and discussion

The present simulation is executed in a region of 1600 meters in 3000 meters and a height of 150 meters in the area around 80 towers with a height of approximately 60 meters. In this research, Open Foam software is used to simulate the wind field and the pressure field. In this research, according to the climate of Tehran wind speed is considered 5 meters per second from the west. Therefore, the large meshed cube has a dimension of 3000*1600*150 meters and except for the ground other faces are free for possible mass transfer. Wind in Initial boundary conditions at west face is 5 meters per second and at other faces considered to be zero.

In this study, to simulate the pressure and the wind speed around the towers actual and proposed situations are considered. Proposed situation unlike the actual situation of towers is a restored situation in which by changing the location and removing some towers to prevailing wind, a reduction in wind speed and an increase in air pressure in the area around the towers can be prevented. In this paper, the scales used in the figures are a tenth of the actual values. Figure 4 shows the air pressure in real mode and at an altitude of 20 meters above ground level. It is visible that two separate and dense locations in thewest and the east can be identified for the towers. In this situation, the air pressure on the windward side of the towers is strongly increased. This position, increases lateral forces especially in the windward of the front towers. High pressure air that is formed in front of the towers shows that there are downward motions. It is clear in figure 6 that the downward movements in front of the towers have increased to 4 meters per second. These downward movements prevent from rising pollutions even when the maximum wind speed in the region is blowing. Although we can see the formation of low pressure and updraft movements of the behind the towers, but according to Figure 6, we learn that the strength of ascending flows behind the towers is not comparable to severe downward flows.

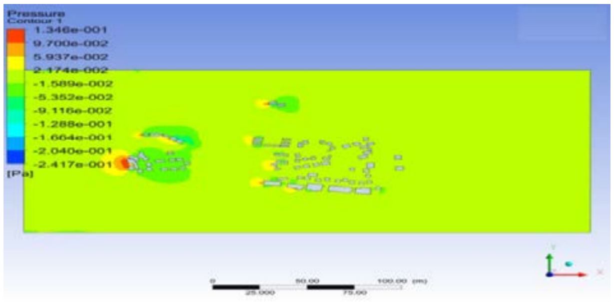

Figure4: Simulation of horizontal pressure field near the towers (actual situation) at an altitude of 20 meters above ground level

In Figure 5 horizontal wind speed at 20 meters is investigated.in pioneer Western towers and on the location of wind impact to towers, wind speed increases on some pedestrians. In the back of towers wind will return to normal, but due to the wind impact to eastern towers, wind speed arrives near zero. The second row of towers are major obstacles to the proper flow of the wind on the pedestrian and up to 1500 meters after the second row of towers at a height of 20 meters will not be any wind.

This indicates that even when the average maximum wind flows, due to inappropriate location of towers a large area behind the towers does not receive the proper flow of wind. Lack of proper flow of the wind on the pedestrians prevents good air conditioning in the interior of the buildings. So in the absence of natural ventilation, building occupants have to use the tools of artificial ventilation. Using various technologies for ventilation of any kind needs to spend energy. This leads to a waste of resources and the spread of pollutants. Of course, this argument is on the assumption that clean energy is not used. In Iran the energy production is based on fossil energies that are polluting the atmosphere. Iran dominates the energy production based on fossil energy that is polluting the atmosphere and increase energy consumption in buildings and increase emissions.

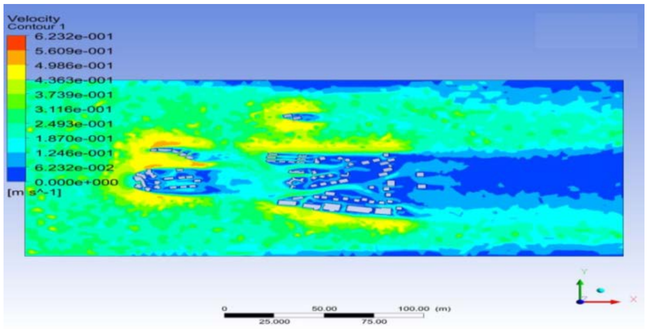

Figure5: Simulation of two-dimensional speed field around the

towers (actual situation)

Figure 6 shows vertical wind shear in the region between towers. It is seen in the vertical wind shear in the western region after the first tower wind returns to its original state and thenwind flow rate declinesafter hitting the eastern towers, as after the second-row towers wind flow is zero.Vertical wind shear index suggests at a height of more than 150 meters wind speed is close to zero and the process affects a wide range behind towers (over a kilometer).

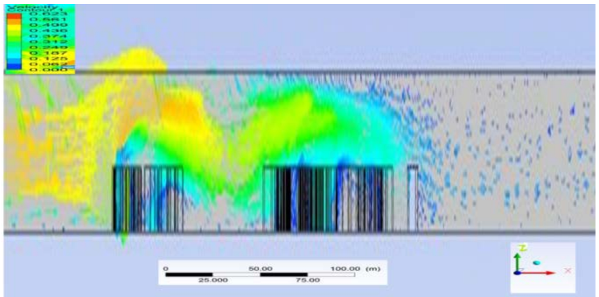

Figure 6: Simulation of vertical profiles of wind speed around the towers (actual situation)

From above results can be found that the design of residential towers is not suitable for air-conditioning. The central towers in both East and West are the worst in terms of air conditioning. A suggestion for improving the conditions of air flow and pollutants ventilation is forming an East- West channel. After assuming a model for locating towers, central towers removed and some of the towers replaced. Therefore, changing in location of towers like Figure 7 is suggested. In this proposal the mid towers marked with black has been removed and place of some towers to improve the situation have changed. With these changes Figure 8 shows the final offer. Again with the same specifications, the wind flow around the towers with a new layout is simulated Figure 8 and wind field and pressure is calculated as the actual state of the towers.

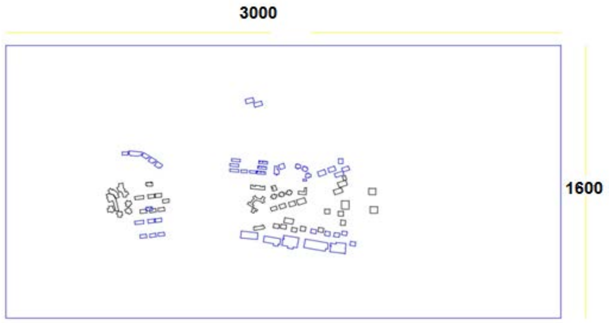

Figure 7: Proposed model for the proper placement of towers, remove or relocate the central tower (black) to improve ventilation

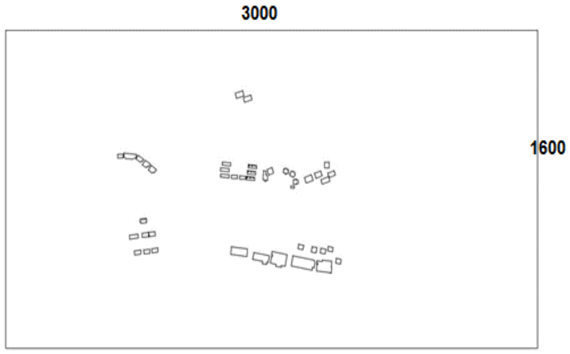

Figure8: The remaining towers to simulate the wind field and pressure field (the proposed situation)

Figure 9 shows the air pressure at an altitude of 20 meters above ground in the proposed layout of the towers. It is seen that by eliminating central towers and replacement of some towers, pressure gradients and areas with high air pressure in front of the leading western and eastern towers remarkably reduced. Therefore, the difference between high pressure in front of towers and low pressure behind towers is reduced. Increase of air pollutants resulting from air accumulation by reducing emissions caused by rising air behind towers is somewhat compensated. The pollution accumulation caused by downward movement's decreases.

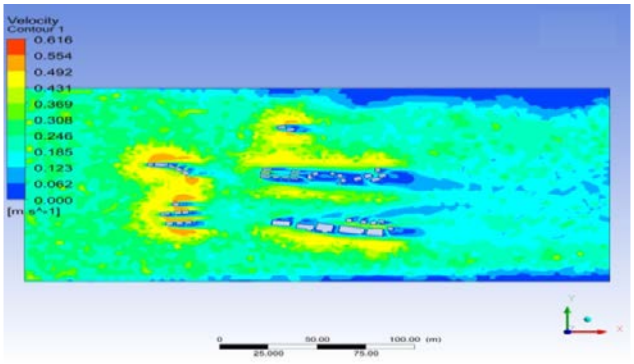

Figure 9: Simulation of horizontal pressure field near the towers (proposed situation)

Figure 10 shows the wind speed at a height of 20 meters above the ground and in the suggested situation. In new layout of towers, movement of wind among towers is good and wind speed is much higher than the actual layout of the towers (Figure 5). It can be said better pollution ventilation takes place on the pedestrian and the wind on the pedestrian and at the level of small buildings located behind the towers are well done.

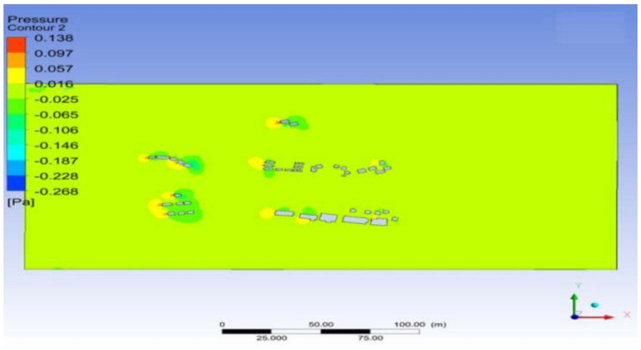

Figure10: Two-dimensional simulation of speed field around the towers (proposed situation)

Vertical cut of wind speed in the proposed situation and within the towers is shown in Figure 11. This cannot be compared with Figure 6 that the wind at height of 150 meters in the towers had reached near zero. By eliminating the intermediate towers in the study area can be seen that the ventilation air flow to the real situation is much improved and air flow hitting primary and secondary towers creates smaller effects on wind flow at the eastern end. Wind speed reduces from 150 meters in height to less than 20 meters in height.

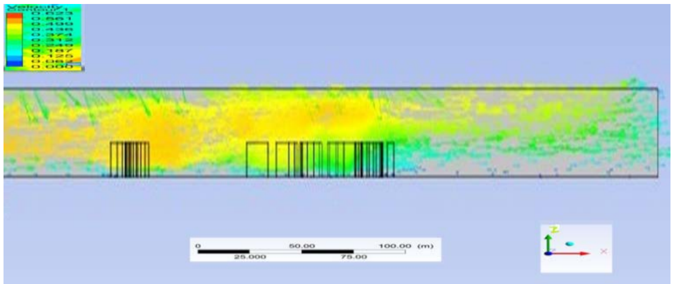

Figure11: Vertical profiles simulation of wind speed around the towers (the proposed situation)

CONCLUSIONS

According to numerous domestic and foreign researches, data, meteorological modeling and application of meteorological knowledge in layout, design and implementation of urban development projects particularly detailed plans, urban development and tall building is necessary. Use of meteorological science in sustainable development issues is fundamental and decisive, because the issue of sustainable development, saving energy, reducing pollution, has a significant and decisive role. In the conducted case study the effects of high rise buildings on air ventilation within the towers is visible. Simulation of wind fields based on the proposed conditions, including relocation and removal of some mid towers provides better conditions for air conditioning. It shows thattall buildings in the direction of wind flow cause poor ventilation of airflow in urban areas. In addition the placement and height of the pioneering buildings compared to other buildings, is an important factor in determining the ventilation air flow in the range of buildings. In other words,locating pioneering high buildings instreets that are perpendicular to the wind flowcauses the entrapment of air flow in the area behind the second row of buildings.

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