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CFD Simulation of Urban Pedestrian Wind Comfort Optimization in a High-Rise Building Cluster – A Case Study

城市超高层建筑群室外人行区舒适度优化的CFD模拟——案例研究

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Abstract

Wind comfort for pedestrians is concerned in urban planning, especially for high-rise building clusters. The computational fluid dynamics (CFD) method is widely used to predict the wind environment of the area by many researchers, which has many advantages compared to e wind tunnel experiments. To obtain more accurate and reliable results simulated by CFD , several sets of best practice guidelines (BPG) have been developed in the past decades. Aa case study of high-rise buildings in Tianjin is studied by CFD software . The neutral equilibrium atmospheric boundary layers (ABL) play an important role in the simulation process; a modified standard k-ε turbulence model, is applied in this paper.. Finally, some specific suggestions including the lawn, the trees, and the water bodies on the ground are proposed, making the district more comfortable and green when the planning is finished.

Keywords: Computational Fluid Dynamics (CFD), Wind Environment, High-Rise Building

摘要

风舒适性在城市规划中受到重视，特别是高层建筑群集的区域。计算机流体力学CFD方式被广大研究者用来演算城区的风环境，因为相比风洞试验的方式，它具有很多的优势。为了通过(CFD)获取更为精确和可靠的模拟结果，在过去的几十年中，人们研发了一系列最佳的实用指导策略BPG。本文运用CFD软件研究分析了一栋座落在天津的高层建筑项目。中性平衡大气边界层ABL在模拟的过程中担任了重要的角色；最近有学者提出了一种修订过的标准k-ε湍流模型，本文尝试了对它的应用。最后，本文提出了一些详细的建议，包括草坪，及地面的水体的设置等等，来使城市区域在绿化之后更为舒适。

关键词：计算流体力学，风环境，高层建筑

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Introduction

With the rapid development of urbanization, more and more high-rise buildings appeared, leading to a series of problems such as light pollution, wind problem, and rubbish problem. Our environment is deteriorating for reasons including the light pollution caused by glass curtain walls on high-rise buildings. Due to the canyon effect between high-rise buildings, local wind speed increases, causing staff feel uncomfortable during outdoor activities. Uncomfortable spaces between buildings will affect property values. Providing a comfortable and healthy environment for citizens is one of the goals when we start to plan a city. [See NEN, 2006a, NEN2006b] There are already relevant evaluation standards abroad and the main index is wind speed around personal activity areas.

Recently, many architects completed research on urban planning in order to improve the urban heat environment. It is proved that due to the optimization of computers for urban planning, the architectural design can use effective methods to improve the urban and buildings heat environment by urban planners and architects.

引言

随着城市化的飞速发展，出现了越来越多的高层建筑（群），随之而来的也引发了一系列问题。城市环境不断恶化，如高层建筑围护结构都采用玻璃幕墙，光污染情况非常严重，据报道，由于玻璃反射作用照射到汽车上，引起汽车自燃；由于高层建筑之间的峡谷效应增加，局部风速增大，引起室外人员活动区域不舒适；建筑与建筑之间没有很好的连通，直接影响商场的效益。城市（区域）规划的目的之一就是为居住在城市中的人们提供一个舒适、健康的室外环境。目前国外也有相关的评价标准，具体见文献[NEN,2006a,NEN2006b]。主要指标是室外人员高度区的风速大小。

近年来，为了改善城市热环境，从城市规划、建筑设计以及城市设计的角度进行了大量的研究工作，并且有很多改善策略被提出。实践证明城市规划师与建筑师通过城市规划、建筑设计以及城市设计的方法来改善城市与建筑热环境，是实现城市可持续发展的一种非常有效的手段。

基于上述讨论，本文利用计算机数值模拟方法改善了天津于家堡金融区的规划与设计，对该区域风环境进行模拟计算，根据模拟结果提出了相应绿化以及种植方案，

Based on the discussions above, the CFD method was used in the urban planning and design of Tianjing Yujiapu Financial District. We proposed the green-planting plan according to the results of outdoor wind environment studies in the Financial District and then further optimized the practical effect of the green-planting plan. The results showed that the optimized green-planting could improve outdoor wind environment.

并对提出的方案实际效果进行了模拟验证，结果显示通过优化绿化种植方案可得到较好的室外风环境。

Theory

Atmospheric boundary layers (ABL) are vitally important for the outdoor environment wind and turbulence simulations. The roughness for ABL of the underlying surface plays a very important role. The wall function method is widely used for considering the flow condition in near-wall regions in commercial software. There are many researchers working on this problem nowadays, to use the wall function method, the following requirements should be simultaneously satisfied.

1. The height of the first cell to the wall should be less than 1m to meet the demand of sufficiently high mesh resolution in the vertical direction close to the bottom of the computational domain.
2. A horizontally homogeneous ABL flow in the upstream and downstream region of the domain.
3. A distance from the center point P of the wall-adjacent cell to the wall that is larger than the physical roughness height.
4. Setting equivalent sand-grain roughness in commercial software according to the relationship between the equivalent sand-grain roughness height and the corresponding aerodynamic roughness length.

In practice, to satisfy the Y plus criterion in the ABL between 30m and 200m, the computing domain is usually very large. Therefore the K_S ($K_S=9.793y_0/Cs$) value which was computed according to the ABL is very high (up 30m to 300m), which does not meet the requirement 1 and 3.

If the grid is meshed according to the requirement 1 and 3, the center of ABL's first grid will fall in the turbulence transition region which should be avoided by using a standard wall function method. Oppositely, if meshing occurs according to KS, there will be not enough grids in the human activity region (usually 1.5m high). There are various remedial measures to rectify or at least address the errors discussed in the previous section(Bert Blocken et al, 2007).

It is possible to separate the flow field into three regions: inlet region, core region and export region. The building region is assigned to the core region; the space between buildings and inlet boundary is assigned to the inlet region and space between buildings and outlet boundary is assigned to outlet region. The grid of inlet and outlet regions should meet the requirements of ABL and grid of core region should meet the Requirement 1 and 3. So the ABL will be horizontally homogeneous before reaching the buildings.

It is possible to use rectangle blocks to fully reproduce the actual roughness effects on the flow, however this will increase required computing power and time. Besides, the accuracy of this method has failed to be proved in unsteady computation.

As there should be a certain distance before ABL turns to IBL, reduce as much as possible the upstream length of the computational domain.

The simulation can be performed using periodic boundary conditions

理论

在模拟室外风环境时，入口处的大气边界层风速和湍流特性对模拟结果的准确性至关重要。大气边界层下垫面的粗糙度对流动起到了不可忽略的影响。而在商业软件中一般采用壁面函数法来求解近壁面的流动状态。目前,已经很多学者在这一方面进行了深入研究，其中包括一般来说，要采用壁面函数法需要满足以下四点要求[Richards and Hoxey，1993；Franke et al.，2004；Ansys Ltd.,2005]：

1. 满足近壁面第一个网格高度要小于1m，才能满足网格精度要求；
2. 进口段与出口段的大气边界层速度应尽量保持一致；
3. 近壁面第一网格中心节点高度应大于壁面所设定的当量粗糙高度；
4. 根据空气动力学粗糙高度与当量粗糙高度的关系式设定商业软件中的当量粗糙高度。

在实际情况中，计算区域往往会很大，根据ABL所计算出来的KS（$KS=9.793y_0/Cs$）会很大（一般为几米甚至十几米），只有这样才能满足ABL的y+在（30,300）之内。这就导致了与要求1、3不符。

假设按照要求1、3进行网格划分模拟计算，就会导致ABL的第一个网格中心点落在紊流过渡区，这是采用标准壁面函数所应该避免的。而如果采用ABL所计算出来的KS进行网格划分，这又会导致风环境所关注的人行区（1.5m高）因没有足够的网格而失真。目前可以采用以下几种推荐的方法提高近壁面模拟的准确度，从而提高整个流场模拟的准确性[Bert Blocken et al,2007]。

可以将整个流场分为三个区域，进口段、核心段、出口段；将有建筑的区域划分为核心区，建筑物到入口这段局域划分为入口段，建筑物到出口的这段区域划分为出口段。入口段与出口段可采用满足ABL的网格要求，而核心段则采用满足要求1、3的网格要求，这样可以保证ABL在到达建筑物之前能有较好的水平一致性；

在入口段可将壁面粗糙度用Block近似表示，但会增加建模时间及计算时间，而且用非稳态计算时，这种方法的准确性并未得到进一步验证；

ABL转变为IBL需要一定的距离，在允许的情况下，尽量缩短入口段的距离，使得ABL并未完全转化前就达到包含建筑的核心区，这样也可减小误差，但要保证入口段的减少不会对增加最终解的误差；

可将入口段划分为若干小段，在每一小段上采用周期性边界条件，强制将IBL转化为ABL；

降低入口处壁面附近的湍动能，如果与方法2相结合，经过验证，可对减小误差起到一定的效果；

对k-ε方程进行修改，放弃商业软件中标准的两方程模型，采用UDS修正k和ε方程并编写程序从而代替商业软件（如Fluent软件）中标准k方程、ε方程进行正常网格划分计算；入口边界则采用ABL作为边界条件。通过实验模型对比证明，采用这种方法后误差将大为降低。

鉴于上述6种方法各有优势，本文采用方法1，并结合壁面函数的四点要求，对于家堡核心起步区高层建筑群进行模拟分析。

at the inlet and outlet of a short domain and turns IBL to ABL compulsorily.

Reducing the turbulent kinetic energy of the inlet, if combined with method 2, could reduce the error effectively.

In order to modify k-ε model in commercial software, it is necessary to employ user-defined scalars to replace the standard k-ε model in commercial software (such as Fluent) and use ABL as the inlet boundary condition. This can reduce error effectively proved by the experimental data and numerical value.

Considering the advantages and disadvantages of the methods above, the first method is recommended in this paper to simulate outdoor wind environment around high-rise buildings in Yujiapu Financial District, combining the four requirements of wall function method mentioned above.

Domain size

For the single-building model, the lateral and the top boundary should be set $5H_{max}$ or more away from the building, where H_{max} is the height of the target building. The outflow boundary should be set at least $15H_{max}$ behind the building. For the size of the computational domain, the blockage ratio should be below 3%, based on the knowledge of wind tunnel experiments.

Turbulence models

Nowadays, standard k-ε is widely applied to solve pedestrian wind environment problems. However, the turbulence energy k is usually overrated at the stagnation point in this model, so a realizable k-εmodel is utilized in this paper.

Grid

A fine grid arrangement is required to resolve the flows near the corners, walls, and roofs and the stretching ratio of adjacent grids should be no more than 1.3. The center line of the adjacent grids should be horizontally parallel. It is better to use hexa-grid and then the prism and tetrahedron grid. The grid near-wall should meet the demand of wall function. If the first grid standard wall function is selected, then the first grid node should located near y+=30.

Boundary condition

Inflow boundary condition

$$U_{(z)}=U_s(z/z_s)^a$$

Where U_s is the velocity at reference height, z_s, and a is the power-law exponent determined by terrain category.

The vertical distribution of turbulent energy $k_{(z)}$ can be obtained from a wind tunnel experiment or an observation of corresponding surroundings. If it is not available, $k_{(z)}$ can be also given by Eq. (6) based on the estimation equation for the vertical profile of turbulent intensity $I_{(z)}$.

$$I_{(z)}=0.1(z/z_G)^{(-a-0.05)}$$

where z_G is the boundary layer height determined by terrain category and *su* the RMS value of velocity fluctuation in stream-wise direction. In the atmospheric boundary layer, the following relation between $I_{(z)}$ and $k_{(z)}$ can be assumed:

$$k_{(z)}=(I(z)U(z))^2$$

$$\varepsilon_{(z)}=C_\mu^{0.5}k_{(z)}U_{sa}(z/z_s)^{a-1/zs}$$

计算区域的选择

计算区域入口距最近的侧建筑边界满足$5H_{max}$（H_{max}为建筑群中最高建筑高度），计算区域侧边边界距最近侧的建筑侧边界满足5 H_{max}，计算域顶部应距最高的建筑物顶部满足5 H_{max}，计算区域出口应距最近侧的建筑边界满足15 H_{max}，建筑物覆盖的区域满足小于整个计算域体积的3%。

方程模型

目前采用比较多的模型是RANS模型，而在RANS中，应用比较多的是两方程模型。其中标准k-ε方程在以前的风环境模拟中应用最广泛。但使用这种湍流模型最主要的问题是会过高的估计在滞点处的湍动能k值。本文采用Realizable-k-ε方程。

网格

网格应能捕捉流场中的突变点；应在具有大的变量梯度处进行局部加密，并且相邻的两个网格的尺寸比应尽量不大于1.3，相邻网格中心线的连线应尽量保持平行。优先采用六面体网格系统，其次考虑棱柱与四面体混合网格系统，尽量不要采用单一四面体网格系统。网格在壁面处应满足壁面函数。若选取标准壁面函数，第一个网格节点应布置在y+=30附近处。

边界条件的选取

入口边界条件

$$U_{(z)}=U_s(z/z_s)^a$$

其中U_s 是在参考高度的速度，z_s，和 a 是幂律指数，由地形类型决定。

湍流动能的竖向分布可以从风洞实验中得到，也能从对相应的环境的观察中获知。如果无法提供的话，$k_{(z)}$也可以通过竖向湍流密度$I_{(z)}$的估算方程式，由Eq得来（6）。

$$I_{(z)}=0.1(z/z_G)^{(-a-0.05)}$$

其中，z_G是边界层的高度，它由地形类型和s_u，气流方向速度的浮动值RMS所决定。在大气边界层，$I_{(z)}$ 和 $k_{(z)}$之间的联系可以假设为：

$$k_{(z)}=(I(z)U(z))^2$$

$$\varepsilon_{(z)}=C_\mu^{0.5}k_{(z)}U_{sa}(z/z_s)^{a-1/zs}$$

其中U_s为在参考面上的速度值；a、z_s由当地地形决定；z_G大气边界层高度（由当地地形决定）；C_μ为常数，通常取0.09。

侧边与顶部边界条件

侧边与顶部边界条件采用对称边界

出口边界

出口边界设置为自由出流边界条件。

地面边界条件

采用光滑壁面对数率法则。

建筑物边界

同地面边界条件。

计算收敛的判定

采用一次迎风差分方式进行初始计算，待稳定时采用二阶迎风差分格式。收敛判定需同时满足以下三点：

- 残差减小到预先设定值；
- 质量守恒、能量守恒；
- 流场中有代表性监视点的值不发生变化或沿一固定值上下波动。

验证网格独立解

为验证计算结果与网格无关，验证网格独立解。在原有网格基础

Where U_s is the velocity at reference height; α, z_s are determined by the local terrain; z_G is the atomospheric boundary layer height; C_μ is the model constant ($C_\mu = 0.09$).

Lateral and upper surfaces boundary condition

Lateral and upper surfaces boundary condition used symmetrical boundary

Downstream boundary condition

It is common to set the normal gradients of all variables to zero for the outflow boundary condition.

Ground surface boundary condition

Smooth surface Logarithmic rate law applied

Building wall condition

The same as ground surface boundary condition

Criteria for convergence

Use the first-order upwind scheme and then change to second-order upwind scheme after computation is steady. Criteria for convergence are as following:

上的长度、宽度及高度方向上网格数量各增加1.5倍、2.25倍，形成三套网格系统。

案例研究

背景介绍

本项目位于天津于家堡，2010年6月19日，第九届APEC能源部长会议在日本福井举行，会议确定于家堡金融区为首例APEC低碳示范城镇，基于这一背景，我们对该项目进行了深入研究，风环境作为该研究内容的一部分。（见图1-11）

结论与建议

本文通过对上述三个方案模拟分析后得出如下结论：

- 对比方案一和二，规划后的绿地虽然改善了气流组织，减少了涡流区，但由于草地和树木的阻力作用，使建筑密集区域风速较小，不利于夏季的降温以及污染物的稀释。
- 方案三在现有规划的基础上改变了绿地位置，从而优化了室外局部气流组织。

Figure 1. bird view of the Yujiapu (Provided by the Yujiapu)
图1. 于家堡鸟瞰图

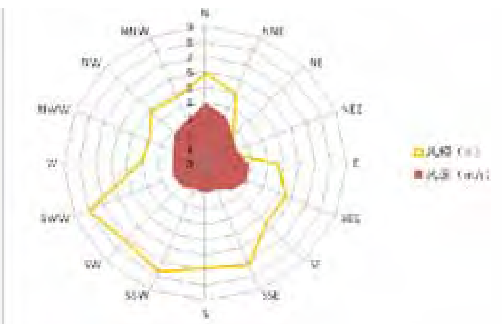

Figure 2. wind rose map of Tianjin district
图2. 天津地区风玫瑰图

Figure 3. model
图3. 模型图

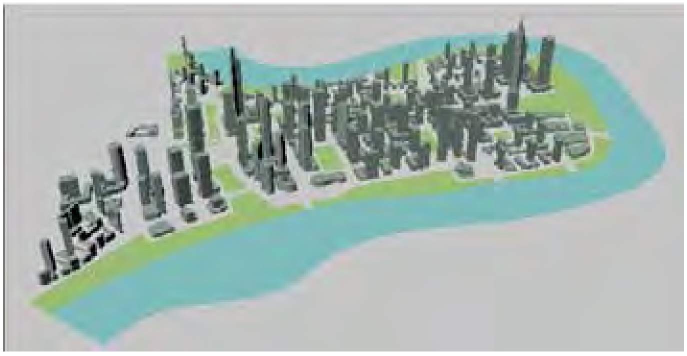

Figure 4. model
图4. 模型图

Figure 5. mesh of the model
图5. 天津于家堡金融区网格划分

Figure 6. mesh of the model. Case1 result with no green
图6. 天津于家堡金融区网格划分。工况1 无绿化结果

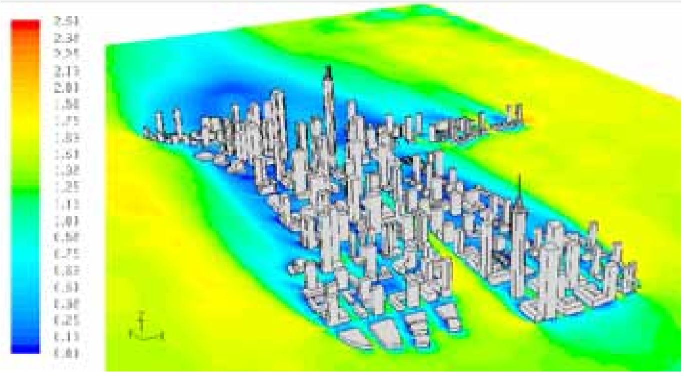

Figure 7. contour map of the velocity in the1.5m height (m/s)
图7. 米高速度分布云图(m/s)

Figure 8. vector of velocity in the 1.5m height(m/s)). Case 2 result with green
图8. 1.5m高速度分布(m/s), 工况2 带绿化的结果

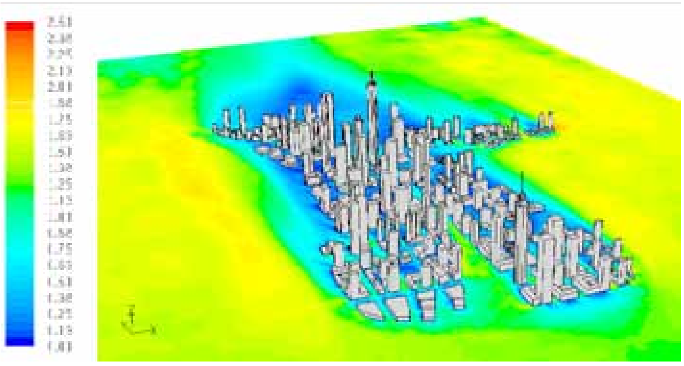

Figure 9. contour map of the velocity in the 1.5m height (m/s)
图9. 1.5米高速度分布云图(m/s)

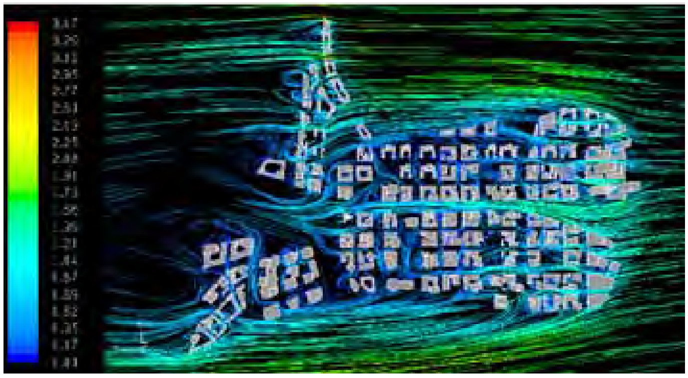

Figure 10. vector of velocity in the 1.5m height (m/s). Case 3 Optimized results
图10. 1.5米高速度分布矢量图(m/s)。工况3 优化后结果

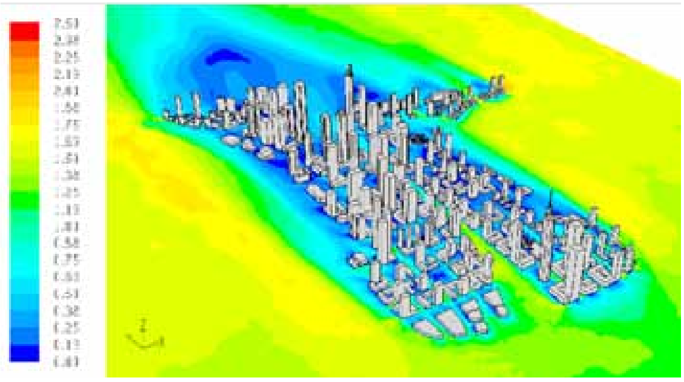

Figure 11. contour map of the velocity (m/s)
图11. 1.5米高速度分布(m/s)

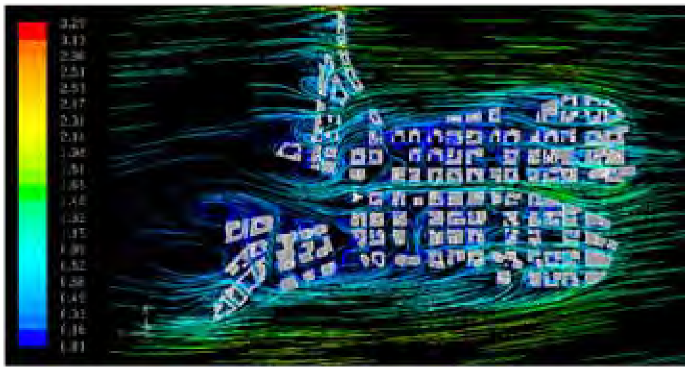

Figure 12. vector of velocity in the 1.5m height (m/s)
图12. 1.5米高速度分布 (m/s)

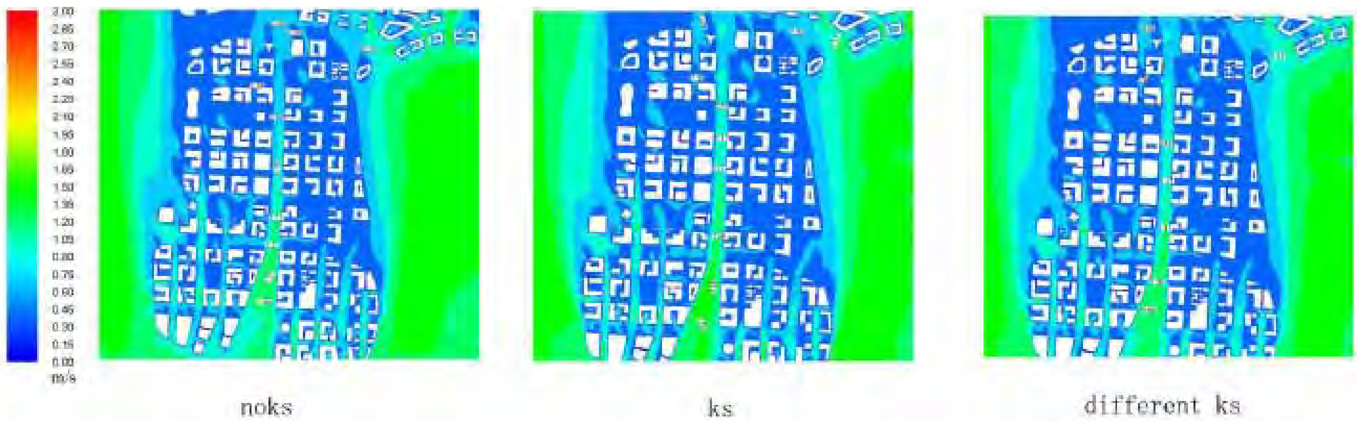

Figure 13. compared contour map of the velocity in 1.5m height
图13. 不同方案速度分布云图1.5m高

- Residual is reduced to the pre-set value;
- Both mass and energy are conserved;
- Value of monitor point in the flow field will be steady or fluctuate around a fixed value.

Grid sensitive analysis

It should be confirmed that the prediction result does not change significantly with different grids. In order to examine grid independence, mesh fine grid 1.5 and 2.25 times the number of coarse meshes in each dimension individually.

Case study

Background

This project was located in Tianjin Yujiapu. On July 19, 2010, the 9th APEC Energy Ministers Meeting was held in Fukui, Japan, which designated this project as the first low-carbon city. We research this project and our results will be a partial content of the achievements (see Figures 1-11).

Conclusions and suggestions

The above three cases are analyzed and conclusions are as following:

- Comparing case 1 and case 2, it is obvious that the greening design strategy improves air distribution and decreases eddy region. However, such green-planting planning will enlarge the uncomfortable area, especially in summer, and it is difficult for the pollution dispersing around the buildings due to the low-velocity.
- It is clear that case 3 is best for outdoor air distribution for the reason of changing the green-planting area.

It is recommended that low vegetation or grass should be planted in the prevailing wind direction and densely built-up areas. This greening strategy will be good for air distribution as well as pollution dilution. However, high trees are suitable for coastal gardens along the river.

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建议在夏季主导风向迎风面以及城市主风道以及建筑密集区种植低矮植被或草地，丰富绿化美观效果，而低矮的植被不会阻碍新风进入金融区，能将新风引入金融区内部，达到稀释污染物浓度以及夏季降温作用，而在沿河滨海花园宜种植较高树木。

致谢

感谢论文的评审者提出的宝贵意见，正是由于他们的意见，才使论文的整体水平得到提高。

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