A COMPUTATIONAL FLUID DYNAMICS STUDY OF STREET-LEVEL VENTILATION IN URBAN AREAS

CHUN-HO LIU[1], WAI-CHI CHENG[2], WENYE LI[3], ZIWEI MO[4], ZHANGQUAN WU[5], LILIAN Y.L. CHAN[6], W.K. KWAN[7], Hing Tuen YAU[8]

[1]*Department of Mechanical Engineering, The University of Hong Kong, liuchunho@graduate.hku.hk*
[2]*Department of Mechanical Engineering, The University of Hong Kong, wccheng2007@yahoo.com.hk*
[3]*Department of Mechanical Engineering, The University of Hong Kong, liwenye@connect.hku.hk*
[4]*Department of Mechanical Engineering, The University of Hong Kong, ziwei.mo@gmail.com*
[5]*Department of Mechanical Engineering, The University of Hong Kong, wzqmec@gmail.com*
[6]*Information Technology Services, The University of Hong Kong, lilianyl@hku.hk*
[7]*Information Technology Services, The University of Hong Kong, hcxckwk@hku.hk*
[8]*Information Technology Services, The University of Hong Kong, billyau_hpc@hku.hk*

Keywords: *Building morphology, Reynolds-averaged Navier-Stokes (RANS) equations, stereolithograph (STL), tracer dispersion, urban-area flows and virtual reality modeling language (VRML)*

Introduction

Economic activities and industrialization unavoidably lead to degrading street-level ventilation and elevating pollutant concentrations in urban areas. Buildings, skyscrapers and infrastructures in metropolises collectively form complicated urban morphology in which the dynamics is different from that in the atmospheric boundary layer (ABL) aloft. Under this circumstance, the conventional (meso-scale) meteorology models would not be fully applicable to diagnose the problems in details [1, 2, 3]. Engineering computational fluid dynamics (CFD), such as OpenFOAM [4], is commonly used to tackle the problems in refined micro-scale. The protocol of using building information for OpenFOAM CFD studies in the city ventilation perspective is reported in this paper.

Methodology

Detailed information of buildings and terrain is collected from the Lands Department, The Hong Kong Special Administrative Region (HKSAR) [5]. The digital maps are three-dimensional (3D) spatial data of the HKSAR territory that include buildings (commercial and residential), infrastructure (roads and bridges) and natural terrain (mountains and slopes) for land assessment, engineering visualization and air ventilation analysis, etc. The 3D geometric models are available in virtual reality modeling language (VRML) format. In this paper, we use one of the HKSAR downtown areas as an example to demonstrate the solution protocol (Figure 1 (a)). The digital models in the files are divided into tile basis so MeshLab [6] is used to assemble and convert the VRML files to STL format for subsequent input into CFD and discretization. The STL files of building information are then merged with the OpenFOAM mesh generation utility *blockMesh* and are discretized by *snappyHexMesh* to 3D unstructured meshes. The mesh generator *snappyHexMesh* uses the triangulated surface geometries in the STL files to generate 3D meshes, approximating the solid surfaces. It also refines the surfaces iteratively to morph the buildings by split-hex meshes to the facades and ground in high spatial resolution. Additional layers of refined spatial resolution are fabricated as well to improve the accuracy of near-wall-flow calculation. The STL model of downtown HKSAR areas, which is reduced in scale approximately 1:300, is discretized into over 5 million hexahedral cells for subsequent CFD calculation (Figure 1 (b)).

Mathematical Models and Numerical Methods

Reynolds-averaged Navier-Stokes (RANS) k-ϵ turbulence model of OpenFOAM version 4.1 is used in this paper. It is assumed that the flows are isothermal and incompressible that are calculated by the continuity and the momentum conservation. Turbulence is modeled by the standard RANS k-ϵ model with the conservation equations of turbulence kinetic energy (TKE) k and TKE dissipation rate ϵ. The CFD spatial domain (1:300 reduced scale) sizes 14 m (length) $\times$ 2.7 m (width) $\times$ 4 m (height), covering one of the downtown areas in HKSAR. No-slip boundary conditions (BCs) are applied on all the solid boundary and a shear-free BC along the top. Neumann BCs of flows are applied on the spanwise boundaries. The prevailing wind is prescribed by an inflow boundary at the upstream inlet together with an outflow

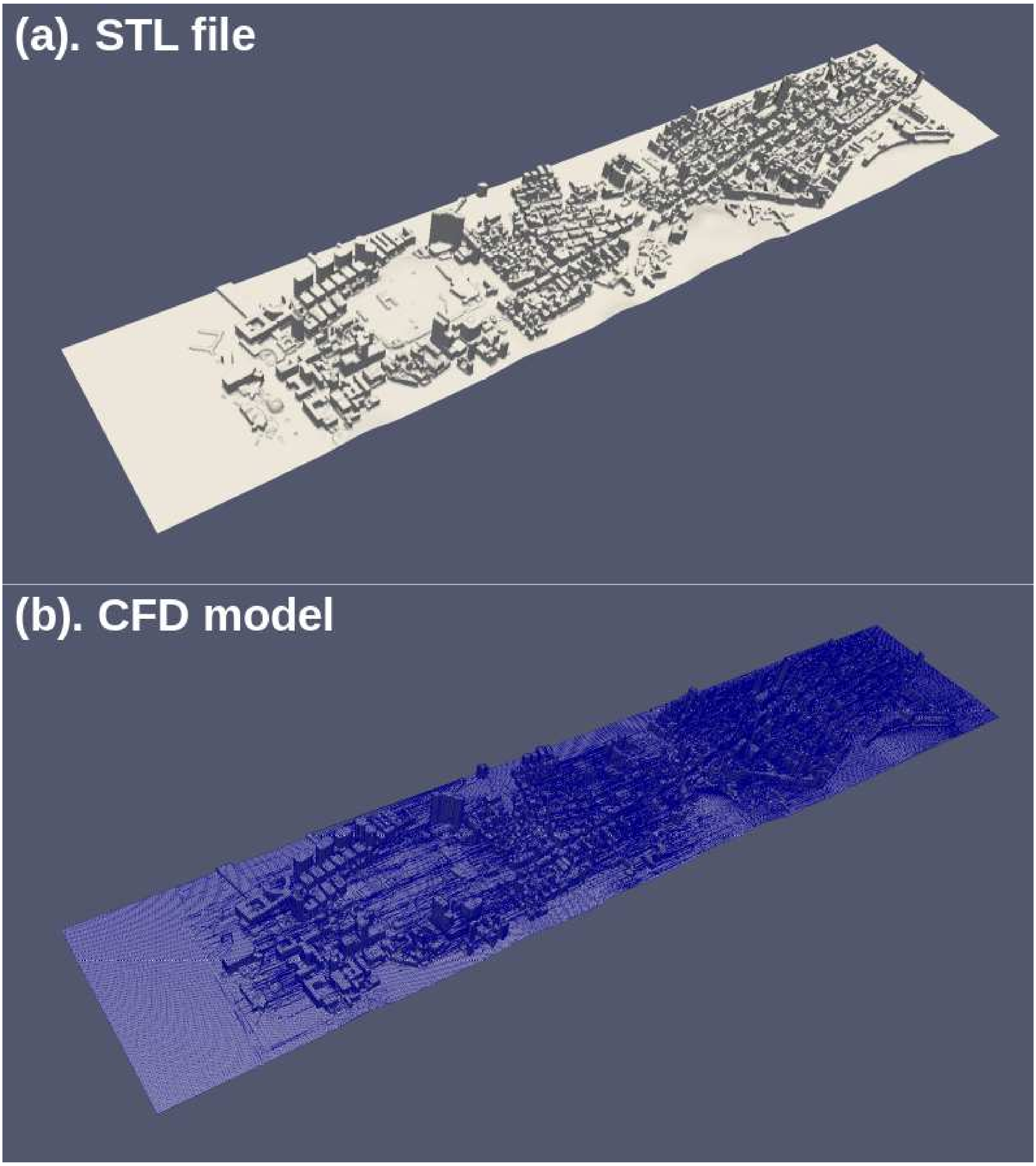

Figure 1: Preprocessing of building information from (a). STL file to (b). CFD model of downtown HKSAR.

boundary at the downstream outflow [7]. The inflow wind profile is given by the power law

$$U\left(z\right)=U_s\left(z/z_s\right)^{\alpha} \tag{1}$$

where U_s is the wind speed at reference height z_s (= 1 m) and α (= 0.2) the power-law exponent. The BCs of k and ϵ are

$$k\left(z\right)=0.01\times U_s^2\times\left(z/z_s\right)^{-0.1} \tag{2}$$

(10% turbulence intensity) and

$$\epsilon\left(z\right)=C_{\mu}^{1/2}k\left(z\right)\times U_s/z_s\times\left(z/z_s\right)^{\alpha-1} \tag{3}$$

(TKE production equal to dissipation), respectively, where C_μ (= 0.09) is a modeling constant. The prevailing wind enters the spatial domain from the upstream inflow is free of pollutant (ϕ = 0). An area source of tracer with constant concentration Φ_0 is placed on the ground right after the upstream inflow. Neumann BCs of tracer are applied on the domain top, spanwise extent and all the solid boundaries. An open BC is prescribed at the downstream outflow so the tracer are removed from the computational domain without any reflection.

Over 5 million finite volume (FV) cells are used to discretize the spatial domain. Trial runs based on approximately 1 million and 3 million FV cells have been performed to check the grid dependence. The minimum and maximum cell volume is about 8×10^{-8} m^{-3} and 4×10^{-5} m^{-3}, respectively. The OpenFOAM standard solver *simpleFoam* is used to solve the steady-state problem. The first-order upwind scheme is employed for all the CFD variables. Successive overrelaxation method is adopted to solve the equation systems. The residuals of all the results presented in this paper are less than 10^{-6}. The Reynolds number (Re) based on free-stream wind speed and domain height is almost 3×10^{6} that is sufficiently large for turbulent flows in neighborhood scale.

Preliminary Findings

Figure 2 (a) shows the wind flows over the urban-area model of downtown HKSAR. A turbulent boundary layer (TBL) is clearly developed in which the wind speed U increases in the wall-normal direction z. The reduction in wind speed in the vicinity of buildings (less than 50% of free-stream wind speed) is clearly depicted, signifying the drag induced by (rough) urban areas and the impact on street-level ventilation. It is clearly shown that the wake behind one of the high-rise buildings, whose size extends almost to the domain outflow, substantially slows down the flows so the potential impact from individual high-rise buildings (on the entire neighborhood) should be assessed. The pressure on the windward facade of that building is large so we also need to pay attention to the turbulence and gust upwind (wind hazard). The domain inflow a harbor so the impingement on the coastal buildings are notable. A zone of low pressure is clearly observed after the coastal buildings, implying the formation of recirculating flows (i.e. weakened aged air removal) at the canopy level. The streamlines help illustrate how the background flows are modified by the buildings. Similarly, the influence of individual high-rise buildings is substantial. The flows in their wakes slow down (or even reverse flows), leading to weakened wind breeze even the local building density is not high. Under this circumstance, the (adverse) environmental impact of buildings could be beyond their length scale.

A hypothetical ground-level line source of tracer is included in the computational domain to examine the tracer transport. It is placed in crossflows so the dispersion is essentially two-dimensional (2D) on the streamwise-vertical (x-z) plane. Figure 2 (b) depicts the tracer distribution over the urban-area model of downtown HKSAR. Ground-level concentration ϕ decreases exponentially in the streamwise direction that is similar to behavior of the conventional plume dispersion over smooth surfaces. It thus arouses our interest of developing a Gaussian dispersion model for urban setting. Isosurfaces of tracer concentration illustrate an interesting finding of the enhanced mixing in the wakes after high-rise buildings. The building blockage diverts the flows, initiating eddies in the wake region. Those eddies are large in size in which the scales of both the velocity and length are substantially enlarged that collectively strengthen the plume dispersion and mixing processes. Hence, the ground-level tracer concentrations in the wakes of high-rise buildings could be (unreasonably) low that cannot be estimated accurately by the current tracer transport models.

Concluding Remark

The protocol of using OpenFOAM modeling urban-area street-level ventilation is briefly introduced. The complicated building morphology is digitized by *snappyHexMesh* to 3D unstructured hexhedrons. Preliminary findings highlight the importance of high-rise buildings on street-level wind environment that could be beyond their length scale. Moreover, large-scale eddies are generated in the wakes after high-rise buildings that could enhance the tracer dispersion. Additional CFD sensitivity tests are being undertaken to examine the roles of buildings in a city in the environmental perspective. More results and findings will be reported in the workshop.

Acknowledgments

Zhangquan Wu wishes to thank the Hong Kong Research Grants Council (RGC) for financially supporting his study through the Hong Kong PhD fellowship (HKPF) scheme. The computations were performed using research computing facilities offered by Information Technology Services, the University of Hong Kong (HKU). This project is partly supported by the General Research Fund (GRF) of RGC HKU 17210115.

References

[1] W. C. Cheng and C.-H. Liu, "Large-eddy simulation of flow and pollutant transports in and above two-dimensional idealized street canyons," *Boundary-Layer Meteorol.*, vol. 139, no. 3, pp. 411–437, 2011.

[2] Z. Wu and C.-H. Liu, "Time scale analysis of chemically reactive pollutants over urban roughness in the atmospheric boundary layer," *Int. J. Environment and Pollution*, vol. 62, no. 2/3/4, pp. 264–273, 2017.

[3] Z. Mo and C.-H. Liu, "Wind tunnel measurements of pollutant plume dispersion over hypothetical urban areas," *Build. Environ.*, vol. 132, pp. 357–366, 2018.

[4] H. G. Weller, G. Tabor, H. Jasak, and C. Fureby, "A tensorial approach to computational continuum mechanics using object-oriented techniques," *Comput. Phys.*, vol. 12, no. 6, pp. 620–631, Nov/Dec 1998.

[5] "Lands Department, the Government of the Hong Kong Special Administrative Region of the People's Republic China," https://www.landsd.gov.hk/, accessed: March 31, 2018.

[6] "Meshlab," https://www.meshlab.net/, accessed: March 31, 2018.

[7] Y. Tominaga, A. Mochida, R. Yoshie, H. Kataoka, T. Nozu, M. Yoshikawa, and T. Shirasawa, "AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings," *J. Wind Eng. Ind. Aerodyn.*, vol. 96, pp. 1749–1761, 2008.

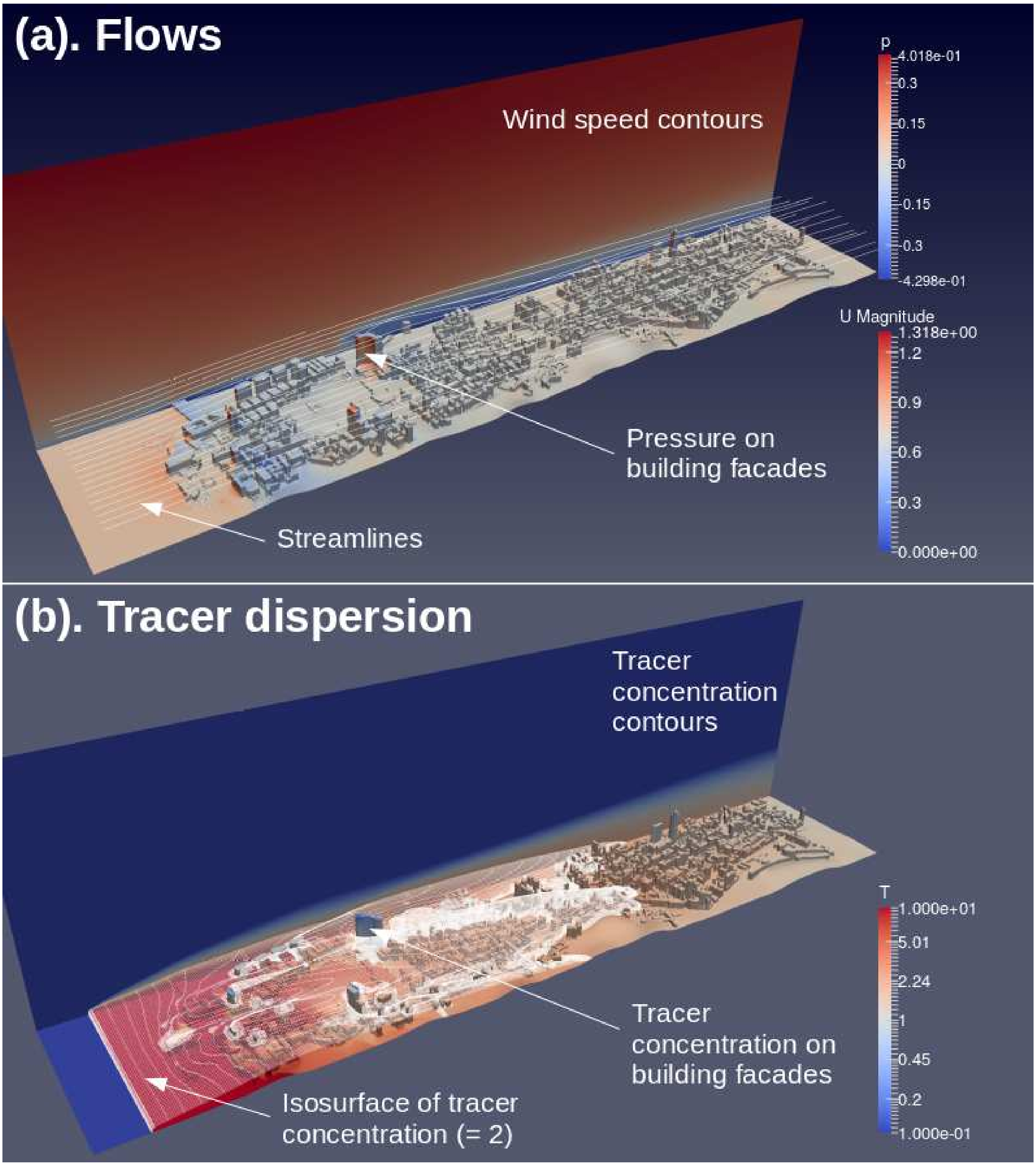

Figure 2: Preliminary CFD results of (a). flows and (b). tracer dispersion over the urban-area model of downtown HKSAR.