Thermal stratification and vegetation effects on the urban micro-climate – a CFD case study

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Dated: 15 June 2015

The effects of temperature stratification (neutral vs. unstable flow) and vegetation on the urban microclimate in a dense, high-rise residential estate in Singapore are studied using two CFD codes (StarCCM+ and OpenFOAM). Preliminary results show good agreement between the two for the velocity field but not temperature. The influence of vegetation on the surrounding micro-climate is found to be small for a specific input of leaf area density and associated cooling power.

1. Introduction

A preliminary CFD simulations using real urban geometry have been carried out with the aim to design an urban microclimate – multiphysics integrated simulation tool (UM-MIST) that will enable town planners, architects, policy makers etc. to develop more sustainable cities, and which will provide better insights into the flow physics in a densely populated tropical city like Singapore. The effects of thermal stratification, vegetation, waterbody and anthropogenic heat flux on urban flow and temperature fields will be incorporated in this multi physics tool, with the goal to carry out urban master planning, urban design & environmental modelling using a single urban digital platform. To meet these objectives, thermal stratification and vegetation are considered in the present simulations. The details of the numerical settings, preliminary results and conclusions are given in the following sections.

2. Computational domain – settings and parameters

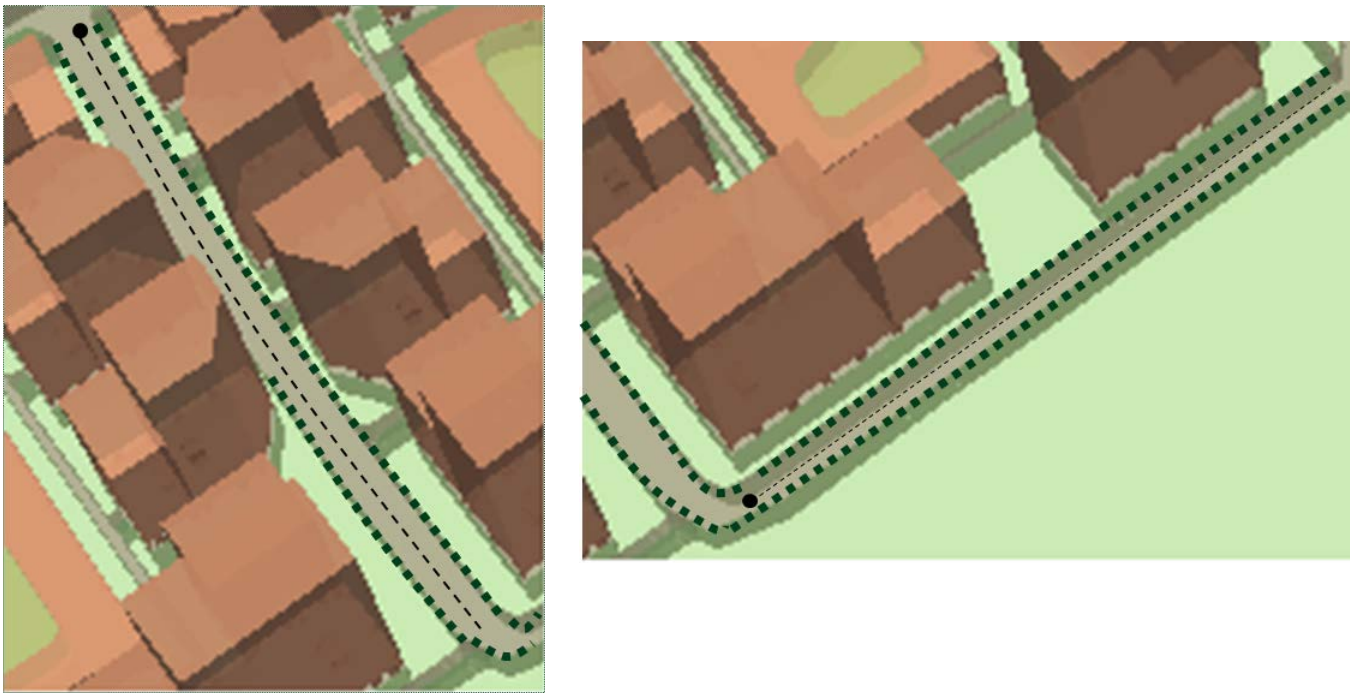
The computations are done for a coastal residential estate (RE) in Singapore. The geometry consists of various features such as tall and short buildings, courtyards, waterbodies, roads, pavement and greenery. These features are approximately 5 m above the ground level, hence terrain effects are considered in the computations. The heights of the buildings range from 15 m to 60 m. The north and east parts of this geometry are bounded by a waterbody and south and west regions are packed with trees, bushes, and a few buildings. The chosen wind direction for the present study is 45^o from North (i.e. NE), which is one of the predominant wind directions in Singapore.

The governing equations of the flow are steady Reynolds Averaged Navier-Stokes (RANS) and the k-ε turbulence model is used for closure. The thermal effects are considered using Boussinesq approximation. The computations are done using CD-adapco's StarCCM+ (SC) version 9.06 and OpenFOAM (OF) version 2.3. The steady incompressible Navier-Stokes equations for the flow and energy equations are solved using second-order schemes. The turbulence is however solved using second-order scheme in SC and first order scheme in OF, as the latter resulted in divergence if second-order is employed. SIMPLE is used for pressure-velocity coupling.

The computational domain size is 1400 m x 1400 m x 500 m in streamwise (x), spanwise (y) and vertical (z) directions respectively. The domain size is chosen such that the distance from the inlet to the RE is approximately 5h and from the outer edge of RE to the outlet 10h, where h = 60 m is the height of the tallest building in the computational domain. The OpenFOAM's snappy hex methodology is employed to generate the mesh. Six levels of mesh refinement are used such that the minimum grid size is 0.3125 m at the corner of the building surfaces and the maximum grid size is 2.5 m for z below 20 m. A uniform mesh size of 20 m is specified for z greater than 60 m. The total number of cells in the computational domain is approximately 8.5 million.

Based on the data from Seletar meteorological station, the reference wind speed is specified as 4 ms^{-1} at 14 m height. At the inlet i.e. north and east boundaries, a logarithmic mean wind speed profile with aerodynamic roughness length, z_0 = 0.1 m, turbulent kinetic energy k and turbulent dissipation rate ε are imposed (Gromke et al., 2015). Although there are various features such as glass windows, waterbody and lawn in the geometry, all the surfaces are modelled as smooth wall. The ground surface surrounding the RE is modelled as 'very rough' with z_0 = 0.5 m. This roughness is specified in terms of equivalent sand grain roughness height k_s and roughness constant c_s such that k_s is smaller than half the wall-normal height of the near-wall cell. The outflow boundary condition was specified on the south and west boundaries, and symmetry on the top surface.

The simulations are done for three scenarios: (i) neutral - without vegetation (ii) unstable - without vegetation, and (iii) unstable with vegetation. To simulate an unstable case, a uniform temperature of 303 K is specified at the inlet and a constant temperature of 308 K is specified on all the surfaces inside the computational domain. Additional source terms are introduced in the transport equations to model the vegetation (Gromke et al., 2015). The size of tree crown is approximately 5 m x 5 m x 6 m and is at 6 m from the ground. The distance between the successive trees are set as 10 m. The black rectangles in Fig. 3b show the location of trees introduced inside the computational domain. Figures 1a and 1b show the details of two streets viz. Avenue 1 (A1) and Avenue 2 (A2). The leaf area density (LAD) and the volumetric cooling power are specified as 0.55 $m^{-2}m^{-3}$ and 137.5 Wm^{-3} respectively (Gromke et al., 2015). These authors deduced the volumetric cooling power of vegetation by systematically conducting a set of simulations using Fluent and comparing the results with the field measurements of Shashua-Bar et al. (2009, 2011). As the current computational settings e.g. wind direction, magnitude, temperature, geometry, latitude and longitude of the region are very different to that of Gromke et al.'s (2015) case study, it is not recommended to use the same value of volumetric cooling power. However, the purpose here is to ensure that vegetation modelling is successfully implemented in OF and SC, which is a preliminary step towards using the 'realistic' values.



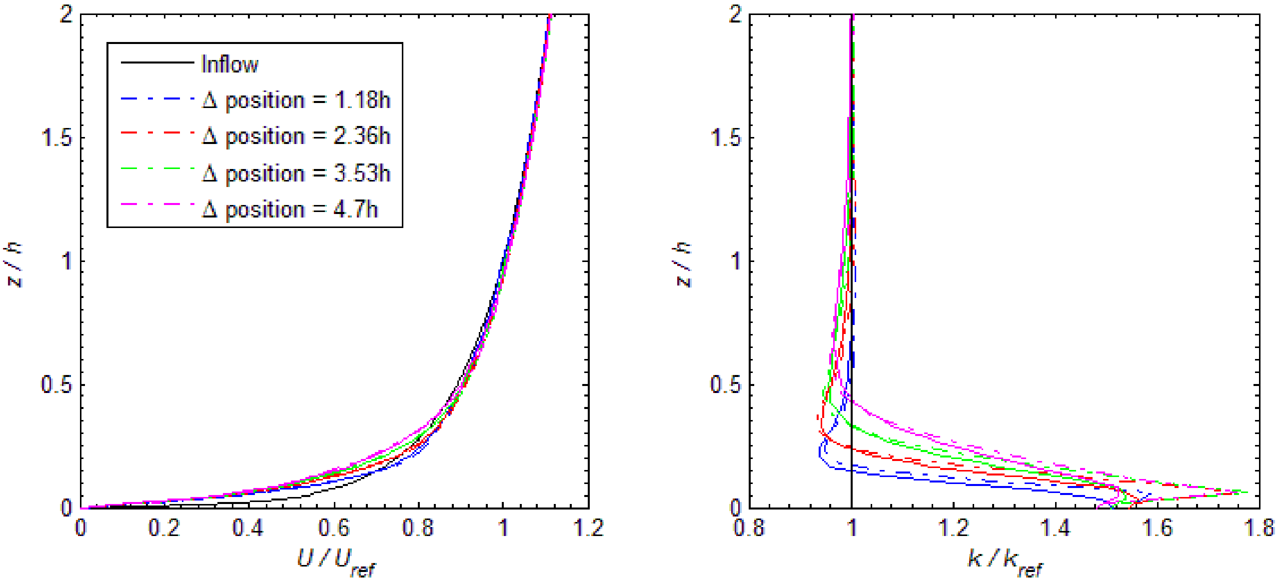
(a) Avenue 1 (b) Avenue 2

Fig. 1 Trees are introduced on either side of two streets named (a) Avenue 1 and (b) Avenue 2.

3. Results

3.1 Approach flow

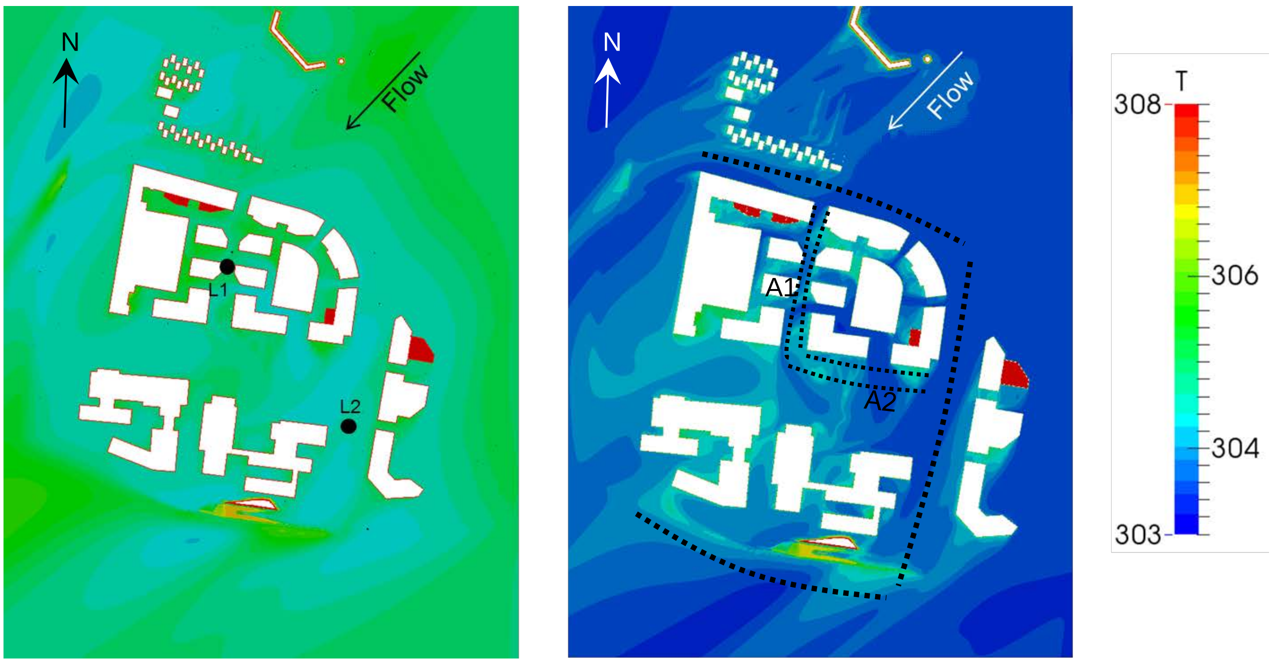
The simulations from OF and SC are compared for neutral and unstable stratified flows. For the neutral case, the vertical variation of normalized velocity magnitude (U) and normalized turbulent kinetic energy (k) at different positions from the inlet are shown in Fig. 2. The inflow velocity magnitude (U_{ref}) and turbulent kinetic energy (k_{ref}) at a reference height, z = 60 m is used for normalization. At successive distances from the inlet (Δ position), the normalized velocity profiles from both OF and SC are almost same to that of specified inflow, except for a marginal difference for z below 0.2h. However, Fig. 2b shows a gradual increase in k from the inlet to RE. Such increase is found in both OF and SC for z/h < 0.5. The k from SC are not only larger than OF, but also consist of sharper peaks at z/h = 0.0625. It is not clear if the usage of second-order upwind scheme in SC is the cause for such sharp peaks near the ground. By comparing SC and OF with a standard benchmark data (e.g. lab measurements), further insights can be obtained on the performance of these softwares. Such benchmark computations will be therefore conducted in the near future. Overall, the approach flow development shown in Fig. 2 is very small and both SC and OF show good agreement with each other, except for the sharp peak in k near the ground.



(a) (b)

Fig. 2 Vertical variation of (a) normalized velocity and (b) normalized turbulent kinetic energy at different distances from the inlet. The solid lines are from OF and dash-dot lines are from SC simulations. Different colours represent various positions from the inlet.

3.2 Comparison of neutral and unstable stratified flows



(a) (b)

Fig. 3 Temperature contours from (a) StarCCM+ and (b) OpenFOAM at z = 10 m. Note that only a part of the full horizontal plane is shown here for clarity. The two black dots in (a) are locations 1 (L1) and 2 (L2) for which vertical profiles are shown in Figure 4.The black rectangles in Figure 3b show the location of trees in the computational domain and the relevant results are discussed in Sec. 3.3.

The temperature contours at an elevation of 10 m in Figure 3 show that SC and OF yield very different values. The OF simulations in Fig. 3b show that the heated surfaces have a marginal influence on the surrounding flow in comparison to SC.

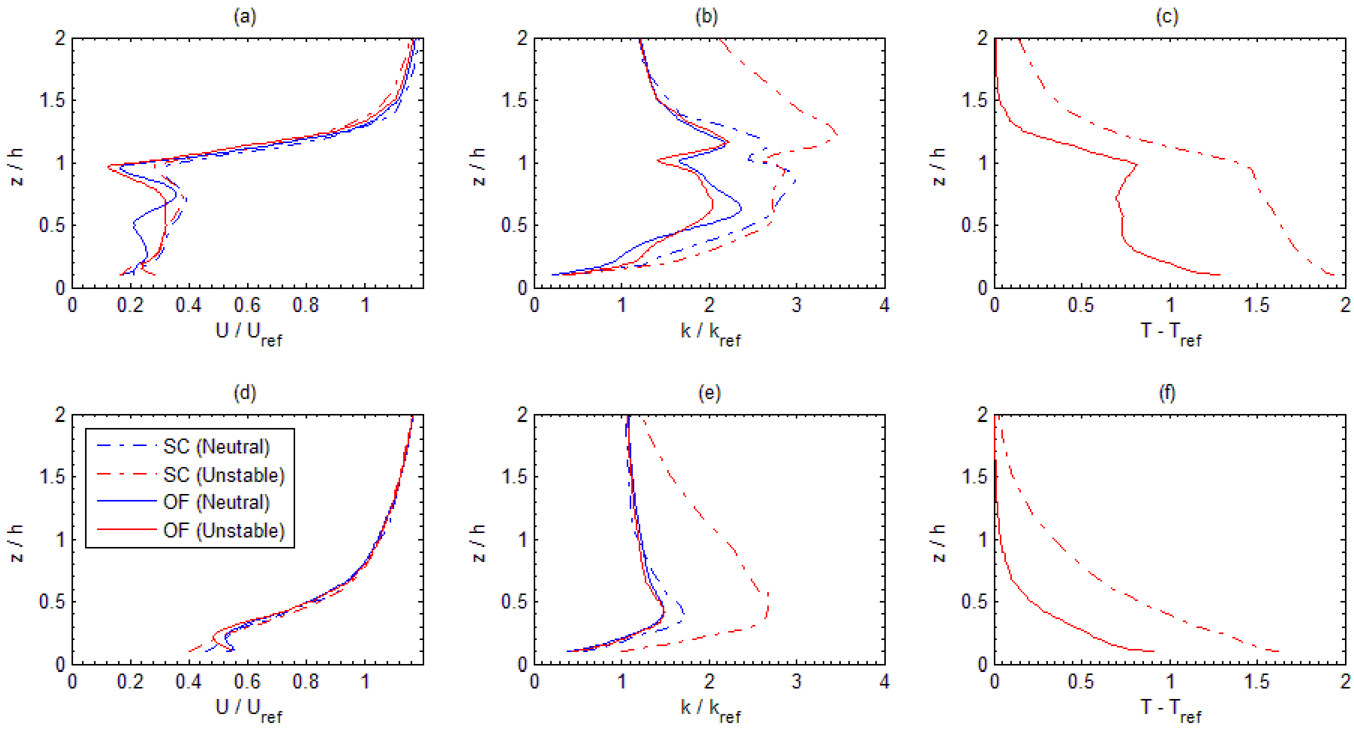


Fig. 4 Vertical variation of (a, d) normalized velocity magnitude, (b, e) normalized turbulent kinetic energy and (c, f) temperature difference at two locations L1 (top row) and L2 (bottom row).

Further comparisons are done between OF and SC in order to understand the variation of such differences locally. For this, two sets of vertical profile data are extracted at L1 and L2. The vertical variation of velocity magnitude, turbulent kinetic energy and temperature difference at these two locations are shown in Fig. 4. Except for small differences for $z/h < 1$ in SC at L1, Figs. 4a and 4d show almost similar velocity magnitude for neutral and unstable flows. Figures 4b and 4e show that the turbulent kinetic energy from OF is same for both neutral and unstable flows at L1 and L2, whereas SC shows larger k for unstable flow. Figures 4c and 4f show that the difference between the local and the inlet temperature (T_{ref}) in SC is larger than OF. It is intuitive that buoyancy enhances vertical mixing thereby increases the turbulent kinetic energy (k). The reason for such low values of T and k in OF is currently under investigation.

3.3 Comparison of unstable stratified flow in the presence and absence of vegetation

To gain an understanding on the role of vegetation on micro-climate in built-up areas, the vegetation is introduced in the computational domain and is shown in Figs. 1 and 3b. It is to be noted that the computations (i) do not consider the shading of buildings and vegetation, (ii) the shape and size of trees does not represent real geometry and, (iii) the leaf area density and the cooling power values used are from Gromke et al.'s (2015) simulations. The computations are run using SC and all other numerical settings are kept same as that of the unstable case. Figure 5 shows the temperature profiles at two different heights and along the centre of Avenue 1 and Avenue 2 streets.

Figure 5c shows almost similar values of temperature in the presence and absence of vegetation. Taking the terrain information in to account, this elevation corresponds to the pedestrian height. However, for the same street, but at z = 13 m, the temperature difference is found to be approximately 0.3 to 1^{o} C and can be seen in Fig. 5a. This elevation approximately corresponds to the centroid of tree crown. Interestingly, Figs. 5b and 5c show the temperature difference is approximately 1.5^{o}C at the start of A2, and this difference gradually diminishes towards the end of the street.

As mentioned earlier, these preliminary computations are done to ensure the correct implementation of the physical and numerical parameters. Further simulations are planned to incorporate the real shapes and sizes of trees to obtain better insights on vegetation influence on micro-climate.

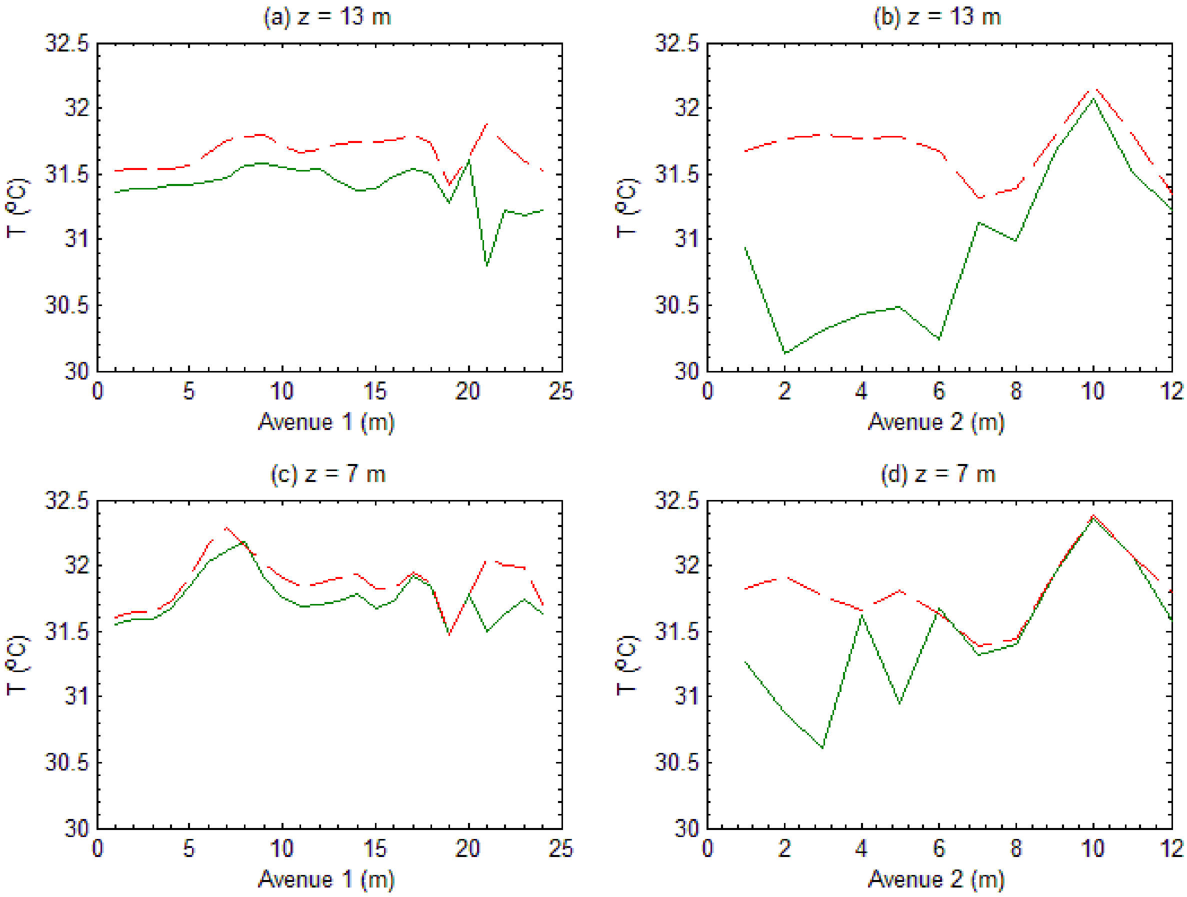


Fig. 5 Temperature variation at two heights along the centre of Avenue 1 and Avenue 2. Solid (dashed) line – with (without) vegetation. The x-axis corresponds to the centre of Avenue1 and Avenue2 streets and corresponds to the black dashed line in Fig. 1. The origin for the x-axis is taken at the starting point of the two avenues and is indicated as block dot in Fig. 1.

4. Discussion and Conclusion

CFD simulations are carried out for a coastal residential estate in Singapore using StarCCM+ (SC) and OpenFOAM (OF) for three scenarios: neutral flow without vegetation, unstable stratified flow without vegetation and unstable stratified flow with vegetation.

The neutral flow field from OF and SC are found to be in good agreement. However, for unstable stratified flow, the temperature difference and turbulent kinetic energy from SC are found to be very different to OF. While it could be possible that high turbulent kinetic energy (k) near the surface in the approach flow might result in larger k inside the residential estate in SC simulations, the contour plots and vertical profiles from OF show that the temperature is severely under-predicted. The validation studies are therefore planned in order to understand the cause of such under-prediction in OF.

The preliminary computations from SC show that vegetation has a marginal cooling influence on the local micro-climate. Because this result is very case specific (i.e. wind direction, leaf area density, temperature etc.) and many assumptions (e.g. no shading of buildings and trees) are made in the present simulations, further studies will aim at implementing real shapes and sizes of trees to the best extent possible and include the shading effects of buildings and trees in order to obtain better insights on the urban micro-climate.

Acknowledgment

This material is based on research/work supported by the Singapore Ministry of National Development and National Research Foundation under L2 NIC Award No. L2NICCFP1-2013-6. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Singapore Ministry of National Development and National Research Foundation. The authors would like to thank the Housing Development Board of Singapore for providing the geometrical model and RightViz Solutions Pte Ltd for providing the water-tight geometry.

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