MICROSCALE FLOW SIMULATIONS OVER URBAN CONFIGURATIONS INCLUDING THERMAL EFFECTS

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Abstract: Climate and air quality in cities are influenced by micrometeorological features induced by the presence of buildings and trees. These obstacles act in two ways: 1) by blocking, deviating and slowing down the flow (mechanical effects); and 2) by exchanging heat with the atmosphere (thermal effects). For clear sky conditions, surface heat fluxes exhibit strong spatial heterogeneity due to surface orientation and shading. To date, numerical microscale flow studies for air quality purposes have either neglected the thermal effects entirely, or accounted for them in a very crude way. On the other hand, urban climate simulations often do not consider the complex flow structures generated within the urban canopy. The aim of this contribution is to quantify the impact of the thermal effects on microscale flow structures in the urban canopy. The tool used is a Computational Fluid Dynamics (CFD) model (STARCCM+) that is run with sufficient resolution to explicitly resolve the obstacles (of the order of meters). The surface sensible heat fluxes are prescribed at the road and building surfaces, using the TUF3D model (Krayenhoff and Voogt, 2007) to ensure realistic distribution of values. The geometrical configuration analysed is a 3D array of cubes and the heat fluxes imposed at walls and road correspond to a solar zenith angle of 30º. Scenarios with varying intensity of both wind velocity and heat fluxes intensity are analysed.

Key words: Urban Configurations, CFD, Heat Fluxes, TUF3D.

INTRODUCTION

Micrometeorology and pollutant dispersion within cities is important for urban climate, air quality and pedestrian comfort. However, the interaction between the atmosphere and urban surfaces (buildings, trees, etc.) induces complex flow patterns within the urban canopy, and thus streets exhibit heterogeneous distributions of temperature and pollutant concentration. The resolution of Computational Fluid Dynamics (CFD) models is high enough to explicitly resolve the flow around the buildings, and can be used to reproduce the flow properties. One important physical process that has not been studied in detail is the interaction between heat fluxes from building surfaces and streets and the airflow. Most scenarios studied to date have only heated one wall of the canyon, or the ground. In this work, a realistic distribution of sensible heat fluxes for each scenario is introduced with a resolution of one meter.

A RANS-CFD model is used to simulate the flow properties over an aligned array of cubes (idealized city) and the TUF3D model (Krayenhoff and Voogt, 2007) is used to provide realistic heat fluxes to the CFD for use as boundary conditions. The effects on averaged flow properties of varying the ratio between buoyancy and dynamical processes are analysed.

DESCRIPTION OF CONFIGURATION

The geometrical configuration studied is an aligned array of cubes with a packing density of $\lambda_p = \lambda_f = 0.25$. The array is aligned with the cardinal directions. The solar configuration is a situation at 10 am during a solar Equinox at the Equator, resulting in a solar zenith angle of ≈ 30º. In Figure 1, the heat fluxes computed by TUF3D are shown. In the street canyon the windward wall and the adjacent part of the canyon floor have reduced sensible heat flux because they are shaded. The wind flows from left to right in the Figure 1 (i.e., perpendicular to the windward cube faces).

NUMERICAL SET-UP

The configuration in Fig. 1 is simulated by the CFD model. Simulations based on Reynolds-averaged Navier-Stokes equations with standard k-ε turbulence closure are performed. In addition, buoyancy terms are taking into account using Bousinesq's approach and an equation for temperature is solved.

A periodic domain in the horizontal directions is used in order to study an infinite array of aligned cubes. At the top of the domain (4*H*, where *H* is obstacle height) a downward flux of momentum $\rho u_\tau^{\,2}$ in the X-momentum equation is imposed to maintain the flow. Concerning temperature boundary conditions at the top, a T_{ref} is fixed allowing a flux equals to $k_{eff}\left(T_{ref}-T\right)/\Delta z$ where k_{eff} is the effective thermal conductivity.

In terms of the heat balance, realistic heat fluxes are imposed at the walls and roof of the buildings and at ground. The heat fluxes are computed by TUF3D assuming simple concrete floor and building construction (surface albedo = 0.40, surface thermal inertia = 1058 J K^{-1} m^{-2} $s^{-0.5}$). TUF3D is a dry, three-dimensional microscale urban energy balance model with a focus on radiative exchange. Plane parallel facets (roofs, walls, streets) are split into identical square patches, each of which exchanges shortwave and longwave radiation, sensible heat and conduction heat. Incident solar radiation on each patch is solved via ray tracing, and diffuse receipt and reflections are computed using view factors and matrix inversion. Simple profiles of wind speed and air temperature are calculated as a function of urban morphology and above-canyon forcing, and these then drive sensible heat exchange from each patch. Patches are divided into layers parallel to the surface, each with unique thermal properties, and heat conduction between the exterior and interior (or deep) surfaces is computed. Further details about the model and its evaluation are available in Krayenhoff and Voogt (2007). A resolution of 16 is used for the current TUF3D simulation (i.e., there are 16 patches across each wall, roof and road).

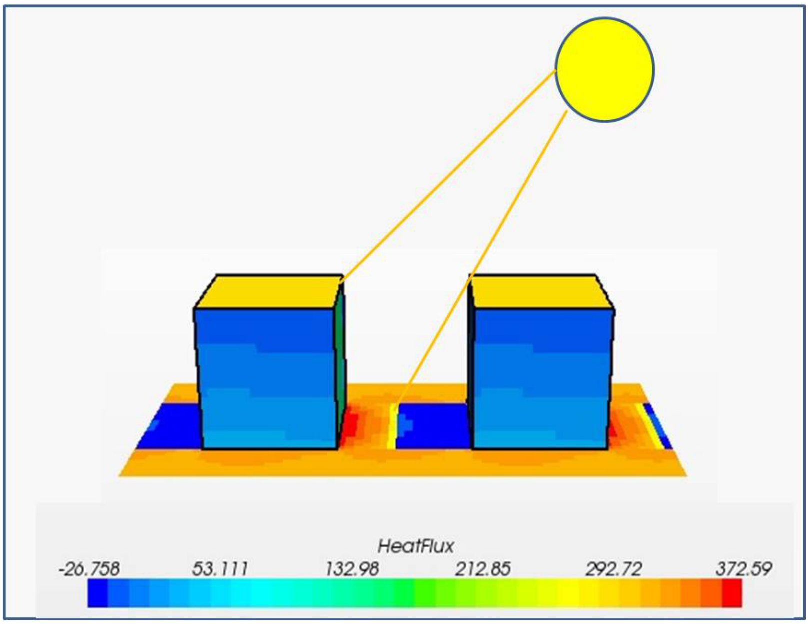

Figure 1. TUF3D surface sensible heat flux distribution corresponding to 10 am (zenith angle 30º) during the Equinox at the Equator.

RESULTS

In order to investigate the impacts of the heat fluxes on the flow, a series of simulations was carried out by multiplying the heat fluxes computed by TUF3D, by a factor that varies from 0 (neutral) to 2 (very buoyant). In this way, only the intensity of the heat flux is varied, but not the relative distribution.

Results are represented as a function of the adimensional number H/L_{urb} where L_{urb} is formally similar to the Monin Obukhov Length and is defined as:

$$L_{urb} = \frac{u_\tau^{\,3}}{\left(\dfrac{g}{T_{ref}} \dfrac{Q_h}{\rho C_p}\right)}$$

where g is the acceleration due to gravity, Q_h is the total heat flux (W m^{-2}) from all urban surfaces, ρ is the density of air, C_p is the specific heat of air, and T_{ref} is a reference temperature (in this case T at the top of domain is considered).

To verify that this is a useful adimensional number, two different configurations are simulated with the same value (H/L_{urb} = 1.5) but with different u_τ and Q_h (ratio between Q_h of the two simulations = 0.5). Q_{hTUF} is defined as the Q_h provided for TUF simulations.

Horizontal spatial averages of each flow property are taken at each height. Figure 2 shows the vertical profiles of mean streamwise velocity (U) and the difference between the temperature at each height and temperature at the top of the domain (ΔT). The wind speed is normalised by u_τ and the temperature by $\frac{Q_h/\rho C_p}{u_\tau}$ (i.e., ΔT_{norm}). The profiles are almost identical and we can conclude that the two simulations are equivalent, and that the adimensional number chosen is appropriate.

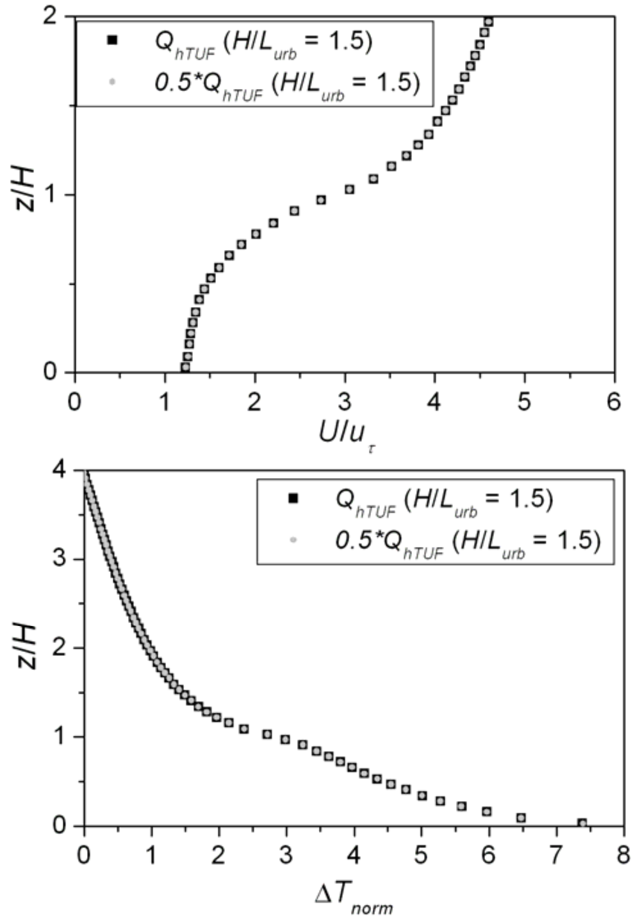

Figure 2. Vertical profiles of spatially-averged streamwise velocity and ΔT_{norm} for cases with the same Q_{hnorm} (= 1.5)

Cases with different intensities of Q_h (H/L_{urb} from 0 to 3) but for the same relative spatial distribution of Q_h are simulated to investigate the relation between buoyancy forces and dynamical forces on the flow properties. This study is focused on the average properties of the flow and horizontal average properties at each height are the focus. Figure 3 shows the vertical profiles of mean streamwise velocity and ΔT_{norm}. Note that the normalization is the same as in Figure 2.

Inside the canopy, the average wind speed is close to that for the neutral case for cases with H/L_{urb} = 0.4 and 0.75. However the wind profiles change notably for $H/L_{urb} \geq 1.5$. The wind speed is reduced at the top and above the canopy. This is likely because the increase of H/L_{urb} increases the vertical mixing of momentum. For $H/L_{urb} \geq$ 1.5 the flow regime seems to change with respect to the neutral case.

To analyse ΔT_{norm} profiles, we have to take into account the normalization of ΔT. ΔT_{norm} is proportional to $\Delta T/Q_h$ and the values of ΔT_{norm} decrease as Q_h increases. ΔT at each height is higher for the cases with higher Q_h (for constant u_τ) (not shown here). However, the values of ΔT_{norm} close to the ground are higher for lower values of

H/L_{urb}. This is due to the fact that an increase of Q_h (for constant u_τ) produces an increase of temperature, but this increase is not proportional to that of Q_h. In other words, the increase of H/L_{urb} results in an increase of the vertical mixing and smaller differences between the normalized temperature in the canopy and above. In a certain sense, ΔT_{norm} profiles show the efficiency of Q_h in terms of its ability to enhance mixing and therefore increase air temperature inside the canyon. An increase of Q_h produces an increase of temperature but at the same time the vertical mixing is also enhanced.

Taking the neutral case (Q_h = 0) as reference, Root Mean Square differences are computed for average streamwise velocity vertical profiles of cases with different H/L_{urb}.

$$RMSD = \left(\frac{\sum_{1}^{n} \left(U(z) - U_{neutral}(z) \right)^2}{n} \right)^{0.5},$$

where n is the number over horizontal slices considered.

The RMSD is computed over the range z/H = 0 to z/H = 2. The values are shown in Figure 4. There is a jump in the RMSD as H/L_{urb} increases from 0.75 to 1.5.

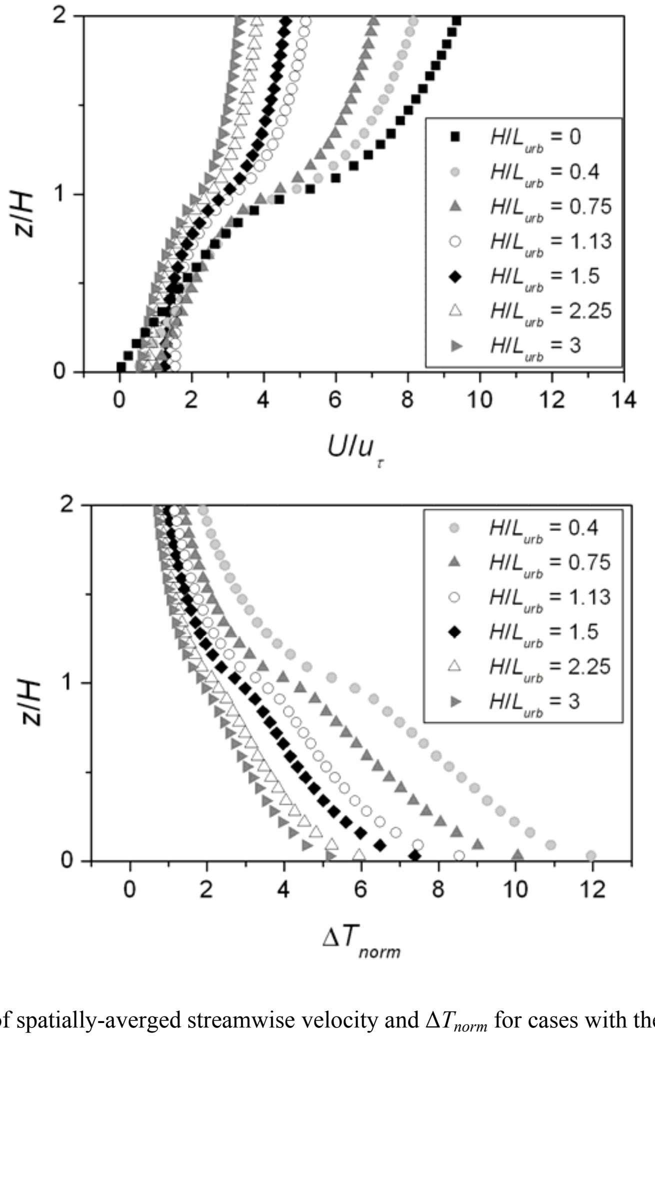

Figure 3. Vertical profiles of spatially-averged streamwise velocity and ΔT_{norm} for cases with the different H/L_{urb}.

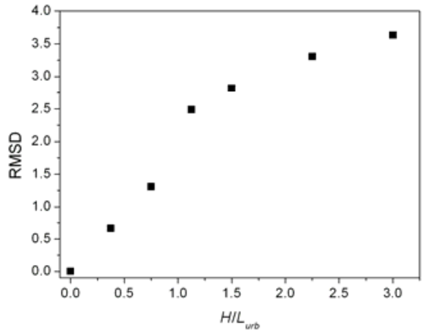

Figure 4. RMSD comparing average streamwise velocity vertical profiles of cases with different H/L_{urb} with the neutral case ($Q_h = 0$). Values are compared from $z/H = 0$ to $z/H = 2$.

An important parameter for modelling wind profiles in urban canopy parameterizations is the drag coefficient. Following the formulation of Santiago et al. (2010) we compute C_{deq} for the different cases as follows,

$$C_{deq} = \frac{\int_0^H \Delta P dz}{\rho \int_0^H U^2 dz}$$

Figure 5 shows the variation of C_{deq} with H/L_{urb}. For $H/L_{urb} \leq 0.75$, C_{deq} is almost constant, but for higher H/L_{urb} its value increases due to the decrease of the average value of U^2 within the canopy.

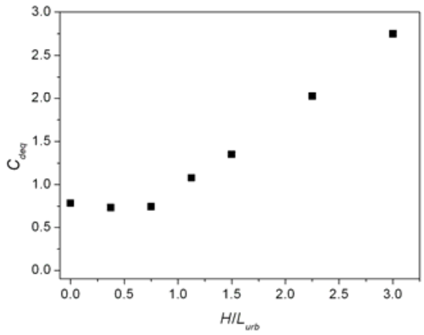

Figure 5. Cdeq for cases with the different Q_{hnorm}.

CONCLUSIONS

Scenarios with realistic heat fluxes imposed at the ground and at the roof and walls of buildings are simulated by a CFD model. The heat fluxes and their spatial distribution are computed by the TUF3D model, and the variation of the average flow properties with the adimensional number H/L_{urb} is analysed. For cases with high buoyancy force $H/L_{urb} \geq 1.13$, the canopy drag coefficient C_{deq} increases substantially relative to the neutral case, suggesting that this effect is important to include in parameterization of drag in urban canopy models. For cases with $H/L_{urb} \leq 0.75$, C_{deq} is similar to the neutral case. In future work, cases with different solar angles will be analysed in order to generalise these results.

ACKNOWLEDGEMENTS

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