10.4 MICROSCALE URBAN FLOW SIMULATIONS WITH REALISTIC DISTRIBUTIONS OF SURFACE THERMAL FORCING

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1. INTRODUCTION

Better understanding of the physical processes within the urban canopy is important for diverse applications related to urban climate, air quality and pedestrian thermal comfort.

Urban micrometeorology is determined by interactions between the atmosphere and urban surfaces. These interactions result in complex flow fields and heterogeneous distributions of temperature and pollutants within the cities. Surface-atmosphere interactions may be classified as mechanical (blocking, deviating and slowing down the flow) or thermal (buoyancy forces due to heat exchange between the atmosphere and street and building surfaces).

Urban surface heat fluxes are responsible for the temperature distribution in the canopy air, which is heterogeneous and depends on several factors such as urban geometry, solar position, etc.

Computational fluid dynamics (CFD) simulations usually neglect thermal interaction, or it is included in a simple way by setting only one facet to a different (but constant) temperature with respect to the other surfaces.

In this study, microscale simulations using a RANS model are carried out over a periodic array of cubes with a packing density of 0.25. Thermal effects are analyzed by imposing realistic distributions of heat fluxes as boundary conditions at building and street surfaces. The microscale heat flux distributions are computed by the TUF3D model (Krayenhoff and Voogt, 2007). Several scenarios are studied to explore the effects of different solar positions and ratios of buoyancy to dynamical forces.

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The main objective is to determine the impacts of “realistic” distributions of urban surface heat fluxes on airflow properties. Flow and temperature distributions within the street canyon are analyzed. In addition, the impact of the microscale thermal forcing on the spatially averaged flow properties is also discussed. This information can be useful for air pollution dispersion models and urban canopy models to parameterize processes that are subgrid relative to typical mesoscale model grid resolutions (e.g., drag forces induced by buildings).

2. DESCRIPTION OF CONFIGURATION AND NUMERICAL SET-UP

The geometrical configuration studied is an aligned array of cubes with a packing density of $\lambda_f = \lambda_p = 0.25$. Figure 1 shows a scheme of the numerical domain and mesh of the RANS simulations. The array is aligned with the cardinal directions and the flow is imposed in the *x*-direction. Seven solar positions are analysed. One scenario for a 0º solar zenith angle, and two cases (one shading the windward wall and the other the leeward wall) for 60º, 45º, 30º. Figure 2 shows an example of two solar positions for a 60º zenith angle. In addition, for each solar position several ratios between buoyant and inertial forces are simulated.

The methodology is the following:

1) Heat flux distribution due to solar position is computed by an urban energy balance model (TUF3D model, Krayenhoff and Voogt, 2007). This model 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 and sensible heat, and store/release conduction heat.

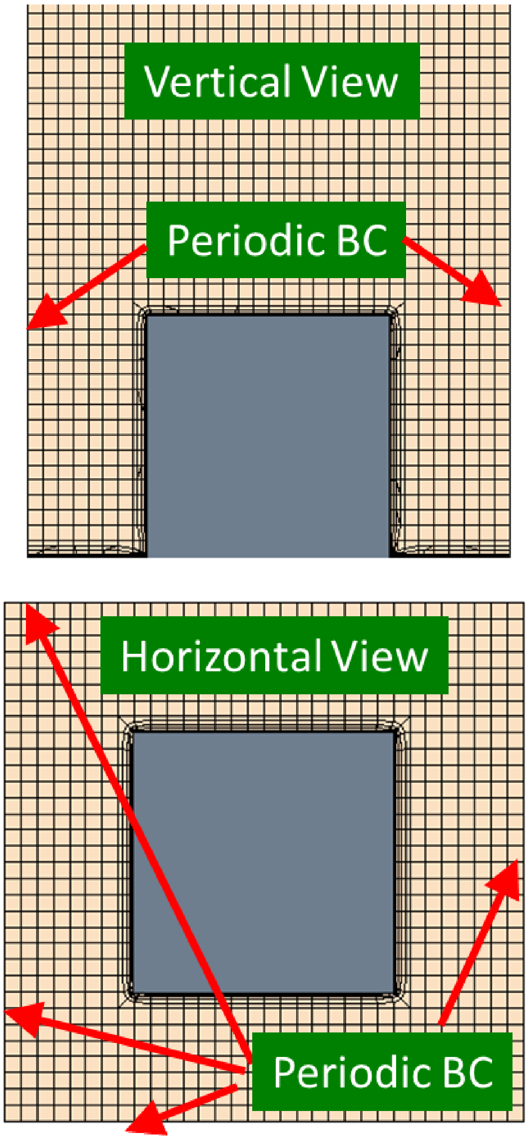


Figure 1. Numerical domain and mesh of the CFD simulations.

2) The flow and temperature around the buildings is simulated by a computational fluid dynamics (CFD) model (STARCCM+ from CD-Adapco) using as boundary conditions the heat fluxes computed by TUF3D model.

The array is aligned with the cardinal directions and the flow is imposed in the *x*-direction. In order to simulate an infinite array, periodic boundary conditions are imposed at four lateral boundaries of the numerical domain (Figure 1). The height of the domain is 4*h* (where *h* is cube height). Reynolds-averaged Navier-Stokes (RANS) equations and the standard *k*-*ε* turbulence model are used. Thermal effects are considered by imposing realistic distributions of heat fluxes as boundary conditions at building and street surfaces. In addition, buoyancy terms are accounted for with Boussinesq's approximation and an equation for temperature is solved. A neutral case (surface heat fluxes are neglected) is also simulated. Flow is maintained by a downward flux of momentum ρu_τ^2 imposed at the top of domain in the *x*-momentum equation, where ρ is air density and u_τ is the friction velocity. There, a T_{ref} is fixed allowing a flux upward out of the domain equal to $k_{eff}\left(T_{ref}-T\right)/\Delta z$ where k_{eff} is the eddy conductivity for heat at the top of the domain, and Δz is the vertical mesh size of the top cells. A cartesian grid is used which resolves each cube with 16 cells in each direction.

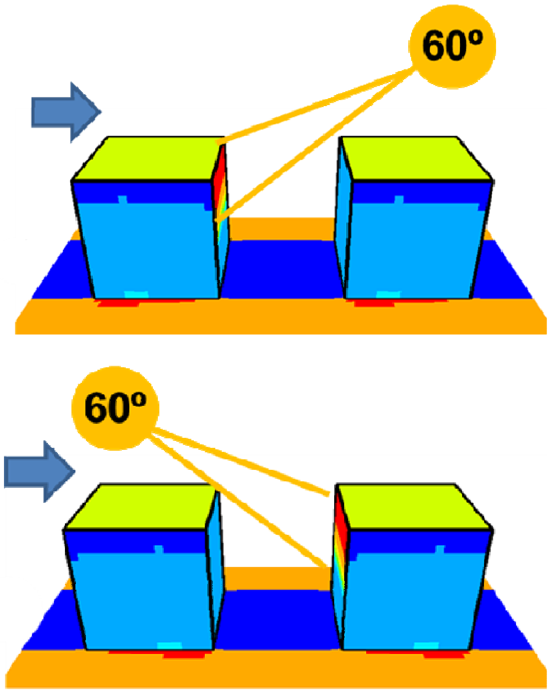


Figure 2. Two of the solar positions simulated (60º zenith angle).

The ratio between buoyancy and inertial forces of the cases studied are characterized in terms of h/L_{urb}, where h is the height of the cubes and L_{urb} is an urban length scale defined analogously to the Monin-Obukhov length as,

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

Cases with h/L_{urb} values from 0 to 3 are simulated. 0 correspond to the neutral case and higher is h/Lurb higher is the buoyancy forces respect to inertial forces.

Velocity is normalized by u_τ and temperature is normalized by $\dfrac{Q_h/\rho C_p}{u_\tau}$ where Q_h is the total heat flux (W m^{-2}) from all urban surfaces, ρ is the density of air and C_p is the specific heat of air.

3. MICROSCALE RESULTS

The main aim is to analyze the influence of solar position and intensity of thermal forcing (respect to inertial forces) on the flow and normalized temperature fields.

As an example, cases with a solar zenith angle of 30º and different h/L_{urb} (intensities of thermal forcing) are analyzed. Figure 3 shows the flow field for neutral case and figures 4-5 show the flow and normalized temperature for h/L_{urb} = 0.4, and 2.25.

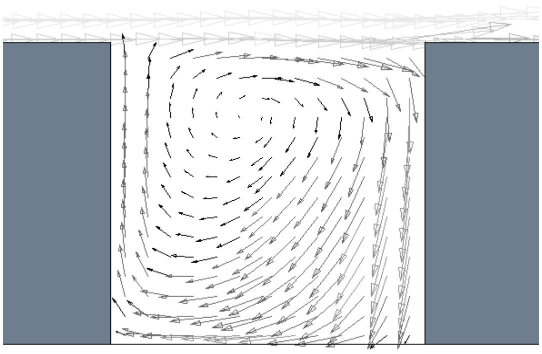
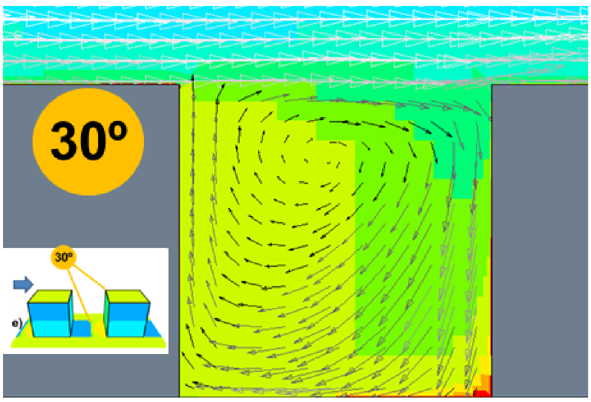


Figure 3. Flow field for neutral case



$$\Delta T_{norm} = \frac{\Delta T}{\dfrac{Q_h/\rho C_p}{u_\tau}}$$

Figure 4. Flow field and normalized temperature for a solar zenith angle of 30º and h/L_{urb} = 0.4.

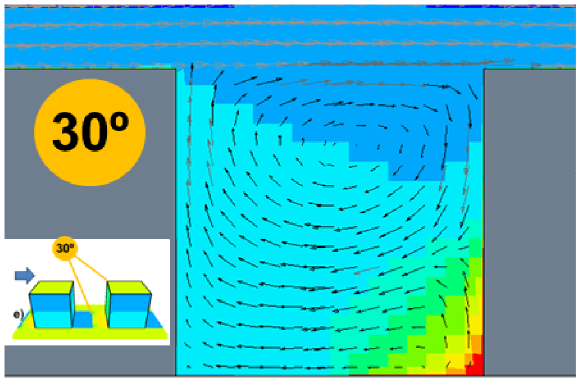


Figure 5. Same as Figure 4 but for h/L_{urb} = 2.25.

For low h/L_{urb} the flow field is similar to neutral case and the distribution of temperature within the canyon is due to the advection of the heat from urban surfaces. For h/L_{urb} = 2.25, the flow field changes and appears a small vortex in the bottom part of the windward wall of the canyon. This induces a high temperature at this corner. Similar conclusions can be found for other solar positions taking into account different temperature fields are obtained. When interpreting the normalized temperature fields, it is important to account for the normalization of the temperature. In general, ΔT_{norm} decreases as h/L_{urb} increases because an increase of Q_h (for constant u_τ) produces an increase of temperature that is less than that of Q_h (e.g. an increase of Q_h [for constant u_τ] by a factor of 4 produces an increase of ΔT by a factor less than 4). This relates to the alteration of the flow field due to enhanced mixing resulting from buoyancy.

4. SPATIALLY AVERAGED FLOW PROPERTIES

CFD models cannot simulate a domain that covers the whole city and its surroundings. However, mesoscale models can simulate these domains but with their spatial resolution (several hundreds of meters) is not possible to solve the flow around the buildings. Usually, urban canopy models (compromise between simplicity and accuracy) are used to parameterize processes at smaller scale than mesoscale resolution (i.e. parametrization of drag forces induced by buildings). In this way, spatially-averaged properties of the flow are computed from CFD results in order to provide this information to urban canopy parametrization.

Figure 6 and 7 show the vertical profiles of spatially-averaged streamwise velocity with different h/Lurb for a zenith angle of 30º but heating different walls (windward and leeward wall respectively) of the canyon. It is observed that the spatially-averaged profiles are more dependent of the ratio between buoyant and inertial forces (h/L_{urb}) than the distribution of surface heat fluxes. Similar conclusions can be obtained from normalized temperature profiles (not shown here).

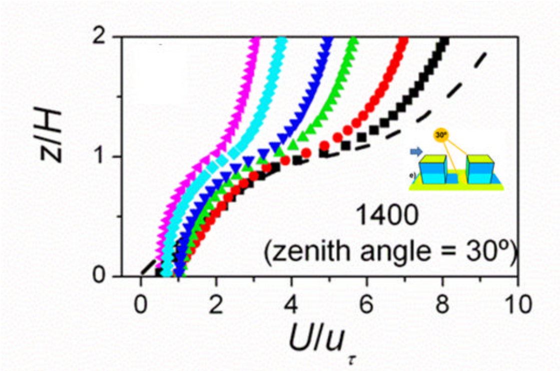


Figure 6. Vertical profiles of spatially-averaged streamwise velocity with different h/Lurb for a zenith angle of 30º heating windward wall of the canyon.

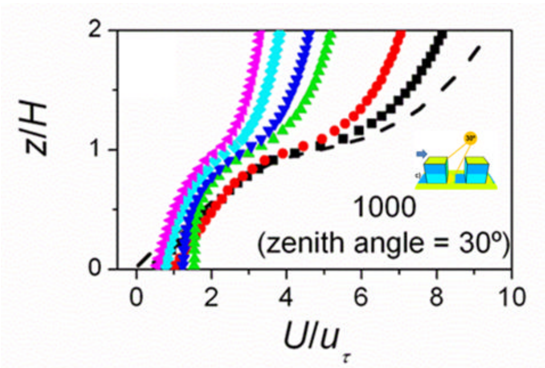


Figure 7. Vertical profiles of spatially-averaged streamwise velocity with different h/Lurb for a zenith angle of 30º heating leeward wall of the canyon.

An important parameter for modelling wind profiles in urban canopy parameterizations is the drag coefficient. Different constant values for Cd have been used from 0.1 (Uno et al., 1989) to 1.0 (Coceal and Belcher, 2004). However, it is known that C_d depends on several parameters: building configuration and height within the canopy, wind direction (Santiago et al., 2008; Santiago et al., 2013; Simon et al., 2014). 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 8 shows the values of C_{deq} for different solar positions and different intensities of thermal forcing.

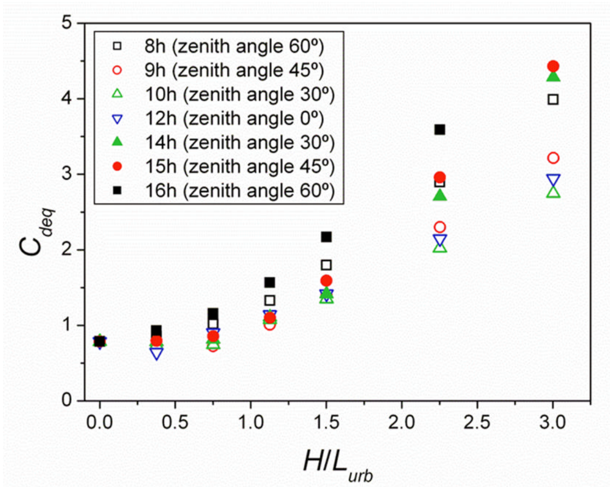


Figure 8. Variation of C_{deq} with h/L_{urb} for the different solar positions.

For $h/L_{urb} < 1.0$, C_{deq} is similar to the value for neutral case. However, it increases substantially for $h/L_{urb} > 1.0$. Then this effect should be important to include in parametrization of the drag in urban canopy models for cases with high buoyancy force.

5. SUMMARY AND CONCLUSIONS

Scenarios with realistic distributions of heat fluxes imposed at urban surfaces are simulated by a CFD model. Cases with different solar positions and different ratios between buoyancy and inertial forces are analyzed. The non-dimensional parameter h/L_{urb} is used to represent the intensity of buoyant forces respect to inertial forces. It has been found as a good parameter to determine the range where the buoyancy forces has to be considered. For example, it has been found that C_{deq} is similar to the value for neutral case for $h/L_{urb} < 1.0$ and it increases substantially for $h/L_{urb} > 1.0$.

ACKNOWLEDGEMENTS

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