MICROMETEOROLOGICAL MODELING OF RADIATIVE AND CONVECTIVE EFFECTS WITH A BUILDING RESOLVING CODE

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Abstract: **:** In this paper, we present results of the full coupling of the radiative and thermal schemes with the 3D dynamical model and compare the results with simpler approaches found in the literature.

Key words: *thermal transfer, radiative exchange, convection modeling, microclimate, surface temperature, CFD*

INTRODUCTION

Knowledge of the surface energy balance is essential for understanding the boundary layer processes, especially in urban area. It is also important to model the atmosphere in non neutral stratification, for instance in dispersion and risk assessment studies. In order to simulate atmospheric flows and surface temperature evolution in urban areas, we have developed a three-dimensional atmospheric radiative scheme in a Computational Fluid Dynamics (CFD) code adapted to complex geometry. The radiative scheme has been validated with idealized cases and the results of a real case (Milliez et al, 2006; Milliez, 2006).

EQUATIONS AND MODELS

1.CFD model

The simulations are performed with the 3D CFD model *Code_Saturne*, which is adapted to complex geometry and complex physics. In this work, we use the atmospheric module, which takes into account the larger scale meteorological conditions and the stratification of the atmosphere. In our simulations, we use a RANS approach with a **k-ε** turbulence closure. The numerical solver is based on a finite-volume approach for co-located variables on an unstructured grid. Time discretization is achieved through a fractional step scheme, with a prediction-correction step (Milliez and Carissimo, 2007, 2008).

2. Radiative model

We have adapted to the atmosphere a radiative heat transfer scheme available in *Code_Saturne* for complex geometry. This model, based on the Discrete Ordinate Method (DOM), solves the radiative transfer equation for a grey semi-transparent media (Milliez et al, 2006; Milliez, 2006).

Surface temperature

To determine the surface temperature, we have tested two methods.

1) Force-restore model:

$$\frac{\partial T_w}{\partial t} = \frac{\sqrt{2\omega}}{\mu_w} Q_w^* - \omega(T_w - T_{g/b}) \tag{1}$$

Where T_w is the surface temperature, ω is the earth angular frequency, μ_w is the thermal admittance, Q^*_w is the total net flux and $T_{g/b}$ is either deep soil or internal building temperature. This simple approach is widely used for soil models in meteorological models.

2)1D thermal model:

$$Q_{cond} = Q_{conv} + Q_{net}^{RAD} \tag{2}$$

$$\frac{\lambda_w}{e_w}(T_w - T_{\text{int}}) = h_f(T_a - T_w) + \varepsilon_w(Q_L - \sigma T_w{}^4) + (1-\alpha)(Q_{S_d} + Q_{S_f}) \tag{3}$$

where Q_{cond} is the conduction flux, Q_{conv} the convection flux, Q^{RAD}_{net} the net radiation flux, λ_w the thermal conductivity of the wall, e_w the thickness of the wall, T_w the surface temperature, T_{int} the internal temperature, h_f the heat transfer coefficient, T_a the air temperature, Q_L the long-wave radiation flux, σ the Stephan-Boltzmann constant, α the albedo, Q_{Sd} and Q_{Sf} are direct solar radiation and diffuse solar radiation, respectively. For the case we present in this paper, it seems that the force-restore scheme gave better results. 1D thermal model may be more suitable for real urban buildings, which will be our future work.

Internal temperature

The internal temperature is a very important parameter which has a large influence on the results. We tested 3 different approaches.

1) T constant:

The internal building temperature is a constant which is computed by averaging the diurnal temperatures of all the building surfaces.

2) Evolution equation:
A temperature evolution equation is used to represent the internal temperature inside the buildings.

$$T^{n+1} = T^{n-1}\left(\frac{\tau - \Delta t}{\tau}\right) + \underline{T}\left(\frac{\Delta t}{\tau}\right) \tag{4}$$

Where T^{n+1} and T^{n-1} the temperatures at the future and previous time step, respectively, Δt is the time step, τ is equal to 1 day, and $\underline{T}$ is the average of the surface temperatures (Masson, 2002).

3) T from measurement:
The internal temperature is usually not measured. We use the previous formula, and replace $\underline{T}$ from the calculation with the average of the surface temperatures from measurement to be more realistic.

RESULTS

Our validation is based on the MUST experiment (Mock Urban Setting Test). It's an experiment carried out in US, where buildings were represented by an array of shipping containers (LxWxH:12.2x2.42x2.54m) (Yee and Biltoft 2004). MUST has already been used to validate the dynamics and dispersion model (Milliez and Carissimo, 2007 and 2008). Since temperature data are also provided, we also used the MUST experiment to study in detail the dynamic-radiative coupling. Since we are just interested in one container within the array, the domain has been reduced to three rows of three containers with an optimum domain size (Fig.1).

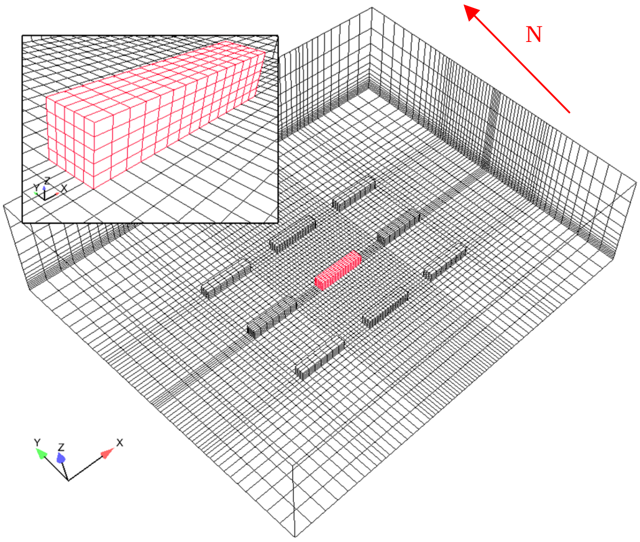


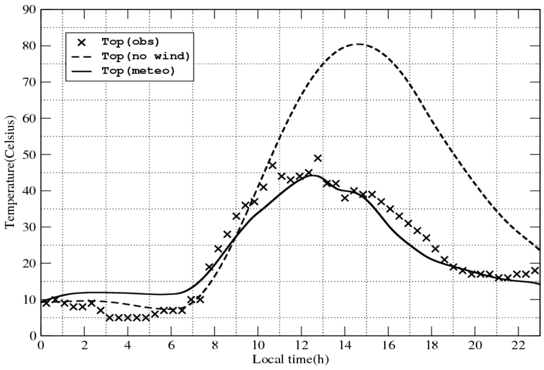
Figure 1. Domain structure and the sub-domain in red, 0.8 x0.5 x0.5m resolution.

1. Sensitivity tests

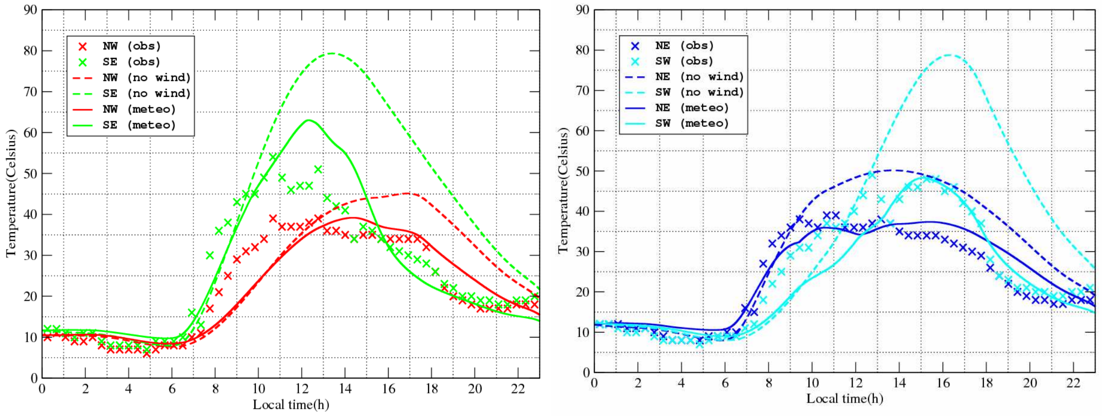
First, we consider how the model parameters influence the predicted surface temperature. This will allow us to determine which of these parameters are important in our simulations. We have tested the evolution of surface temperature with grids with different resolutions. Finally, the number of cells is about 55,000 for all cases. The Discrete Ordinate Method (DOM) has two kinds of angular discretization. Choosing 32 or 128 directions influence on the prediction of the diffuse solar flux and the infrared flux. In this investigation, the accuracy of the results obtained by 32 directions is very close to 128 directions, but 5 times faster during the calculation. So we suggest 32 directions in the remaining simulations.

2. Whole day case

Then, we simulate the day of September 25th 2001 from the MUST experiment. The boundary conditions are an essential feature of any CFD simulation. In order to be consistent with the experiment, the wind inlet boundary conditions are determined from the measurements. We use a meteorological file which gives every 2 hours the wind velocity, turbulence kinetic energy, dissipation rate and temperature profiles. The time step for the dynamics is 0.01s. A different time step was introduced for the radiative scheme. After a sensitivity test, we found that 5 minutes is an optimum time-step to run the whole day case. The variation of the deep soil temperature is neglected. The internal building temperature is updated by computing the average surface temperature from the previous radiative time step. In addition, the values of albedo, emissivity and thermal admittance are not available; we took their values form literature. Figure 2 shows the evolution of modelled and measured surfaces temperatures, with two modeling approaches: radiative model only and coupling radiative–dynamics model. The diurnal evolutions of the temperatures at top face, S-N face, and N-E face are correctly reproduced by our coupling model. At N-W face and S-W face, there is a delay in warming. This may be due to the conduction that is not taken into account in the simulations. However, the simulation results show a large different amplitude between the coupling model and the only radiation model, showing the importance of accurately modeling the dynamics in microscale modeling.



(a) Top face



(b) NW and SE face

(c) NE and SW face

Figure 2. Different surface temperature evolutions during a whole day (obs: measurements; no wind: simulation with only radiation; meteo: simulation with the dynamic-radiative coupling).

DISCUSSION: COMPARISON OF THREE SCHEMES FOR PREDICTING SURFACE SENSIBLE HEAT FLUX

In this section, we will compare three schemes used for predicting surface sensible heat flux. The simulated case is based on the previous simulated case: it took place from 12h to 12h30 the same day. A wind -45° is generated at upstream. The air temperature is 18°C, $U_{ref} = 4$ ms^{-1} is the reference wind speed. The sensible heat flux Q_H is classically estimated as:

$$Q_H = h_f (T_a - T_w) \tag{5}$$

Where h_f is the heat transfer coefficient, T_a is the air temperature at a given height above the canopy, T_w is the surface temperature.

1. Constant h_f model

This scheme is usually used in architecture simulation tools(Miguet and Groleau, 2002). This scheme considers a constant h_f for each of the 3 surface types: roof, wall and street. In addition, in order to take into account the surface orientation, we took in our simulations a constant h_f for each wall.

2. 1D h_f model

It is a simple model originally derived for mean wind speed profiles in vegetative canopy and modified for application to urban-type canopy. We adopted the simple exponential profiles to model vertical velocity (Macdonald, 2000) as following equation:

$$u(z) = u_H \exp(a(z / H - 1)) \tag{6}$$

Where u_H is the mean velocity at the top of the obstacles, and the constant *a* is the attenuation coefficient. And the h_f is calculated by this expression (Krayenhoff and Voogt, 2007):

$$h_f = 11.8 + 4.2u(z) - 4.0 \tag{7}$$

3. 3D h_f model

The CFD models solves the Navier-Stokes equations in the entire fluid domain. In our simulation we use a rough wall boundary condition:

$$u(z) = \frac{u_*}{k} \ln(\frac{z}{z_0}) \tag{8}$$

Where u_* is the friction velocity, determined at each iteration, k is von Karman constant, z the distance to the wall and z_0 is the roughness length.

Figure 3 summarizes the three convective schemes by visualizing the surface temperatures. For this study case, the three convective schemes gave a difference of the sensible flux around 150~180 Wm^{-2} to the S-E face and N-E face. The average surface temperatures calculated by three convective schemes are similar. With the constant h_f model, the surface temperatures which are not uniform, seem more homogeneous than in the other two cases. In the MUST configuration, the building array is not dense, so the effect of the shadow and the multi reflection are small. That is the reason why the temperatures in the constant h_f approach show little differences on each wall. With the 1D h_f model, we can obviously see the 1D inhomogeneity of the surface temperatures which is linked to the exponential law. The 3D h_f model results show the 3D inhomogeneity of the surface temperatures, linked to the inhomogeneity of the 3D wind. On the same face, we can have a difference of the temperature about 3*K*. This results demonstrate the effect of the computation of the convection fluxes on the surface temperatures in urban areas. It is to be noticed that in the comparison of the three convective schemes, we changed only the transfer coefficient and not the air temperature (which is computed for each grid cell of the fluid domain).

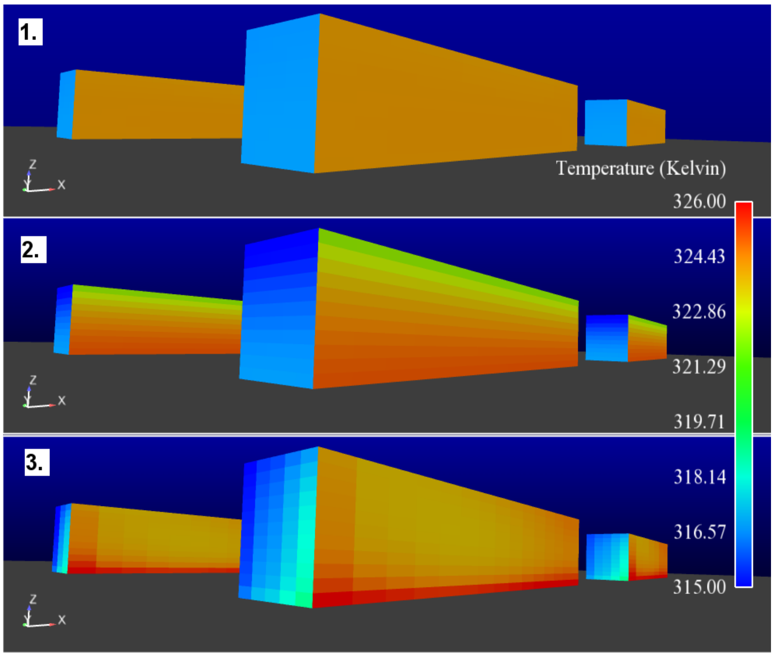


Figure 3. Comparison of three convective models with visualization SE and NE wall at 12h30: (1. Constant h_f model; 2.1D h_f model; 3. 3D h_f model).

CONCLUSIONS AND PERSPECTIVE

Sensitivity studies were performed on the mesh resolution, parameters and initialization for both dynamics and radiative models. The model is able to reproduce the evolution of the surface temperatures for different faces of a container during a whole day. There is a good agreement between the experimental data and the computations for the MUST case. The coupling between the radiative model and the dynamics model was studied in detail. Sensitivity studies show the high dependence on initialization and parameters describing the building, especially the interior building temperature. The 3D calculation of the sensible heat fluxes allows predicting more accurately the non uniform surface temperatures. The perspective of this work is to improve the thermal model. The coupled dynamic-radiative model will then be used on a real urban area with the CAPITOUL experiment (City of Toulouse, France).

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