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Session III. Mathematical modeling of technological processes

Numerical Simulation of Turbulent Pollution Transport in Thermally Stratified Atmosphere

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Abstract. This paper presents numerical simulations of pollutant transport in urban area including effects of developed turbulence, buoyancy and stratification. To incorporate the effect of stratification in the incompressible flow solver Boussinesq approximation to the density variation was used. To properly model vertical turbulent heat and concentration fluxes Algrebraic Flux Model was used. The results presented in this paper have demonstrated that the inversion layer creates strong capping region, disallowing polluted air to mix with fresh air in the upper layer of the atmosphere.

Keywords: Atmospheric Boundary Layer, turbulence, pollution transport

1 Introduction

As a result of human activity most of the urban areas contains various heat and pollution sources like a power plants, transport, agriculture etc. Asphalt and other buildings may store and reflect sun radiation leading to high surface heating. This processes causes urban territories to become heat and pollution sources in the environment. City topography with hight buildings and complex street net creates complex configuration that affects air flow and pollution dispersion.

At the moment simulation of the pollution transport at large scales is based on semi empirical and simple integral methods which takes into account wind intensity and direction [1,2]. However such approaches cannot be applied to simulate micro and mesoscale processes in the atmosphere.

In recent year, a growing interest has been found in applying Computational Fluid Dynamics (CFD) techniques to simulate complex environmental flows, like air flow in urban areas, over complex topography [3]. Numerical simulation of the atmospheric flows hardened by the fact that this kind of flows contains different spatial scales, ranging from the small scale typically used in engineering to the large scale used in meteorology.

2 Physical problem and model description

In the work we considered 24 hour temperature change of the atmosphere of the Almaty city. The city atmosphere is a complex configuration where air flow was influenced by city topography and high repeating factor of the windless situation. Presence of the strong temperature inversions [2] also influences city atmosphere.

Simulation of the air flow includes the following equations: continuity, mean momentum conservation (Reynolds equations), energy conservation and passive scalar transport.

$$\frac{\partial \langle U_i \rangle}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \langle U_i \rangle}{\partial t} + \langle U_j \rangle \frac{\partial \langle U_i \rangle}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \langle U_i \rangle}{\partial x_j} - \tau_{ij}\right) - \frac{1}{\rho}\frac{\partial\left(\langle P \rangle - \langle P_{ref} \rangle\right)}{\partial x_i} + \beta g_i \left(\langle T \rangle - \langle T_{ref} \rangle\right) \tag{2}$$

$$\frac{\partial \langle T \rangle}{\partial t} + \langle U_j \rangle \frac{\partial \langle T \rangle}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu}{Pr}\frac{\partial \langle T \rangle}{\partial x_j} - \tau_{\theta j}\right) \tag{3}$$

$$\frac{\partial \langle C \rangle}{\partial t} + \langle U_j \rangle \frac{\partial \langle C \rangle}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu}{Sc}\frac{\partial \langle C \rangle}{\partial x_j} - \tau_{cj}\right) \tag{4}$$

Reynolds stresses were modeled using standard Eddy Viscosity Model (EVM) framework adopting additional equations for the kinetic energy of the turbulence and its dissipation.

Simplified approaches exists to model temperature and concentration fluxes, where, for example, temperature flux is modelled using Simple Gradient Diffusion Hypothesis (SGDH) or itB's further improvement - Generalized Gradient Diffusion Hypothesis (GGDH). But as it has been shown by [4,5] that both SGDH and GGDH lacks of proper modeling of the vertical heat flux in buoyancy affected flows when gravitation vector is parallel to main heat flux direction. That is why turbulent temperature and concentration fluxes were modeled using Algebraic Flux Model (AFM).

$$\tau_{ij} = -\nu_t\left(\frac{\partial \langle U_i \rangle}{\partial x_j} + \frac{\partial \langle U_j \rangle}{\partial x_i}\right) + \frac{2}{3}\langle k \rangle \delta_{ij} \tag{5}$$

$$\tau_{\theta i} = -C_\phi \frac{\langle k \rangle}{\langle \varepsilon \rangle}\left(\tau_{ij}\frac{\partial \langle T \rangle}{\partial x_j} + \xi \tau_{\theta j}\frac{\partial \langle U_i \rangle}{\partial x_j} + \eta \beta g_i \left\langle \theta^2 \right\rangle\right) \tag{6}$$

$$\tau_{ci} = -C_\phi \frac{\langle k \rangle}{\langle \varepsilon \rangle}\left(\tau_{ij}\frac{\partial \langle C \rangle}{\partial x_j} + \xi \tau_{cj}\frac{\partial \langle U_i \rangle}{\partial x_j}\right) \tag{7}$$

Periodic boundary conditions for all variables were used in both of the horizontal directions, while the symmetry boundary condition was used for all variables in the upper top of the domain except for temperature for which the prescribed value of 22 C was used. Because of the high Ralaygh number describing the problem it is impossible to properly resolve near wall viscous sublayer. That restriction lead us to use the so called wall function approach on the bottom of the domain. Numerical solution of the equations (1)-(4) were based on a Finite Volume Method (FVM) [6]. Convective terms were discretized by 2nd order upwind and SMART schemes, diffusive terms were discretized by 2nd order central scheme, unsteady terms were discretized by 2nd order three time level approach. Velocity-pressure coupling was taken into account with iterative SIMPLE algorithm. Rhie-Chow interpolation technique [7] was used to get oscillation free pressure and velocity fields on a collocated grid. SIP solver [8] was used to solve all fields except for a pressure, for which Incomplete Cholesky Conjugate Gradient method was applied.

3 Results

Simplified scenario of the ground heating and pollution dispersion was used to simulate diurnal change of the air temperature and pollution transport. Satellite images of the city were used to mark main city ground areas that can be a main source of the heat and pollution. Diurnal heat source intensity were modeled as a sin dependence from the time changing in the interval 18-22 C (Fig. 1). Other city ground heating were modeled as a sin dependence from the time in the interval 19-21 C. Pollution was treated as a passive scalar, for which we used non dimensional value of 1 at the pollution source. Initial temperature was set to create temperature inversion on a height of 1 km (Fig. 2). The study case corresponds to a horizontal domain of 54x36 km and 4 km height. The results shown correspond to a mesh of 100x80x70 grid points with small mesh refinement up to the wall. City topography was created using available SRTM digital elevation data with a space resolution 90 m.

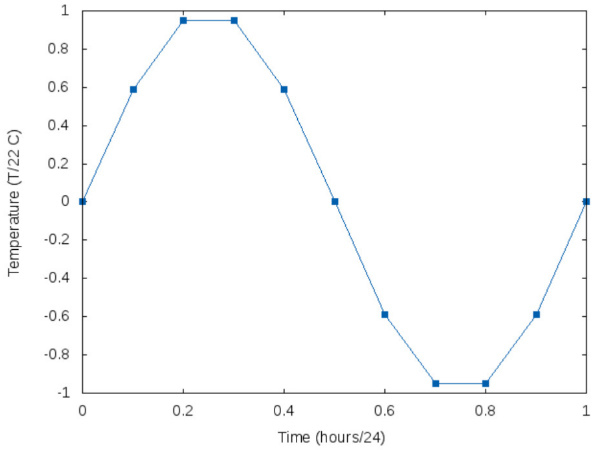

Fig. 1. Diurnal ground temperature change.

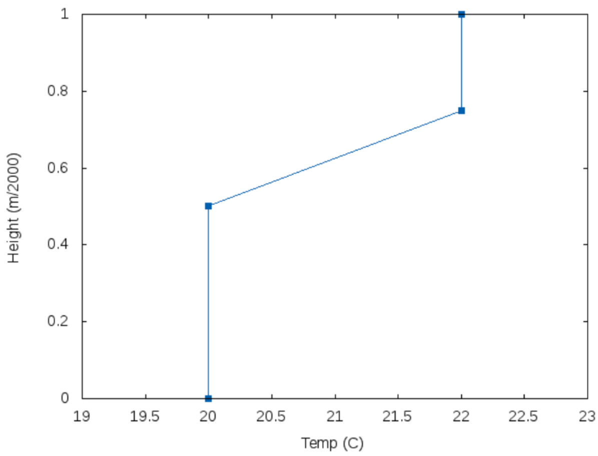

Fig. 2. Initial temperature profile.

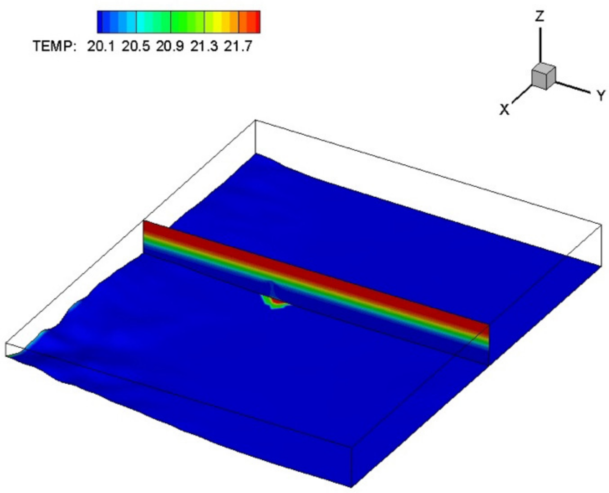

Fig. 3. Temperature distribution at 14:00.

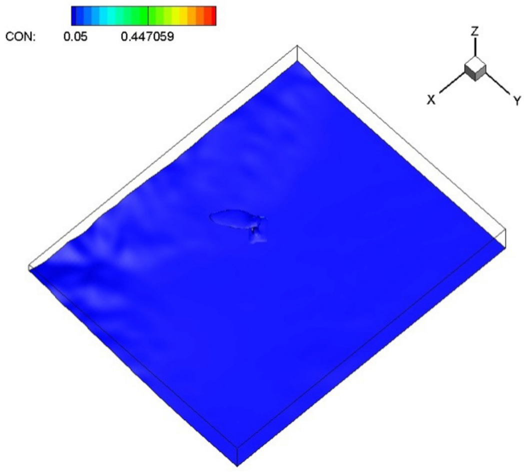

Fig. 4. Concentration distribution at 14:00.

Figures 2-3 shows presence of temperature inversion that blocks vertical air flow, disallowing polluted air to enter into the upper layers of the atmosphere, where it can be mixed with a fresh air or moved by upper layer wind. Blocked by capping region polluted air stays in the lower layer of the city atmosphere. This leads to accumulation of the polluted air on a top of the city.

4 Conclusions

Numerical simulation of turbulent pollution transport in thermally stratified atmosphere of the city was performed with algebraic turbulent flux model for the heat flux and the concentration. Density variation was treated by Boussinesq approach allowing to properly model buoyant flow under small temperature gradients. Finite volume method with realistic digital elevation data from SRTM project allowed to use non orthogonal mesh. Diurnal windless scenario used to investigate the influence of strong temperature inversion. Inverse layers creates strong capping regions making the polluted air to stay in the lower atmosphere of the city, causing accumulation of pollutants in the air.

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