A computational fluid dynamic approach to validate the wind effect in air pollution of Ulaanbaatar city

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Abstract. In the past two decades, inhabitants of Ulaanbaatar city have been increased more than three times. The Air and soil of Ulaanbaatar city contaminated seriously due to the densely populated behavior. We proposed to develop a massive computational model for pollution, which cares about contamination factors. This paper is a part of the purpose. We consider the filtered equation express conservation of mass and momentum in a Newtonian incompressible flow in a computational fluid dynamic model for Ulaanbaatar's wind field. The terrain around the city has been built for numerical computation. The finite element method was used for numerical analysis, from the results, we can characterize the wind field.

1. Introduction
Nowadays, the rapid climate change in the world is a global environmental problem. Thus, every country has been faced with many difficult situations in ecology and economy. With this global reason, most cities have severely deficient air condition problems, especially in developing countries. Mongolia's capital Ulaanbaatar (UB), is one of the world's most polluted towns. Its" harmful dust" is 6–7 times higher than the most lenient World Health Organization standards, [1]. Several factors can be added to the source of UB's air pollution as dust from both insides, outside, partially covered soil surface, less horticulture, smoke from a coal stove, and so on.

Nevertheless, one of the main factors of air pollution is the geographical location of UB. The UB city is built between big mountain [2], which is the town's unique behavior. Figure 1 shows a real wind field layers and air pollution during wintertime, b denoted surrounding big mountains of the city. It has been a long time to use the wind field's computational fluid dynamics (CFD) for pollution dispersion. Thus, massive studies have been carried on the distribution of air pollution with complex models, including buildings of city and terrain of it [3–8]. Early work was mostly focused on theoretical and numerical aspects in the numerical study: the finite difference method (FDM) was used commonly for less computational time. More precisely, the second-order central difference scheme in space is used to demonstrate the wind flow in the model, which is the obstacles approximated into rectangular shapes [9, 10] and [11]. However, FDM is mostly used for comfortable computing time in computational fluid dynamics (CFD). The method is fragile in modeling specific and complex geometry such as mountains or modern designed buildings.
Figure 1. Air pollution and atlas of Ulaanbaatar: a) the air pollution of UB in the winter time; b) elevation map of UB, mountains in the area of 1, 2, 3, 4 and 5 named as Songino Khairhan, Chingeltei, Sukhbaatar, Bayanzurkh, and Bogd Uul. The top of them around 1670m, 1890m, 1981m, 1934m and 2268m, respectively.

Therefore, at some time with FDM, the finite element method (FEM) was developed and mainly used in CFD [12], [13] and [14]. Although FEM requires a particular time for convergence, to avoid the disadvantage, the parallel computation has been developed for large predict flow field and pollutant dispersion over tricky obstacles. This paper is part of massive US air pollution; we will investigate pollution dispersion from the soil and temperature inversion. To do that, we develop a computational fluid dynamic model in the large eddy domain, which can be coupled with the equation of temperature and with particle tracking motion that considered pm type mass. The first approach is considered in this paper as the numerical computation of the wind field in three-dimensional space, based on a finite element model used with an adaptively distributed unstructured mesh for simulation with boundary data as a condition of boundary that simulated to real averaged wind information. It has been noticed intensively in many official reports and papers that the primary source of UB's air pollution is smoke from suburbs, which does not connect to the water pipe system and uses coal for heat. In Figure 3b we denote the suburb areas as the red and blue area is the UB city's full area. But real measurement proves that air pollution includes many PM type particles from the soil, and frequent inversion of temperatures must be considered.

2. Model problem
We assume that the observing large domain $\Omega$ (Figure 2) is completely occupied with three-dimensional space $\mathbb{R}^3$ and let the wind velocity potential $u$ has $u, v, w$ components on Cartesian coordinates. Then following unsteady governing equation holds for large eddies that interpolate the velocity components of $u$ along the direction of the flow in low pass.

Figure 2. The domain for computation in Comsol Multiphysics, it is a three-dimensional subspace of $\mathbb{R}^3$. 
The filtered equation express conservation of mass and momentum in a Newtonian incompressible flow written as in conservative form combined with $k-\omega$ and $k-\varepsilon$ turbulence models as

\[
\begin{align*}
\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u &= \nabla \cdot \left[ -p + \mu (\nabla u + \nabla u^T) \right] + F \\
\rho \nabla \cdot u &= 0 \\
\rho \frac{\partial k}{\partial t} + \rho (u \cdot \nabla) k &= \nabla \cdot [\mu + \mu_T \sigma_k \nabla k] + F_k \\
\rho \frac{\partial \omega}{\partial t} + \rho (u \cdot \nabla) \omega &= \nabla \cdot [\mu + \mu_T \sigma_\omega \nabla \omega] + F_\omega
\end{align*}
\]

where $\rho$ is the density of dry air; $p$ is filtered pressure; $\mu$ is the viscosity; $(\nabla u + \nabla u^T)$ is scaled strain rate tensor; the variables are defined as $F_k = P - \beta^* \rho \omega k$, $F_\omega = \frac{Z}{v_T} P - \beta \rho \omega^2 + 2(1 - F_1) \frac{\rho \sigma_\omega}{\omega} \nabla k \cdot \nabla \omega$. The turbulence model parameters are can be founded in [15].

The computational domain is interpolated with exact behavior real landscape shown Figure 3 and scaled as $10^4 m \times 10^4 m \times 10^4 m$. The geometry is approximated from the information of topography that created from the official source. We consider following boundary conditions to the governing equations. Since the domain is computationally large the top and two besides are set to be non-slipping wall:

\[
\begin{align*}
\mathbf{u} &= 0, k = 0 \text{ and } \omega = \lim_{t_\omega \to 0} \frac{6u}{t_\omega \beta^* l_\omega} \\
\mathbf{u} &= -U_0 \mathbf{n}, U_0 = U_{ref}, k = \frac{2}{3} \left( \frac{u_0}{T} \right)^2 \\
\omega &= \frac{k}{(\beta^*)^{1/4} L_T}
\end{align*}
\]

In all four seasons, the average UB’s wind speed is $6 m/s$ and mostly directed from northwest to southeast. So the inlet wind flow boundary condition defined as

\[
\begin{align*}
\mathbf{u} &= -U_0 \mathbf{n}, U_0 = U_{ref}, k = \frac{2}{3} \left( \frac{u_0}{T} \right)^2 \\
\omega &= \frac{k}{(\beta^*)^{1/4} L_T}
\end{align*}
\]

In outlet wind flow the pressure should be free with free divergence for turbulence,

\[
\begin{align*}
[ -p + (\mu + \mu_T) (\nabla u + \nabla u^T) ] \mathbf{n} &= -p_0 \mathbf{n} \\
\nabla k \cdot \mathbf{n} &= 0, \nabla \omega \cdot \mathbf{n} = 0
\end{align*}
\]

where $U_{ref}$ and $p_0$ are the reference wind flow and pressure, for other turbulence parameters we refer to see [15].
3. Experiment and results
In the experimental domain, we set all surrounding five mountains described in Figure 4, the square area (Figure 3a). We normally distributed free mesh (tetrahedrons), 205808 number of elements and 19414 node points for computation—the wind inflow and laminar conditions are considered Dirichlet and Neumann boundaries. Figure 5a) is the three-dimensional solution of the governing equations defined in (1). The convergence rate is acceptable but not direct as FDM; from the answer, we can visualize many different analysis kinds. For instance, in Figure 5b), we show the isosurface images that illustrate the wind field dispersion. Figure 6 shows a cross-sectional view of the solution in streamlines and contour plots that gives information about turbulence and wind field layers.

Figure 4. The discretization of the domain into finite tetrahedrons.

Figure 5. Computational results: a) the wind flow in slice images b) the isosurface graphics in six different levels.

Figure 6. The cross-sectional view of the domain is described in a), contour and streamline representation shown in b).
4. Conclusion
The sizeable computational fluid dynamic model-based numerical setting has been considered. The purpose of the research is completed, and some more management is needing in future work. The computed distribution is used to couple with the thermal flow. From the coupled system PM sized particle motion can be calculated. Some more additional conditions need to consider the smoke distributions of suburban areas. Also, the large eddy simulation would be simple to analyze based on these results.

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