Numerical analysis of flow structure behind a bluff body under conditions of unstable thermal stratification

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Abstract. In the paper, the authors describe some results of a numerical simulation of the air flow around a bluff body mounted on a flat plate taking into account the injection of a tracer gas through a hole located in the substrate behind the body. The aim of this paper is to describe flow structure in the vicinity of a prism taking into account unstable stratification of the boundary layer which is characterized by a negative vertical temperature gradient. The results of numerical simulation for an unstable thermal state were compared with those obtained for the case of stable stratification for the same geometry configuration.

1. Introduction
Air quality is one of the most important criteria for urban ecology. High concentration of gas pollutants and aerosols injected from various anthropogenic sources into the air reduces quality of life in large agglomerations and may cause various diseases among its population. Air in large cities is often characterized by a high concentration of CO, NOx, SO2, heavy metals and their oxides, aldehydes, hydrocarbons, ammonia, atmospheric dust, etc. According to [1, 2], the main sources of gas and aerosols emission in large cities are industry and transportation system. Emissions of gases and aerosols from thermal power plants and enterprises are strictly controlled and regulated by standards at the design stage of equipment and during its operation. However, monitoring emission transfer from vehicles in an urban environment is more difficult due to a number of factors such as small spatial and temporal scales of the process and a high level of difficulty in identifying pollution sources. In addition, transport and transformation of gas pollutants and particles from high and low pollution sources depend on the characteristics of the atmospheric boundary layer significantly, as well as on interaction of the atmospheric turbulent flow with local flows, the structure of which is formed during the flow around buildings and structures.

Evaluation of concentrations for air pollutants is based nowadays on atmospheric monitoring at stationary observation posts. For example, in [3], data on microclimatic parameters of air and concentrations of dust particles PM2.5 and PM10 are delivered in real time taking into account daily dynamics. However, a small number of monitoring posts does not allow describing and evaluating the sources of formation of pollutants and its distribution and their transformation in time and space. Studies [4, 5] showed that restoring data on pollution sources based on a small number of observation
posts is quite problematic. Existing pollution prediction systems (e.g., WRF-CHEM [6]) as a rule operate large spatial scales and do not allow one to consider the local transformation and transfer emission effects in an urban landscape, the scale of which is determined by hundreds of meters. Thus, predicting the transfer of pollutants from low sources in the urban environment remains a difficult task requiring solution by means of computational fluid dynamics.

In the paper, the authors describe some results of a numerical simulation of an air flow around a bluff body mounted on a flat plate, considering an injection of a tracer gas through a hole located behind the body in the substrate. This statement of the problem was proposed in the experimental work [7] and is a good test for studying processes of heat and mass transfer behind a bluff-body. The aim of this paper is to describe a flow structure in the vicinity of a prism taking into account unstable stratification of the boundary layer which is characterized by a negative vertical temperature gradient. The results of the numerical simulation for the unstable thermal state were compared with the results obtained for the case of stable stratification for the same geometry configuration. The work continues the study described in [8].

2. Problem statement and numerical methods

Figure 1 shows schematically the problem statement corresponding to [7]. A bluff-body is a prism of a square cross-section with a characteristic transverse dimension \( b = 0.08 \) m and a height \( H = 2b \). The gas tracer (ethylene) enters the zone behind the body through a hole with a diameter of \( 5 \times 10^{-3} \) m located at the distance \( b/2 \). A mass flow rate of tracer gas is \( 1.12 \times 10^{-5} \) kg/s. The stratification of the boundary layer is specified through the set of boundary conditions described in [7]. The velocity, turbulent kinetic energy (TKE) and temperature profiles are set at the inlet boundary of the computational domain and surface temperature boundary conditions, which vary depending on the case (stable or unstable state), are set on the walls of the prism and substrate. The problem was considered in three-dimensional formulation.

![Figure 1](image)

(a) Scheme of the problem statement: \( YX \) view (a) and sectional \( ZX \) view, \( y=0 \) m (b).

The simulation was carried out in ANSYS Fluent [9] using the unsteady 3D Navier-Stokes equations for a multispecies flow supplemented by the energy equation. The ideal gas equation of state was chosen for the gas mixture. To predict turbulent effects in the flow, the DES model based on the realizable \( k-\varepsilon \) model was used. In the DES approach, the unsteady RANS \( k-\varepsilon \) model was employed in the near-wall region, while the LES-like subgrid model was applied to the separated regions. To generate time-dependent inlet conditions for scale resolving turbulence simulations, a Fourier based synthetic turbulence generator was used. The “no-slip” boundary conditions were used for the walls of the prism and the flat plate. At the external boundaries of the computational domain, the conditions of constant static pressure were used.

The control-volume-based method was used to convert general scalar transport equations to algebraic equations. The general grid included about 15 million cells. To resolve the flow vortex
structure in the LES sub-grid model manner, the fine grid was used in a region behind the prism. Approximately 5 cells were built across the integral length scale \( l_0 = \frac{k^{1/3}}{\epsilon} \) to resolve 80% of the turbulent kinetic energy. The \( y^+ \) values at walls did not exceed 1. The NITA/fractional-step method with the second-order of approximation was used for the time-discretization. The bounded central-differenced scheme was used for the momentum equations and the second-order upwind schemes were used for scalars.

3. Results of numerical simulation for unstable thermal flow stratification

The instantaneous and time-averaged fields of temperature, velocity, mass concentration of the tracer gas and turbulent parameters were obtained as the results of calculation for the case of the unstable thermal stratification. Figure 2 (a) shows the time-averaged static temperature field in the central section (ZX plane, \( y = 0 \) m). The surface boundary layer is characterized by a negative vertical temperature gradient. The temperatures on the walls of the prism and on the substrate are significantly higher than the gas temperature at the prism height \( H \) and in the free stream flow and the temperature difference is about 34 °C. This state of stratification drives vertical movement in the atmosphere and it is a condition for the development of convection.

![Figure 2](image)

**Figure 2.** The mean static temperature \(<T> \) [°C] field (a) and instantaneous velocity \( U \) [m/s] (b) at the central ZX section \((y = 0 \) m) for the unstable thermal state.

To evaluate the characteristics of turbulent gas mixing in the recirculation zones around the prism, the TKE profiles in the characteristic cross-sections in the vicinity of the prism were plotted and compared with those obtained for the case of stable stratification (Fig. 3, (a)). The characteristic sections XI-4 are located at the central ZX plane (see Fig. 1 (b)). As Fig. 3 (a) shows, for the case of unstable stratification, the TKE level is significantly higher comparing to that for the stable stratification state. The unstable thermal state of the boundary layer leads to more intense turbulent mass transfer.
The uniformity of air-ethylene mixing can be evaluated by the uniformity index $\gamma_a$ based on the area-weighted average mass concentrations of ethylene. The uniformity index $\gamma_a$ [9] represents how a mass concentration of ethylene varies over the cross-section surfaces, where a value of 1 corresponds to the highest uniformity. Fig. 3 (b) shows the uniformity index values $\gamma_a$ at the characteristic cross-sections $z/b$ behind the prism for stable (red line) and unstable (blue line) stratification regimes.

It can be seen from Fig. 3 (b), the fields of the mass concentration of ethylene are more uniform for the case of the unstable state. A more uniform mixing of gases in the recirculation zone behind the prism in the case of unstable stratification is caused by the intensive convection transfer in the vertical direction.

![Figure 3](image.png)

Figure 3. The TKE profiles (a) for the characteristic sections $X1=-b$; $X2=2b$; $X3=4b$; $X4=6b$ for the cases of the stable (1) and the unstable (2) thermal states; Uniformity index $\gamma_a$ at the characteristic cross-sections $z/b$ behind the prism for stable (red line) and unstable (blue line) stratification regimes.

4. Conclusion

The features of the unstable thermal state of the boundary layer in the vicinity of a bluff-body were reproduced. Based on the calculation results, the fields of the main gas flow parameters in characteristic sections were obtained, the flow structure and the nature of the pollutant transfer behind the body were described. It is shown that the regime of unstable stratification is accompanied by more intense turbulent mixing of gases and contributes to faster dispersion of gas emission from a low source in the zone behind the body compared to the case when the surface boundary layer is stable.

Acknowledgments

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