Calculation of wind flows in residential areas and assessment of their impact on pedestrian comfort

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Abstract. This article presents the results of numerical modeling of wind flows around a microdistrict. The distribution of suspended solids of 50 and 100 microns in urban environments is considered. The characteristic of urban development in terms of a comfortable stay of people is given.

1. Introduction

The city of Krasnoyarsk is included in the rating of million-cities of Russia and occupies the 12th place in terms of the population [1]. On average, in Russia, almost 75% of the population lives in cities. Since the all-Russian census of 2010, Krasnoyarsk has seen a population growth of 16% (Fig. 1) [2]. The main trend in urban development is the over-urbanization or “flocking” of residents of small and medium-sized cities to larger ones that occurs because large cities have a higher standard of living.

![Figure 1. The population of Krasnoyarsk city over a 10-year period.](image)
The growth of the urban population leads to an increase in the rate of construction of residential areas, usually consisting of dense housing development and high-rise buildings located along relatively narrow streets. The typical configuration of areas leads to the formation of adverse environmental conditions caused by a decrease in the aeration regime of the territory. Numerous stagnation zones are formed with an increased concentration of pollutants. High-rise construction reduces the level of pedestrian comfort due to the formation of zones with increased wind speeds. This causes a rise in dust and harmful impurities on the upper floors of buildings. In winter, this leads to an undesirable snow transfer and a snowdrift of low buildings, recreation areas, and roads. These factors were poorly studied, or were not taken into account at all in urban planning, or were simulated during the implementation of particular technological solutions.

The problems that have arisen in contemporary society require a detailed study of the emergence mechanism of the certain negative conditions in the urban environment, for further corrective actions to minimize and eliminate adverse effects.

Assessing the impact of wind on people’s comfort includes a comprehensive methodology that takes into account the combination of statistical meteorological data with aerodynamic information.

The traditional methods for estimating turbulent flows streamlining built-up areas are field experiments and wind tunnel tests. These approaches require large labor costs and are not economically feasible. There are difficulties in obtaining data for the entire velocity field, since, as a rule, measurements are conducted just at several points.

Due to advances in high-performance computing and spread of software for numerical analysis of fluid dynamics (CFD, computational fluid dynamics methods), it has become possible to obtain detailed information about the flow-around buildings and structures. The CFD has several advantages as compared to physical experiments, namely, reduced analysis time, cost savings, obtaining information about the relevant parameters at all points of the computational domain, as well as the rapid search of various options for buildings’ shapes for conducting comparative analysis and optimization of wind conditions.

A distinctive feature of the contemporary approach of using CFD to simulate the transport of pollutants in the urban environment is that it is possible to take into account the three-dimensional flow-past pattern of buildings, which allows obtaining more realistic distributions of concentrations when simulating aerodynamic effects.

2. Statement of the numerical simulation problem

The present work studies the aerodynamic transport of impurity (suspended particles of 50 and 100 microns) from road dust, and the assessment of pedestrian comfort in real urban development of Krasnoyarsk.

A non-stationary micro-scale model based on the Reynolds-averaged Navier-Stokes equations and a differential two-parameter turbulence model have been developed.

The numerical implementation of the proposed micro-scale model is based on finite volume methods, implicit monotonized difference schemes of the second order of approximation in time and space. The SIMPLE-C procedure is used to coordinate the velocity and pressure fields.

The mathematical model is implemented in the SigmaFlow software package. SigmaFlow is a non-commercial universal software package, created and advanced by the Krasnoyarsk Branch of the Kutateladze Institute of Thermophysics SB RAS, and the Department of Thermophysics of the Siberian Federal University. The package is intended for research of a wide class of hydrodynamic and thermophysical processes and allows performing parallel calculations on modern multi-core processors and cluster systems [4–6].

A turbulent isothermal flow of air in the vicinity of buildings, representing a system of poorly streamlined (bluff) bodies was considered taking into account the inhomogeneities of the underlying surface. An unstructured hexagonal grid constructed using the octo-tree method with the SigmaMesh3D tool was used for the calculation [7]. A uniform flow with a velocity of 2.5 m/s at
normal atmospheric pressure was set as the initial condition; the SST k-ω turbulence model was used [8].

3. The results of numerical simulation

3.1. Analysis of wind environment

Building system affects the wind flow, deforms its direction and changes the wind flow velocity creating various effects, such as:

- "screening" effect, which reduces the ability of dispersion and removal of pollutants outside the urban built-up area that results in the emerging of stagnation zones (zones with an increased level of pollution of the surface layer of the atmosphere);
- the "Venturi" effect, whose emergence is caused by the impact of high-rise buildings which deflect the wind flow at high altitudes to the level of pedestrians, and lead to an increase in wind flow velocity.

As a rule, the average velocity and intensity of turbulent flows for determining pedestrians’ comfort are carried out at a height of 2 m in the area where people walk. A characteristic picture of wind flows for the considered problem is shown in Fig. 3. When analyzing the flow pattern, it can be seen that behind the buildings, numerous recycling zones are formed in the shadow zones. The wind flow velocity decreases to the critical values of 0-1 m/s. At such velocities, the process of dispersion and removal of pollutants in these zones is almost suspended, and harmful impurities lodge and accumulate (Figs. 3, 4).

In the area under consideration, there is a high-rise building. According to EN 1991-1-4:2005, the influencing zone of this building on the nearest structures is 65 m. Peak values of the wind velocity head were used for the calculation [9].

In the location of high-rise buildings, velocities increase to 12-13 m/s. This leads to emergence of the Venturi effect. The flow pattern shows that the air flow comes through a large area, while the buildings in the first row narrow the flow cross-section decreasing wind pressure. Because of the pressure difference between the front (with high pressure) and the sides (with low pressure) of the flow, lateral vortices are formed, which causes an increase in wind speed (Fig. 3).

According to the Dutch standard (NEN 8100), whose criteria are based on the uncomfortable wind speed threshold of 5 m/s, the concerned territory belongs to the D comfort class [10]. It is recommended to avoid placing restaurant terraces and public areas near these locations due to discomfort and even security concerns.
Visualization of wind flow around the urban microdistrict under consideration allows revealing the formation structure of the three-dimensional separated flows. When considering the flow area in the immediate vicinity of the first row of buildings, one can observe horseshoe-shaped vortices that arise due to the flow around the front walls of buildings and extend along the sidewalls of buildings in the wind flow direction. Near the horseshoe vortex, the flow is unstable. Recirculating zones are formed on the side faces of buildings. In the area behind the buildings, vortex structures are generated in the form of two opposite rotating vortices (Figs. 3-4).

3.2. Analysis of the impurity distribution

The study of impurity behavior in the built-up area is performed based on the analysis of particle propagation. Particles of different sizes are introduced at the location of the source (from the side of the road), and their trajectory is tracked within an hour of physical time.

The simulation results have shown that large-scale flow structures have a strong influence on the movement of particles. The lighter are the particles, the more intense is the process of vertical dispersion, and the particles are lifted out over the buildings. In the case of heavy particles, they are deposited in the shadow and recirculating zones, which leads to their accumulation and, ultimately, the emergence of unfavorable conditions for humans (Fig. 5).
Figure 5. Model of impurity behavior in a flow in a vertical section.

The maximum concentration of impurity is observed along the source of emission, and a local maximum is also observed in the area of secondary rotational movements of air masses downstream near the low-rise buildings.

Figure 6. Model of impurity behavior in a flow in a horizontal section at a height of 2 m.
Figures 3-6 show that sedimentation and accumulation of suspended substances occur in the locations of stagnation zones. Entrances to buildings, playgrounds, recreation benches, and other places where people stay are located in these zones. Thus, the created conditions do not provide the population with a proper level of comfort and security.

The proposed model allows considering in more detail the formation mechanisms of the comfort of pedestrians’ walking in the streets, and the conditions for the occurrence of adverse situations in the territory of urban built-up area.

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