Computational modeling of architectural and construction aerodynamics problems

V D Meshkova, S A Filimonov and A V Shebelev

Siberian Federal University, Krasnoyarsk, Svobodny av., 79, 660041, Russia

Redel-VD@yandex.ru

Abstract. The article presents topicality of computational modeling of architectural and construction aerodynamics problems. Mathematical model of air streams motion around structures was considered. Verification of mathematical model is carried out using example of flow around a rectangular prism. Calculation model is created and flow calculation is carried out on example of block of the Krasnoyarsk city.

1. Introduction

In the past decade in Krasnoyarsk, steady of urban population has been increase. In this regard, there are economic, social, environmental, urban and other problems, both for the city and for the residents themselves to be solved. And in the foreground, in this case, there is a rapid growth problem of urban areas. Rational use of urban space makes architects, designers and builders look for new formats in the field of solving this problem. As a rule, this leads to high-rise buildings development and complexes, as well as to an increase in the density of construction, which leads to a worsening of the ecological situation both inside the border of new building and the city as a whole.

Influence of natural and climatic conditions on urban development formation is not a new problem. The wind regime of the city's territory is one of the most important factors that must be taken into account in construction. History of urban development gives numerous examples of solving problems by different countries. At this point in time, the greatest interest is attempts to take into account wind conditions as bioclimatic formation of residential development. Specific nature of climatic conditions and, in particular, wind regime is to this day taken into account only for developing individual projects, mostly experimental ones. There is no differentiated approach to planning and building cities located in different wind conditions, and urban areas in a single city system.

One of the first, a group of scientists under the leadership of A. Mochida began to engage in numerical modeling with the tasks of building aerodynamics. In Japan, on the basis of the Architectural Institute of Japan [1]. Later in 2007, a group of European specialists led by J. Franke and B. Blocken in the framework of the SOST project also began to work on numerical modeling of these problems [2]. O. I. Podadaeva and I. V. Dunichken described in their work a technique for numerical modeling of wind effects on high-rise buildings [3].

On the territory of Russia, mandatory standards/criteria are not available, taking into account aeration regime and pedestrian comfort, there are only recommendations. The only valid normative document in the world for assessing wind comfort in urban development is the national standard of the Netherlands (NEN 8100) [4]. The criteria are based on an uncomfortable threshold of wind speed of 5 m/s.

The building affects the wind flow, changes its direction and speed. There is a decrease in dispersion process ability and pollutants removal beyond the limits of building, stagnation zones forming (with an increased contamination level of the atmosphere surface layer). Increase speed of wind flow leads to a decrease comfort level of a person finding in the city.

Traditional methods for estimating wind aerodynamics in vicinity of complex buildings' structures are experimental studies in wind tunnels. Alternative approach to this problem solving is a computer simulation of air streams, based on solution of gas dynamics equations. Present studies are a continuation of the previous researches of local atmospheric circulation formation in urban conditions [5]. In this paper, we simulate air flows in an urban environment. Places of formation of stagnation zones are considered, where particles can accumulate.

2. Mathematical approach

As a mathematical model for describing processes of air flow around buildings, an incompressible gas dynamics model is adopted that includes mass and momentum conservation law equations:

$$\nabla \cdot (pv) = 0 \tag{1}$$

$$p(v \cdot \nabla) = -\nabla p + \nabla(\hat{\tau}^{m} + \hat{\tau}^{t}) + F \tag{2}$$

where p is pressure, **v** is the velocity vector, F is the force vector, $\hat{\tau}^{m}$ is the viscous stress tensor и $\hat{\tau}^{t}$ is the Reynolds stress tensor:

$$\tau_{ij}^{m} = \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right), \tag{3}$$

$$\tau_{ij}^{t} = \mu_t\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}\, pk \tag{4}$$

where v_i are the velocity vector components, μ is the viscosity, μ_t is the turbulent viscosity, k is the turbulent kinetic energy. To close the equations, we use *k-ω* SST turbulence model [6]. Discretization of the conservation law equations in computational domain is performed by the control volume method [7].

The mathematical model implementation of turbulent air flow impurities propagation is performed in the SigmaFlow software package [7]. The SigmaFlow was created and is being developed in the Krasnoyarsk branch of the RAS Thermophysics Institute and the Thermophysics Department of SFU. It is designed to study a wide class of hydrodynamic and thermophysical processes, allows parallel computing on modern multi-core processors and cluster systems. For calculation, an unstructured hexagonal grid is constructed using the octo-tree method [8]. Sources of impurity distribution correspond to location of road.

3. Verification of mathematical model on the example of flow around a rectangular prism

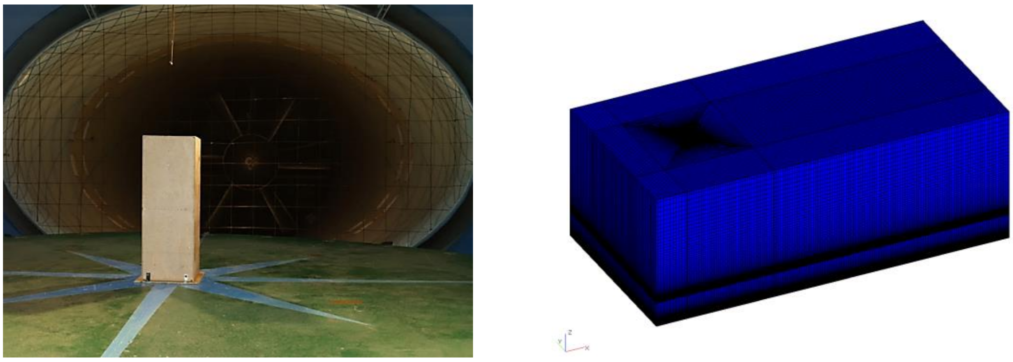
The above mathematical model was verified using a natural experiment. One of typical objects considered in industrial aerodynamics is a rectangular prism. Residential buildings and structures very often have a rectangular prism form with a varied ratio of faces horizontal dimensions. In literature there are reference data on wind loads of these form bodies [9], but there are no quantitative and qualitative criteria for air exchange and urban areas purging. The aim of the research is to establish relationship between the obtained flow patterns of airflow model system with pressure coefficient distribution pattern obtained during wind tunnel experiment, as well as structure evaluation of separated flows, nature and size of separation zones.

Comparison of the simulation data is carried out with the results of experimental unsteady three-dimensional flow around a rectangular prism (Figure 1,a) installed on a horizontal rotary table in A-6 wind tunnel working part of the Institute of Mechanics, Moscow State University [10]. The wind speed at the entrance section is 2.5 m/s. The direction of the wind is south-west.

Model parameters. A multi-block structured grid is constructed for calculations. The dimensionless distance y^+ of the first grid node is in range $1 < y^+ < 10$ for the lower wall, and it is $1 < y^+ < 30$ for the parallelepiped surface.

We use Quick scheme of the second order of approximation to solve the equations for turbulence, and Umist TVD scheme of the second order of approximation to solve the equations for velocity. Approximation by time is second order of accuracy.

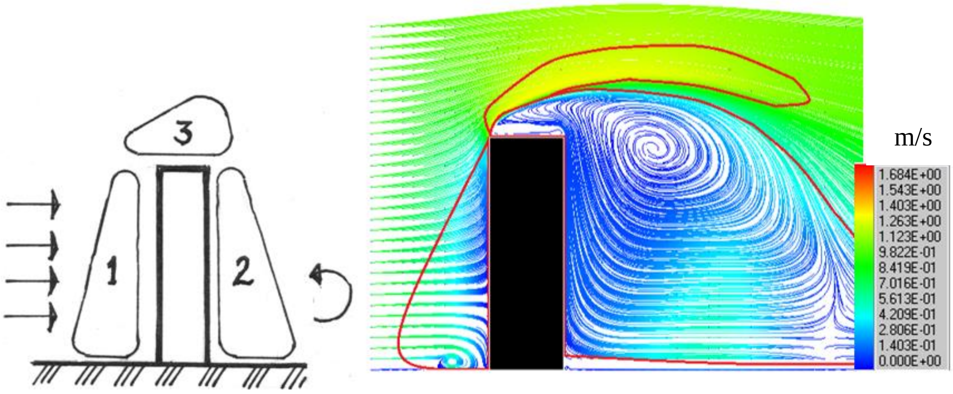
At the side faces, the symmetry conditions are applied. A minimum value of velocity was specified at the top boundary of computational domain to minimize effect of walls to solution. An impact velocity profile was specified at the inlet. At the outlet, the normal gradients of all variables and the value of the pressure were set to zero. Direction of flow is from left to the right (Figure 1b).



(a) (b)

Figure 1. Arrangement of the prism in the wind tunnel working part (a) and visual representation of the grid (b).

The qualitative picture of flow obtained as a result of the calculation is shown in Figure 2. It can be seen that calculation corresponds to wind loads scheme on building [10]. Approaching obstacle (building), air flow slows down, creating a positive pressure in air supply zone (1) on windward side and negative pressure (wind shadow (2)) from leeward side. At same time, the air flow is accelerated flowing from top and from sides, compensating for decrease in its section area caused by the building presence (3).



(a) (b)

Figure 2. Scheme of wind loads on the building (a) and calculated flow streamlines with the characteristic zones (b).

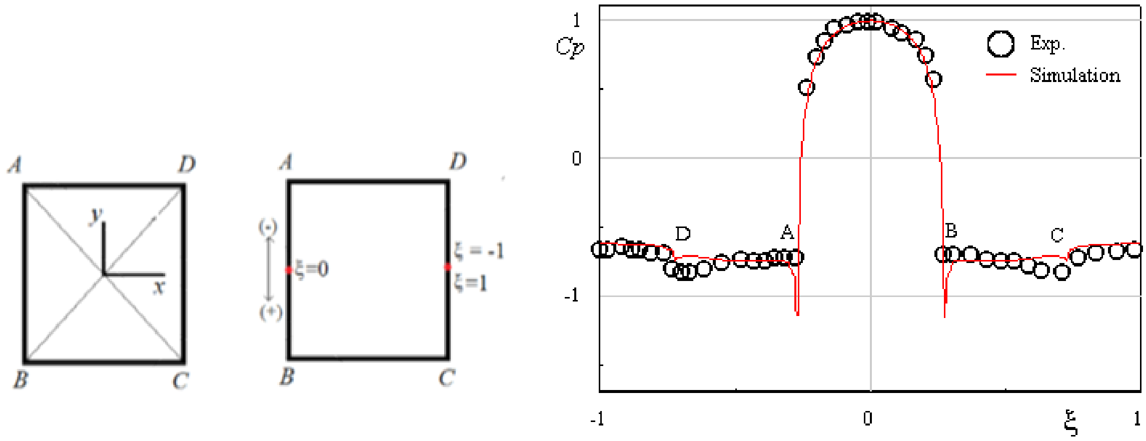
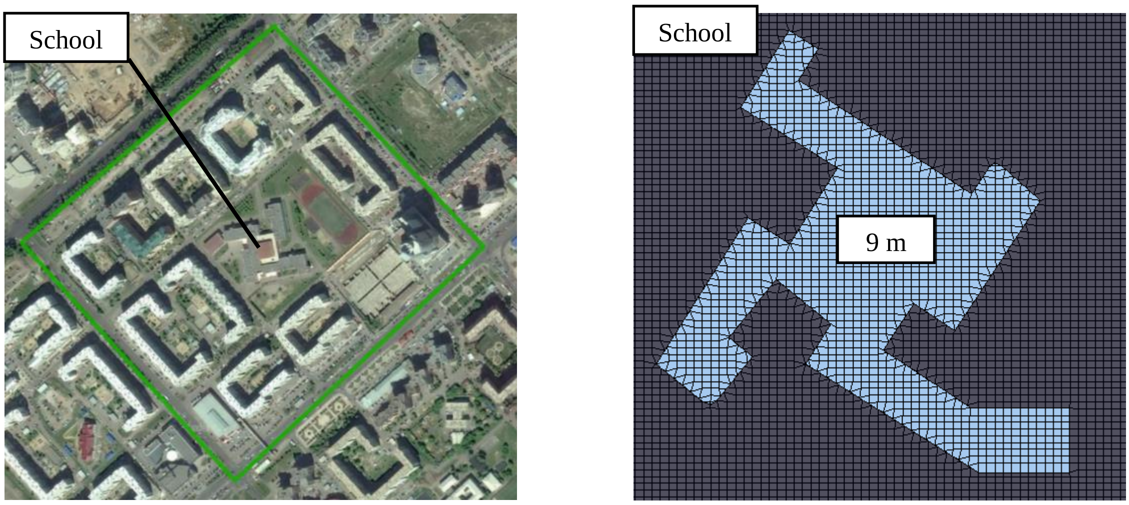


Figure 3. Experimental and calculated results on distribution of pressure coefficient around parallelepiped.

A quantitative comparison with experimental data on distribution of pressure coefficient around parallelepiped is shown in Figure 3. Graph demonstrates that results of simulations of the flow around a rectangular prism have a good agreement with the experimental data.

4. Numerical simulation of flow around the block of Krasnoyarsk

Since we rarely deal with stand-alone buildings outside the city, it is very important to know how complex of the buildings affects the wind flow. At the next stage, calculations are performed in a computational domain which is parallelepiped of 570 m width, of 700 m length and of 200 m height. The area under the study includes buildings of various configuration and number of storeys. An unstructured hexagonal grid is constructed for calculation using the octo-tree method [8].



(a) (b)

Figure 4. Location of the simulated urban development area in Krasnoyarsk (a) and grid (b).

The velocity profile at the inlet of the computational domain is set in accordance with power law which corresponds to urban development (Figure 5). The height of the profile corresponds to the height of the building (134 m).

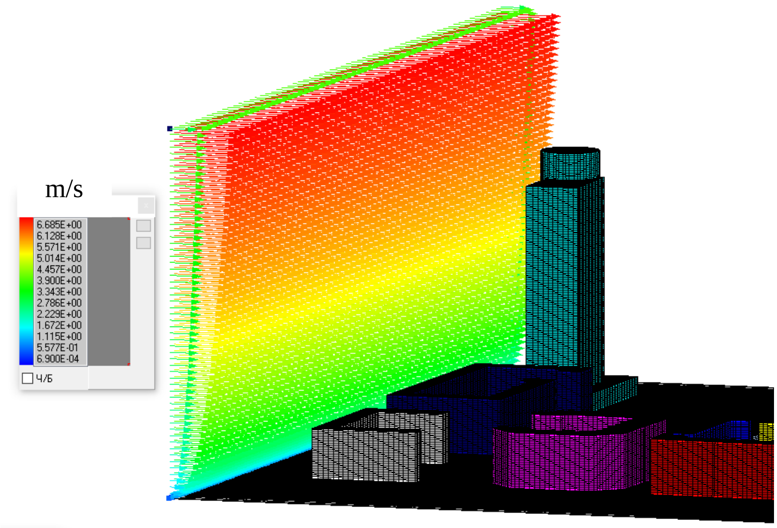


Figure 5. Location of buildings and wind speed distribution at the inlet.

Velocity field in a horizontal section at a height of 2 m is shown in Figure 6. Behind the buildings, stagnant zones with velocities less than 1.5 m/s are formed. In area of the dominant building of 134 m height, there is an increase in speed with flow around corners and roof of building. Than it is higher, than greater air volume is forced to flow around building, hence speed of flow increases up to 8 m/s.

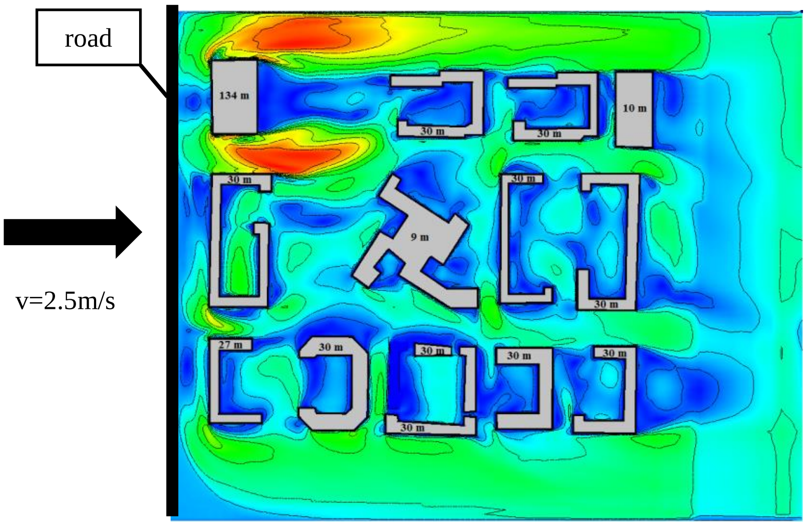


Figure 6. The velocity field in the horizontal section at a height of 2 m.

A typical picture of air flow is shown in Figure 7 with the help of streamlines. There is a low building (9 m) in the center of the block. Wind flow that comes from the road is struck in front of standing building and school (building of 9 m height) is in zone of stagnant zone (red oval at center of Figure 7). This zone is characterized by low wind speed, and as a result, it is possible to precipitate dust particles from the road.

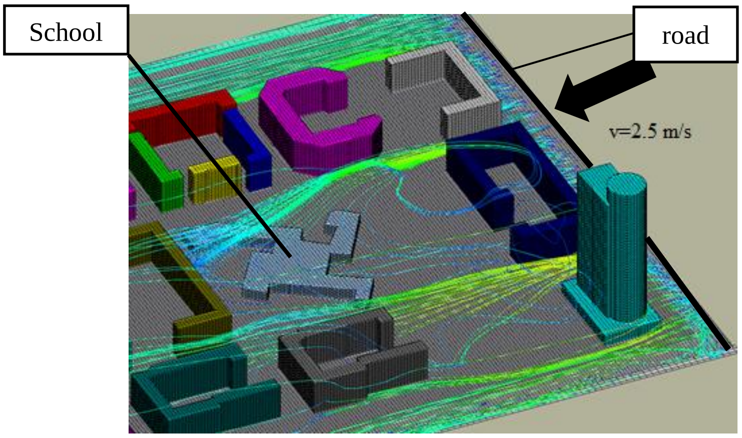


Figure 7. Visualization of airflows in urban areas using streamlines.

5. Conclusions

According to the results, the numerical simulation of wind speed in a urbanized area including buildings of various heights, taking into account density and permeability of the region can be effectively used to plan urban environment development, assess air potential for the purpose of protecting public health and also for predict anthropogenic disasters in urban areas and for develop effective means of protection against their consequences.

Accounting only for airflow is insufficient to fully calculate impact of urban development on ecological situation of the city. In future, it is planned to develop a mathematical model taking into account thermal effects including natural convection and transfer of pollutants and dispersed impurities.

Acknowledgments

The reported study was funded by RFBR and the government of Krasnoyarsk region according to the research project №18-41-242006.

References

[1] Tamura Y 2009 Wind and Tall Buildings *5th European&African Conf. on Wind Engineering* Florence Italy, July 19th-23rd 2009 (Firenze: Firenze University Press 1534) p 25

[2] Franke J, Hellsten F and Schlunzen H 2007 *Environm. Pollut*. **44** 359-67

[3] Podadaeva O I and Dunichken I V 2017 *Vestnik MGSU* **12** 602-9

[4] *Wind Comfort and Wind Danger in the Built Environment* NEN 8100 2006 (Netherland: Netherlands Standards)

[5] Khrebtov M Yu, Gavrilov A A, Dekterev A A and Tepfer E S 2017 *J. Siberian Federal University: Engineering & Technologies* **10** 1000-6

[6] Menter F R 1993 Zonal Two Equation k-w Turbulence Models For Aerodynamic Flows, 23rd Fluid Dynamics, Plasmadynamics, and Lasers Conference, *AIAA Paper 93-2906*, 13 pp

[7] Patankar S V 1980 *Numerical Heat Transfer and Fluid Flow* (Taylor & Francis)

[8] Lezhenin A A, Raputa V F and Yaroslavtseva T V 2016 *Optics Atmos. Ocean.* **29** 467-471

[9] Code of Regulations SP 20.13330.2016 2016 *Updated version of SNiP 2.01.07-85 Loads and effects* (Moscow: OJSC TsPP) p 85

[10] Gouverniuc S V and Sinyavin A A 2017 *Experimental Tests of a Parallelepiped Model on a Flat Wall* (Moscow: Moscow State University) p 32