Numerical simulation of heat and mass transfer in air in vicinity of bluff body

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Abstract. In the current study, the authors present a brief overview of the main factors that affect the processes of heat and mass transfer in the urban environment, and also consider the possibilities of using the ANSYS Fluent software to simulate urban climate problems. A test configuration, which corresponds to the open experimental data, was chosen for the numerical simulation. The boundary and initial conditions for the configuration were set in such a way as to reproduce the conditions of the weakly-unstable thermal stratification of the air flow. Satisfactory agreement of the experimental and simulation data on velocity and temperature profiles was obtained.

1. Introduction

The prediction of urban climate is one of the most important tasks for the development of large cities that combine areas for various purposes: industrial and residential areas, transport infrastructure, recreational areas, etc. It is well-known that climatic conditions in cities are essentially different from those in an open countryside or unpopulated areas. The atmospheric surface layer in urban areas is influenced by a combination of technogenic factors such as:

- the presence of buildings and structures with diverse thermal properties different from those of the natural surface, as well as their impact on air filtration in the surface boundary layer;
- the presence of industrial production initiating thermal pollution;
- the presence of various kinds of transport that causes changes in the air temperature;
- the presence of smoke and soot emissions that cause changes in the composition of atmospheric air, etc.

All these factors give rise to complex effects and processes in the atmospheric surface layer in the vicinity of cities such as a local increase in temperature, changes of relative humidity, solar radiation levels, concentration of noxious substances in the air, etc.

Studying and forecasting these effects allow us to optimize and improve the planning of the urban environment through intelligent design of new industrial and recreation zones. It also helps to create favorable conditions for human lives, to prevent the diffusion of noxious emissions, to improve the efficiency of energy-saving technologies, etc.

Computer modeling of urban climate is particularly attractive for such studies, because it provides opportunities to fully explore the urban environment and take into account the variety of physical
processes in the atmosphere, the diversity of input data and boundary conditions, and large geometric scale of city areas.

However, such simulation is a challenging research task. There are many issues related to the formulation of the physical and mathematical models for such problems and the development of computational methods for their calculation. In the current study, the authors present a brief overview of the main factors that affect the processes of heat and mass transfer in the urban environment, and also consider the possibilities of using the ANSYS Fluent software to simulate urban climate problems. At this stage of the study, a test configuration, studied experimentally in [1], was chosen for the numerical simulation. The boundary and initial conditions for the configuration [1] were set in such a way to reproduce the conditions of the weakly-unstable thermal stratification of the air flow.

2. The main factors which affect on urban climate
A city environment is a complex system included a lot of elements (civil structures and their complexes, industrial clusters, bodies of water, transportation network, pedestrian traffic etc.) which interact actively with the lower layer of the atmosphere and other elements over a wide range of scales. Generally, urban climate is determined by processes in a turbulent atmospheric boundary layer (ABL). One of the main features of ABL is its significant thickness, which is on average 10% of the thickness of the troposphere. Average ABL thickness is about 1 km, but at certain latitudes it can range from 100 m to 3 km [2]. Taking into account the evolution of ABL during the day, generally caused by temperature changes, the structure of ABL can include some characteristic layers. The lowest part of ABL (Surface or Prandtl Layer) covers ~ 10% of the ABL thickness. Within this layer, high vertical gradients of flow parameters are observed. Ground boundary layer comprises the viscous sublayer (its thickness can reach up to few centimeters) located directly at the surface which is characterized by a predominance of the molecular viscosity. The rest of the surface layer includes a buffer zone and a logarithmic law area.

The stable and unstable (convective) states of ABL can be observed considering the diurnal temperature variation. During daylight hours, the ground surface is heated by solar radiation, and it leads to the development of air convection. The convective motion of the air intensifies turbulent mixing. Zone of active air mixing is called the mixing layer. At night, boundary layer is the most stable. By cooling the air convective transport is weakening, and the intensity of the air turbulent motion decreases. Over stable layer, the residual (neutral) layer is formed, which stores partially flow parameters state from the mixing layer, but it is not characterized by strong turbulence stresses due to the lack of contact with the ground. The changes in the ABL structure during the day should be taken into account in numerical simulations of air flow in the vicinity of the city environments.

The structure of the atmospheric boundary layer described above is very simplified. There are many other factors that can significantly modify the distribution of the flow parameters in the ABL. For example, a complex terrain (hills, mountains, hollows etc.) or roughness of the ground surface (forests, water resources, urban environments etc.) can modify air flow structure in the surface layer and increase/decrease wind speed.

In addition, there are some factors in an urban environment which can lead to a change in the thermal conditions of the air flow. According to observations [3-5], the mean air temperature in urban areas is slightly (∼3–5°C) higher than that in the surrounding areas. This phenomenon is called the urban heat island (UHI). UHI is a zone of increased temperatures in the vicinity of urban and industrial areas caused by increased release of heat energy and thermal waste. Usually this effect can be observed in large cities, where the temperature is higher by several degrees than in the surrounding areas during the year. The UHI effect is observed both during the day and at night time. It is supposed that the largest elevations of the urban temperatures occur during clear and still-air nights [6]. There are some factors which play a significant role in the formation of the UHI effects. UHI effects are caused by meteorological reasons (e.g. cloud cover, wind speed, humidity etc.) and by urban factors, such as thermal properties of a building surface, geometry of civil structures etc.
The studies [3-10] describe the following factors contributed to the urban climate state:

- thermo-physical properties of building materials;
- anthropogenic heat sources, such as industrial processes and power generation; heating, ventilation, air-conditioning in buildings (HVAC) and other technical devices; transport vehicles; human metabolism;
- geometry of buildings and city topology;
- pollution, greenhouse gas emissions;
- evapotranspiration;
- surrounding area.

In figure 1, the urban boundary layer (UBL) scheme is shown explaining an influence of various factors on the urban climate.

As a preliminary study of the effect of thermal factors on the urban climate, we consider a simple test case of an air flow around a bluff body placed on a flat plate transversally to the incoming air flow taking into account the injection of tracer gas (C\textsubscript{2}H\textsubscript{4}) under conditions of weakly-unstable thermal stratification.

3. Test case description, numerical methods and tools

The test configuration was chosen under the condition of experimental data [1]. In the experiment, the multispecies flow of a mixture of air and ethylene in a non-isothermal boundary layer near a 2D fence was investigated. The 2D fence of 100 mm height, 5 mm thick and with its upper edge cut at a 45° angle is located orthogonal to the flow. Tracer gas (C\textsubscript{2}H\textsubscript{4}) was released at a flow rate \( Q = 0.6 \) l/min from a hole (\( d = 5 \) mm) on the floor behind the fence.

In figure 2, the computational domain of the test configuration is shown. The inflow velocity was \( U_\infty = 1.6 \) m/s. The free-stream Reynolds number calculated by the characteristic linear scale \( L = H \) and by the flow velocity \( U_\infty \) was \( Re = 1.09 \times 10^4 \). In the calculation, the weakly-unstable thermal stratification of the air flow was reproduced using the following temperature boundary conditions: surface temperature of the bottom wall was \( \Theta_f = 42.57^\circ C \); temperature of the air flow at the inlet boundary was \( \Theta_a = 12.87^\circ C \); mean air temperature inside the boundary layer \( \Theta_0 = 21.23^\circ C \); temperature of the tracer gas was \( \Theta_{\text{gas}} = 30.4^\circ C \); temperature of the 2D fence was \( 40.1^\circ C \).

![Figure 1. Micro-scale factors affecting the urban climate](image-url)
Figure 2. The computational domain scheme of the test configuration (a) and the flow structure in the vicinity of the fence (b)

The numerical simulation was carried out on the basis of the 3D Navier-Stokes equations for a compressible multispecies flow supplemented by the energy equation and the \( k-\omega \) SST turbulent viscosity model [11]. For the flow the incompressible ideal gas law was used:

\[
\rho = \frac{P_0}{R \theta} \frac{1}{M_w},
\]

where \( M_w \) is the molecular weight of the gas; \( P_0 \) is the operating pressure; \( \theta \) is the gas temperature and \( R \) is the universal gas constant. In this form density depends only on the operating pressure and temperature and not on the local relative pressure field.

To solve the initial-boundary problem, the finite-volume method and the method of splitting taking physical processes into account were used. The solution was obtained using the upwind scheme of second-order accuracy for convective terms and the central-difference scheme of second-order accuracy for the viscous terms. The ANSYS Fluent software supplemented with user-defined functions for settings the initial and boundary conditions was used.

The finite-volume computational grid consists of a set of the hexa-elements. The general number of grid elements was about 3.5 million. The non-dimensional distance to the wall at the first calculation node was \( y^+ = 1 \) for the case.

4. Results and conclusions

Let us consider the structure of the flow in the vicinity of the fence taking into account the injection of tracer gas \( \text{C}_2\text{H}_4 \) behind the fence at the distance \( x / H = 1.5 \). Figure 2, b shows velocity streamlines in the vicinity of the fence. Using velocity streamlines structure it is possible to describe the location of characteristic flow features. There are two recirculation zones located in front of the obstacle (recirculation zone \( Z_1 \)) and behind the obstacle (recirculation zone \( Z_2 \)). Zone \( Z_2 \) has a length of about \( 12H \). The maximum of velocity in the flow is observed behind the fence above the zone \( Z_2 \) and reaches 2.04 m/s. Figure 3, a shows the temperature distribution. High temperatures are observed in zones \( Z_1 \) and \( Z_2 \).

The tracer gas is injected into the recirculation zone \( Z_2 \), whereupon the tracer gas moves in the direction opposite to the direction of the incoming flow. The highest mass concentration of the tracer gas is located in the stagnant zone behind the fence (figure 3, b).

The obtained numerical results were compared with the experimental data [1] on the velocity and temperature profiles in the cross-section located behind the fence at \( x/H=1 \) (figure 4). The satisfactory agreement with experimental data was obtained.
The authors presented a brief overview of the main factors that affect the processes of heat and mass transfer in the urban environment, and also considered several possibilities of using the ANSYS Fluent software to simulate urban climate problems. Modeling of the flow in the vicinity of test configuration of the fence was performed taking into account the tracer gas injection and thermal effects for weakly-unstable thermal stratification of flow. Satisfactory agreement of the experimental data [1] on velocity and temperature profiles was obtained.

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