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ESTIMATION OF PEDESTRIAN COMFORT ON THE BASIS OF NUMERICAL MODELING OF WIND AERODYNAMICS OF BUILDINGS IN THE ENVIRONMENTAL DEVELOPMENT

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Abstract: The distinctive paper is devoted to the methodology of pedestrian comfort estimation in the nearby area of the object under construction. A verification example of the wind flow simulation around and through a porous object is considered in order to select correct permeability parameters of the computational model of green spaces. The methodology of pedestrian comfort estimation is tested on the example of a real residential complex in Moscow. The results of the numerical simulation of velocity fields are used to calculate the criteria for pedestrian comfort specified in MDS 20-1.2006. Numerical results are obtained and compared for two study cases - without and with green spaces (bushes),to assess their impact on pedestrian comfort and the possibility of its adjustment.

Keywords: numerical simulation, computational fluid dynamics (CFD), pedestrian comfort, porous body, wind chill effect

ОЦЕНКА ПЕШЕХОДНОЙ КОМФОРТНОСТИ НА ОСНОВЕ ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ ВЕТРОВОЙ АЭРОДИНАМИКИ ЗДАНИЙ В ОКРУЖАЮЩЕЙ ЗАСТРОЙКЕ

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Аннотация: Настоящая статья посвящена методике оценки пешеходной комфортности в близлежащей территории строящегося объекта. Рассматривается верификационный пример расчета ветрового потока в воздушной среде с пористым объектом для подбора параметров проницаемости расчетной модели зеленых насаждений. Методика оценки пешеходной комфортности апробируется на примере реального жилого комплекса в г. Москва. Результаты численного моделирования ветровых потоков используются для вычисления критериев пешеходной комфортности, указанных в МДС20-1.2006. Численные результаты получены и сопоставлены для двух расчетных случаев – без и с зелеными насаждениями (кустарниками), с целью проведения оценки их влияния на пешеходную комфортность и возможность ее корректировки.

Ключевые слова: численное моделирование, вычислительная гидродинамика и газодинамика (CFD), пешеходная комфортность, пористое тело, ветровое охлаждение

INTRODUCTION

Recently, due to significant growth and compaction of urban buildings in the regions of Russia due to the erection of buildings and complexes of various architectural forms and original design solutions, one of the most important factor to consider during construction of buildings and structures is the type of wind conditions at the construction site. Wind loads and impacts in urban areas are formed taking into account velocity and temperature fields inside and above urban areas due to a wide range of atmospheric processes, which in turn are modified to take into account the topography and configuration of the land surface of the area [1]. The impact of velocity in urban areas can lead to a negative change in the microclimatic conditions of the air environment, and can also be a source of unfavorable situations [1-5]. The lack of a culture and residential practices in designing the wind patterns of residential areas, taking into account the existing and future development, has already led to the emergence of neighborhoods where the velocity does not decrease, as is usually the case in a city, but increases by 20% or more at the end gaps between the buildings, there is a strong narrowing of the air flow, and as a result velocity acceleration zones and/or high turbulence zones are formed, which creates uncomfortable conditions for pedestrians [6]. Wind speeds provided by meteorological stations may differ significantly from the wind conditions on the ground due to the influence of local urban development, unique in its kind for each district of the city. Modeling of aerodynamic conditions (using numerical and /or experimental methods) allows to analyze the occurrence of adverse situations in pedestrian areas, considering the specificity of the landscape and the surrounding buildings, and propose measures to eliminate them or reduce their negative impact.

The aim of this paper is to perform an approbation of the methodology for assessing pedestrian comfort with correct consideration of green spaces using the example of a real construction object, and to determine the design parameters, such as required number of wind angles of attack. As an expected result of an assessment, recommendations on green spaces arrangement that provides pedestrian comfort improvement should be formulated.

1. NORMATIVE AND ANALYTICAL APPROACH TO ASSESS PEDESTRIAN COMFORT

According to SP 20.13330.2016 [7], when developing architectural and planning solutions for urban neighborhoods, as well as when planning the construction of buildings inside existing urban neighborhoods, it is recommended to assess the comfort in pedestrian areas in accordance with the requirements of the standards or technical conditions. However, any criteria for pedestrian comfort in [7] are not formulated. Such criteria are described only in MDS 20-1.2006 [8], according to which the comfort condition for pedestrian areas is as (eq. 1):

$$\forall V < V_{cr} : T_c(V_{cr}) < T_{lim} \qquad (1)$$

where V is the velocity in a gust at the level of 1.5 meters; T_c is the duration of the appearance of velocity V, more than a certain critical value V_{cr}; T_{lim} is T_c limit value.

The V_{cr} and T_{lim} values for the three established comfort levels are listed in table 1.

Usually, when assessing the comfort in pedestrian zones with velocity V at a characteristic height of z_c=1.5 meters, the frequency of its occurrence T_c is determined by the relations (eq. 2):

$$T_c = \Delta T_m P(V > V_{cr}) \qquad (2)$$

where ΔT_m is the interval of measuring velocity V_m at meteorological stations (usually ΔT_m = 3 hours); $P(V>Vcr)$ is the probability that the velocity exceeds the critical value V_{cr}.

Table 1. Critical velocity V_{cr} (m/s) and the maximum duration T_{lim} (hour /year) of their appearance.

Comfort level	I	II	III
V_c, m/s	6	12	20
T_{lim}, hour/year	1000	50	5

2 METHODOLOGY OF PEDESTRIAN COMFORT LEVEL ESTIMATION WITH APPLICATION OF NUMERICAL METHODS

2.1. Basics of the methodology.

In [6, 9], the following method for pedestrian comfort estimation based on numerical modeling of the aerodynamics of buildings in the surrounding buildings is presented. After calculations performed for all wind directions, the results are processed using a special computer module. The values of the wind gusts at the characteristic monitoring points of the urban area are summed with the weight coefficients corresponding to the frequency of occurrence of the wind impact of a given direction and a given speed range. 1.5 m is taken as the estimated height.

After numerical modeling for all wind directions (usually j = 1, ..., 24), the «discomfort time of level *l*» K_{crl} (l = 1,2,3) for a representative set of points of pedestrian zones is determined by the relations (eq. 3):

$$K_{cr} = \sum S_{ij}T_{ij}, \quad V_{ij} = V_i/V_{10}(1 + \theta \cdot I) \tag{3}$$

where V_i, i=1,2,3 is the velocity in the table of weather data ("wind rose"); T_{ij} is the duration (according to meteorological data, hours per year) of wind influence of direction j and mean velocity V_i; V_j is the mean wind speed at this point according to the calculation for direction j at speed V_{10} at a height of 10 m; $V_{ij}$is the maximum velocity at the point in the gusts at the wind velocity V_i; θ is the assurance coefficient(usually in the range from 1 to 3); S_{ij} is an indicator (0 or 1) that shows the local wind speed exceedance of the critical value V_{crl} for a given comfort level $l$at the point V_{ij}; $I=(\rho \cdot TKE/abs(P)/3)^{1/2}$ is the turbulence intensity (standard of velocity pulsations); $P = \rho V^2/2$ is the mean pressure; $TKE=3/2(I \cdot V)^2$ is the turbulence kinetic energy.

The wind rose is received according to the weather data. To assess the distribution of wind speeds inside the rumba, in practice, as a rule, the Weibull distribution is used [9-12].

Estimation of the standard deviation of the pulsation velocity component is based on the steady state simulation results using calculated values of turbulence kinetic energy TKE and considering the $\theta = 2$ (eq. 4):

$$\sigma = \sqrt{\frac{4}{3}TKE} \tag{4}$$

2.2. Wind chill effect.

In the winter season, due to the cold wind currents and wind gusts, the human body may experience wind chilling, as a result of which the temperature feels completely different than it actually is. Scientists and medical experts of the Joint Action Group on Temperature Indices [13] implemented an index of wind chill. The resulting model can be approximately, with an accuracy of one degree, formulated as equation 5:

$$T_{wc} = 13.12 + 0.6215 \cdot T_a - 11.37 \cdot V^{+0.16} + 0.3965 \cdot T_a \cdot V^{+0.16} \tag{5}$$

where T_{wc} is the wind chill index, T_a is the air temperature in Celsius, V is the velocity in km/h.

2.3. Features of green spaces modeling.

Modeling of the decorative green spaces, both in wind tunnels and numerically, is a very difficult task. This is due, primarily, to the complexity of their form.

When conducting experiments in wind tunnels, trees are modeled simply, or toy models are used [14].

In numerical modeling, it is possible to create a realistic tree model up to the modeling of leaf geometry, but this approach is incredibly resource-demanding and time consuming. It is also possible to set a tree area in a simplified way - as a porous body, and when solving the Navier-Stokes equations, an additional term is added to the equations of motion that characterizes the loss of momentum when air passes through the porous region (eq. 6):

$$\begin{cases} \rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}+\rho w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+S_{M,x} \\ \rho\frac{\partial v}{\partial t}+\rho u\frac{\partial v}{\partial x}+\rho v\frac{\partial v}{\partial y}+\rho w\frac{\partial v}{\partial z}=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+S_{M,y} \\ \rho\frac{\partial w}{\partial t}+\rho u\frac{\partial w}{\partial x}+\rho v\frac{\partial w}{\partial y}+\rho w\frac{\partial w}{\partial z}=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+S_{M,z} \end{cases} \quad (6)$$

where μ is the coefficient of dynamic viscosity; loss of momentum through the isotropic porous region can be formulated based on permeability and loss coefficients (eq. 7),

$$\begin{cases} S_{M,x}=-K_{loss}\frac{\rho}{2}u\sqrt{u^2+v^2+w^2} \\ S_{M,y}=-K_{loss}\frac{\rho}{2}v\sqrt{u^2+v^2+w^2} \\ S_{M,z}=-K_{loss}\frac{\rho}{2}w\sqrt{u^2+v^2+w^2} \end{cases} \quad (7)$$

K_{loss} is the loss factor associated with inertial losses (m^{-1}).

The model of porosity allows taking into account the Darcy Model [15, 16], which is the continuity equation for flows in porous regions and is characterized by such a parameter as the volume porosity γ.

The volume porosity is the ratio of the volume V' of space in the final volume through which air can flow, to the entire final volume V (eq. 8):

$$V'=\gamma V \quad (8)$$

The Darcy model is summarized as follows (eq. 9):

$$-\frac{\partial p}{\partial x_i}=\frac{\mu}{K_{perm}}U_i+K_{loss}\frac{\rho}{2}|U|U_i \quad (9)$$

where μ is the dynamic viscosity, K_{perm} is the permeability.

When modeling a tree in a simple, porous domain, the difficulty lies in the selection of an adequate loss factor and volume porosity, which will reflect the permeability of the real green planting.

3. VERIFICATION OF THE METHODOLOGY OF NUMERICAL MODELING OF GREEN SPACES AERODYNAMICS

3.1. Problem statement.

For the numerical simulation of the aerodynamics of green spaces, a group of scientists from the Institute of Architecture of Japan (AIJ) [17] proposed a benchmark. A tree with a height of 7 meters in the air flow is considered. At the inlet of the air domain the velocity profile obeys the vertical power law (eq. 10). Sensors (monitoring points) are installed behind the tree, measuring the instantaneous velocity at each height in increments of 1.5 meters. The tree model and flow direction are shown in Figure 1, the layout of the monitoring points is shown in Figure 2.

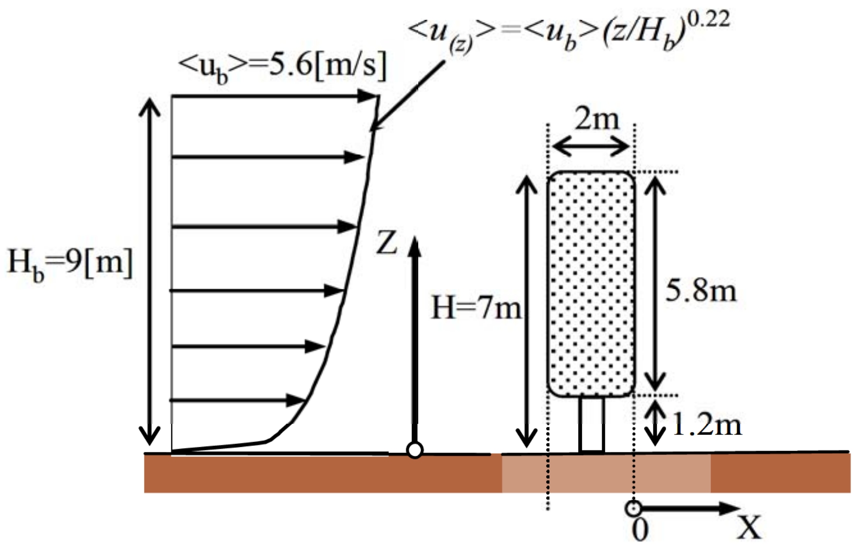


Figure 1. Tree model with indication of characteristic dimensions and wind direction of the inlet flow.

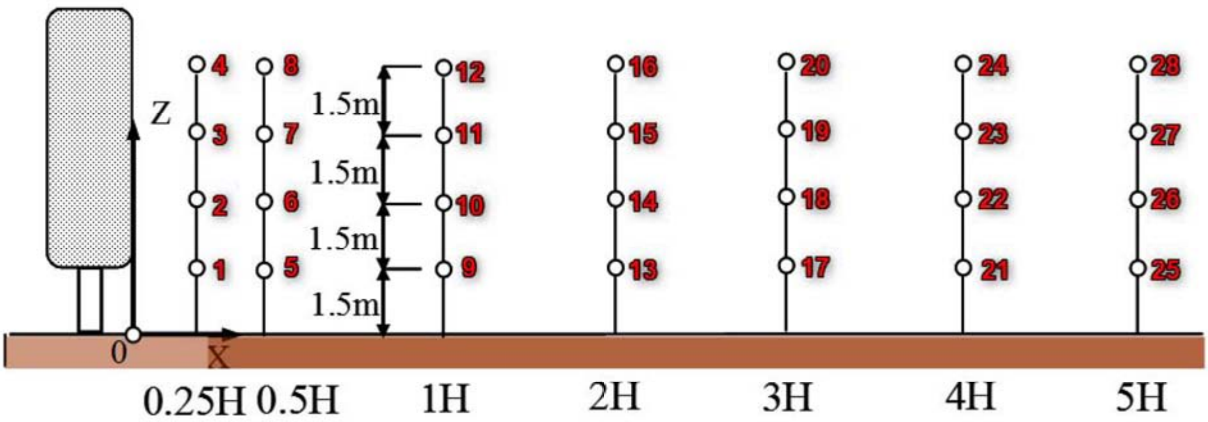


Figure 2. Layout of the monitoring points in a given coordinate system with an indication of the characteristic dimensions.

The tree was modeled as an isotropic porous region. Loss of momentum that occurs when passing through a porous body, are formulated based on permeability and loss coefficients (eq. 7). The loss coefficient K_{loss} was taken equal to 1.75, based on the data obtained [14], which proved to be the most accurate result in comparison with the experimental data.

A comparison of numerical and experimental results (velocities at monitoring points for different values of volume porosity γ (0.3-0.9 with a step of 0.1; 0.99 and 1))was made. Recommendations on the design parameters for modeling the permeability of shrubs crowns (as one of the ways to improve pedestrian comfort) was formulated.

All aerodynamic simulations were performed using ANSYS CFX 17.0 software package [15, 16].

3.2. Simulation Parameters.

The problem was solved in a two-dimensional formulation. As a turbulence closure model, the SST (Shear Stress Transport) model was utilized.

The following basic physical characteristics of the flow for aerodynamic simulations are used:

$$\rho^f = 1.184 \text{ kg/m}^3$$

- air density,

$$\eta = 1.831 \cdot 10^{-5}$$

- the coefficient of dynamic viscosity,

$$\bar{v}_{in}^f = 4.77 \text{ m/s}$$

– the mean velocity at the inlet,

$$Re = 2.1609 \cdot 10^6$$

– the Reynolds number.

The High Resolution advection scheme and the implicit First Order Backward Euler scheme were used. Maximum residuals of 10^{-4} were set as an criterion for convergence and termination ofsteady state solution.The maximum number of iterations was 300.

3.3. Initial and boundary conditions.

The mean flow velocity profile at the inlet obeys the power lawdepending on the tree height and turbulence kinetic energy (eq. 10):

$$u(z) = u_b \left(\frac{z}{H_b}\right)^{0.22} \quad (10)$$
$$k(z) = 3.02$$

where u_b is velocity at the characteristic height H_b, $k(z)$ is the turbulence kinetic energy.

At the outlet and at the upper boundary of the domain, opening boundary conditions with a relative pressure equal to zero and the same turbulence parameters as at the inlet are assigned. On the «ground», «No Slip Wall» (U=V=W=0 m/s) boundarycondition is specified, which excludes penetration of the fluidthrough the surface.

On the surface of the tree crown interface «Fluid-Porous Domain») is set to ensure the penetration of air through the porous body (domain).

As initial conditions, zero velocities

$$(U=V=W=0 \text{ m/s})$$

and zero relative pressures areset in the entire domain.

3.4. Simulation results.

Figure 3 and Table 2 demonstrate the main results of the performed computational studies and the comparison of the numerical results with the experiment data.

In the Table 2 the relative errors for real velocity at the monitoring points in comparison with the experiment are presented.

The numerical simulation of hedge aerodynamics showed that the closest to experimental data result was obtained for the values of volume porosity from 0.9 to 1.The maximum discrepancy from the experiment is 29%, and the minimum one is 0.15%.

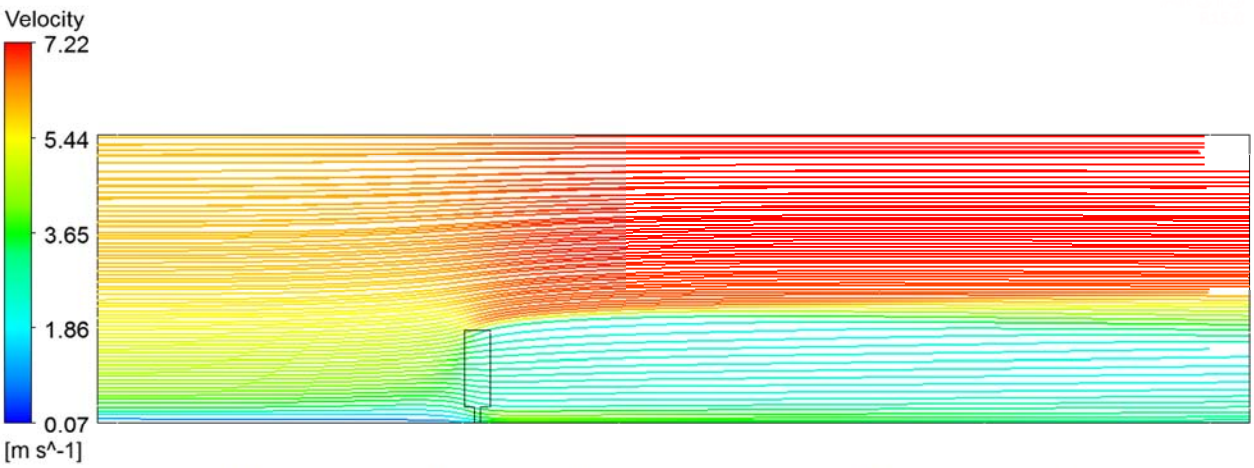


Figure 3. Velocity stream lines, m/s. Volume porosity γ = 1, loss coefficient K_{loss} = 1.75.

Table 2. Comparison of numerical (u) and experimental (u^*_{exp}) velocity simulations at the monitoring points for each considered volume porosity value.

Monitoring points	u^*_{exp} [м/с]	γ=0.3		γ=0.4		γ=0.5		γ=0.6		γ=0.7		γ=0.8		γ=0.9		γ=0.99		γ=1	
		u	ε,%	u	ε,%	u	ε,%	u	ε,%	u	ε,%	u	ε,%	u	ε,%	u	ε,%	u	ε,%
1	2.05	2.20	7.33	3.24	58.11	2.99	45.99	2.77	35.03	2.62	28.15	2.55	24.30	2.50	21.86	2.47	20.49	2.47	20.36
10	2.13	2.60	21.98	2.51	17.45	2.48	16.29	2.48	15.98	2.48	16.00	2.48	16.11	2.48	16.28	2.48	16.44	2.49	16.45
11	2.14	2.39	11.32	2.41	12.35	2.43	13.19	2.44	13.97	2.46	14.61	2.47	15.09	2.47	15.47	2.48	15.73	2.48	15.75
12	2.42	2.75	13.48	2.61	7.59	2.51	3.62	2.45	1.25	2.41	-0.41	2.38	-1.66	2.36	-2.63	2.34	-3.32	2.34	-3.39
13	2.76	2.52	-8.88	2.81	1.84	2.80	1.34	2.70	-2.38	2.63	-4.83	2.60	-5.80	2.59	-6.33	2.58	-6.56	2.58	-6.58
14	2.16	2.52	16.68	2.43	12.58	2.40	11.20	2.39	10.52	2.38	10.20	2.38	10.03	2.38	9.98	2.38	9.96	2.38	9.96
15	2.05	2.27	10.81	2.32	13.35	2.34	14.44	2.36	15.15	2.37	15.67	2.38	16.04	2.38	16.32	2.39	16.51	2.39	16.52
16	2.45	2.52	2.68	2.48	0.88	2.41	-1.61	2.37	-3.37	2.34	-4.70	2.31	-5.75	2.29	-6.57	2.28	-7.16	2.28	-7.22
17	2.83	2.63	-6.91	2.85	0.91	2.86	1.14	2.81	-0.67	2.77	-2.13	2.75	-2.74	2.74	-3.08	2.73	-3.27	2.73	-3.28
18	2.39	2.50	4.67	2.40	0.53	2.37	-0.89	2.35	-1.79	2.33	-2.39	2.32	-2.81	2.31	-3.10	2.31	-3.30	2.31	-3.32
19	2.38	2.23	-6.48	2.28	-4.28	2.30	-3.26	2.31	-2.79	2.32	-2.55	2.32	-2.44	2.32	-2.38	2.32	-2.36	2.32	-2.36
2	2.90	2.72	-6.13	2.62	-9.83	2.61	-10.03	2.62	-9.70	2.63	-9.31	2.64	-8.96	2.65	-8.65	2.66	-8.40	2.66	-8.38
20	2.79	2.44	-12.61	2.41	-13.49	2.37	-15.12	2.33	-16.53	2.30	-17.69	2.27	-18.64	2.25	-19.41	2.23	-19.98	2.23	-20.03
21	2.65	2.69	1.33	2.88	8.64	2.90	9.36	2.86	7.91	2.83	6.67	2.82	6.17	2.81	5.87	2.80	5.67	2.80	5.66
22	2.47	2.49	0.99	2.38	-3.43	2.34	-5.10	2.31	-6.32	2.29	-7.24	2.27	-7.94	2.26	-8.47	2.25	-8.84	2.25	-8.88
23	2.61	2.20	-15.43	2.25	-13.47	2.27	-12.70	2.28	-12.53	2.28	-12.57	2.27	-12.69	2.27	-12.83	2.27	-12.95	2.27	-12.96
24	3.08	2.39	-22.40	2.38	-22.92	2.33	-24.34	2.29	-25.68	2.26	-26.84	2.23	-27.80	2.20	-28.57	2.19	-29.14	2.18	-29.19
25	2.50	2.71	8.24	2.89	15.56	2.92	16.42	2.89	15.23	2.86	14.26	2.85	13.84	2.84	13.55	2.84	13.34	2.84	13.32
26	2.45	2.50	2.00	2.37	-3.18	2.32	-5.22	2.28	-6.84	2.25	-8.11	2.23	-9.10	2.21	-9.86	2.19	-10.39	2.19	-10.45
27	2.62	2.19	-16.72	2.24	-14.76	2.25	-14.24	2.25	-14.37	2.24	-14.67	2.23	-15.01	2.22	-15.31	2.22	-15.55	2.22	-15.57

4. APPROBATION OF THE NUMERICAL METHODOLOGY OF ESTIMATION AND IMPROVEMENT OF PEDESTRIAN COMFORT

4.1. Problem statement.

The application of the developed numerical methodology of pedestrian comfort estimation-was performed on a realresidential building surrounded by existing urban area (Figure 4). As it will be shown below, for the considered group of buildings, it was necessary to improve pedestrian comfort using the above-described methodologyby incorporation of thegreen spaces to particular locationswhere pedestrian comfort criteria were not satisfied.

For the correct shrubs arrangement near the considered buildings, the results of criterion assessments of pedestrian comfortobtained for the model without green spaces were used.Decisions on the location of green space were made based on an analysis of the most unfavorable wind attack angles, a planning scheme for the land plot near the designed building, as well as currently existing planted shrubs (Figure 5).

Figure 4. General view of the building. Project proposal (photo montage).

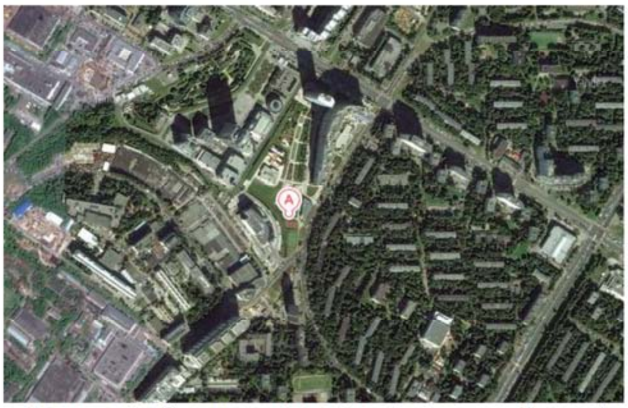


Figure 5. Construction site (maps.yandex.ru) of the projected residential building (South-West Administrative District, Moscow).

4.2. Geometric model of the building surrounded with nearby buildings with bushes consideration.

The radius of the nearby building area was taken equal to 600 m.The actual location of the buildings relative to the target object, their height and cross section in the plan, as well as the local terrain relief (elevation differences near the target object) were consideredfor the geometric model including surrounding buildings.

Geometric model of the main building surrounded with nearby buildingswas created in ANSYS Mechanical 17.0 [18]. The first-floorlevel was taken as a zero level. The created model of the building, taking into account the development for a certain perspective, is shown in Figure 6-7.

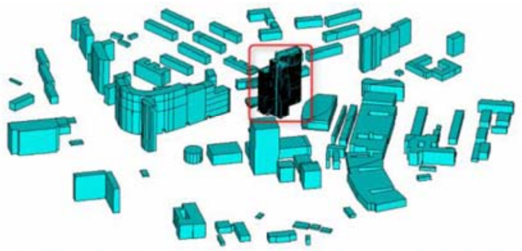


Figure 6. Geometric model of the building surrounded with nearby buildings.

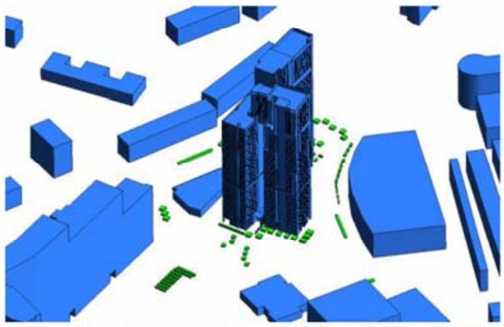


Figure 7. Geometric model of the building surrounded with nearby buildings with bushes consideration.

4.3. Boundary and initial conditions.

The simulated area (Figure 8) is assigned the Air domain with the following physical parameters: incompressible air at a temperature (25°C) and pressure 1 atm.

The boundary conditions at the inlet correspond to the 1st wind region, and the type of terrain B «suburb» in accordance with building codes [7, 19]. The mean pressure and pulsation profiles were converted to theinput data for the ANSYS CFX using the developed macro CFX_PROFIL_SNIP as a vertical profiles (along the height)of mean velocity, turbulence kinetic energy and dissipation energy, corresponding to the loads, taking into account the load reliability factor of 1.4. The integral turbulence length scale is assumed to be 300 m in accordance with the recommendations of Eurocode [20].

At the outlet and at the upper boundary of the domain, opening boundary conditions with a relative pressure equal to zero and the same turbulence parameters as at the inlet are assigned. On the «ground» and on all buildings, «No Slip Wall»

$$(U=V=W=0 \text{ m/s})$$

boundary condition is specified, which excludes penetration of the fluid through the surface.

On the surface of the tree crown interface «Fluid-Porous Domain» is set to ensure the penetration of air through the porous body (domain).

As initial conditions, zero velocities ($U=V=W=0$ m/s) and zero relative pressures are set in the entire domain.

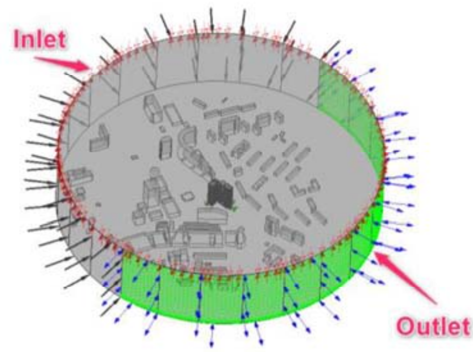


Figure 8. Simulated area (ANSYS CFX) with designated boundary conditions. Wind angle of attack 0°.

4.5. Simulation Parameters.

All aerodynamic calculations were carried out in a three-dimensional steady-stateformulation using the RANS SST turbulence model.

The internal parameters for the shrubs are following: the surface porosity is isotropic; the volume porosity is 1. An isotropic model with a loss coefficient of 1.75 $m^{-1}$was set as the loss model.

Maximum residuals of 10^{-4} were set as a criterion for convergence and termination ofsteady state solution. The maximum number of iterations was 500.

4.6. Results of steady state aerodynamic simulations.

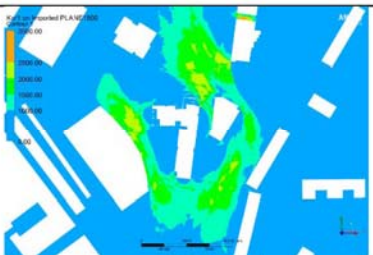
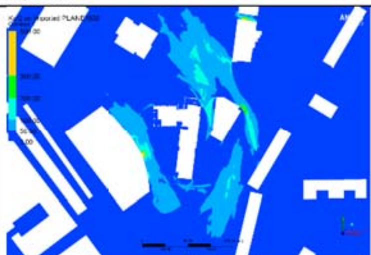
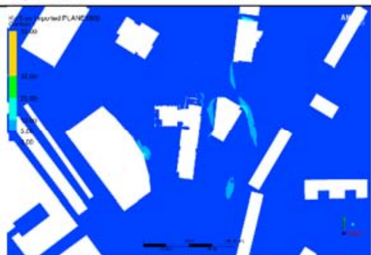
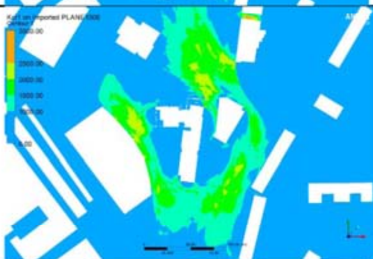
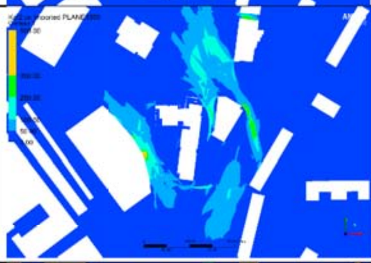
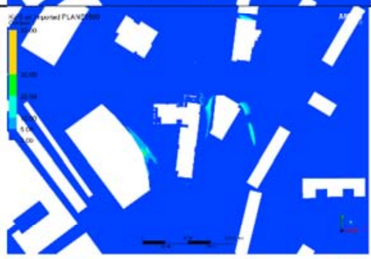
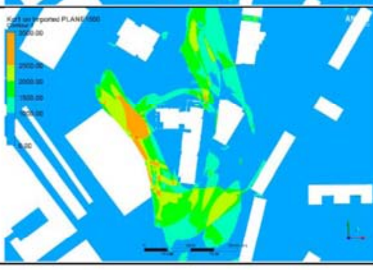
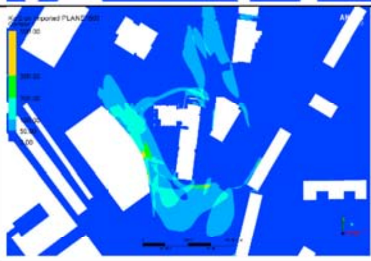
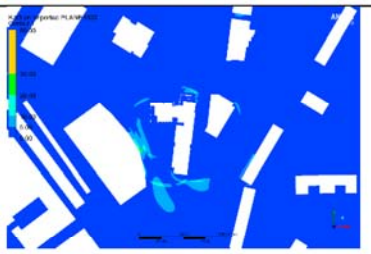
Pedestrian comfort levels (repeatability of meanvelocity, hr/year) according to the 3rd regulatory criteria (K_{cr1}, K_{cr2}, K_{cr3}) were calculated using the data from weather stations named after Michelson [6, 14].

It was necessary to get a set of results for different wind angles of attack was in order to calculate the pedestrian comfort level criteria. The comparisonof the simulation results for 24, 12 and 6 wind directionsevenly distributed in a circle was conductedin order to determine the minimum required number of windangles of attack.

The convergence study resultsfor thepedestrian comfort level criteria depending on the number of wind directions considered, and the determination of the optimal number of simulationcases excluding bushes are presented below (Table 3).

As it can be seen from the results, the difference is insignificant with the number of 12 and 24 wind angles of attack. This allows usto consider only 12 wind attack angles to perform accurate estimation of the pedestrian comfort level.

Table 3. The results of criterion assessments for different number of wind angles of attack.

Number of angles	1st level of pedestrian comfort, exceeding *Vcr1*=6 m/s, not more than *Kcr1*=1000 hours per year in the pedestrian zone at a height of 1.5 m	2nd level of pedestrian comfort, exceeding *Vcr2*=12 m/s, not more than *Kcr2*=50 hours per year in the pedestrian zone at a height of 1.5 m	3st level of pedestrian comfort, exceeding *Vcr3*=20 m/s, not more than *Kcr3*=5 hours per year in the pedestrian zone at a height of 1.5 m
24			
12			
6			

A comparison of the criterion assessment of pedestrian comfort based on numerical modeling of the building surrounded with nearby buildings without bushes consideration and numerical modeling of the building surrounded with nearby buildings and bushes consideration is presented below (Figure 9-11). Results comparison show the significant decrease in the occurrence frequency of winds exceeding 6 m/s for the first criterion, 12 m/s for the second criterion and 20 m/s for the third criterion for the case where bushes were incorporated in to the model.

The results allow us to conclude that bushesplaced near the building help to improve pedestrian comfort.

Pictures of wind speeds amplification at the level of the pedestrian zone of 1.5 m for some wind directions with and without bushes are shown in Figure 12-14. Comparison of the meanvelocity amplification at 1.5 m shows significant improvements in pedestrian zones where highvelocities were observedfor the study cases without bushes.

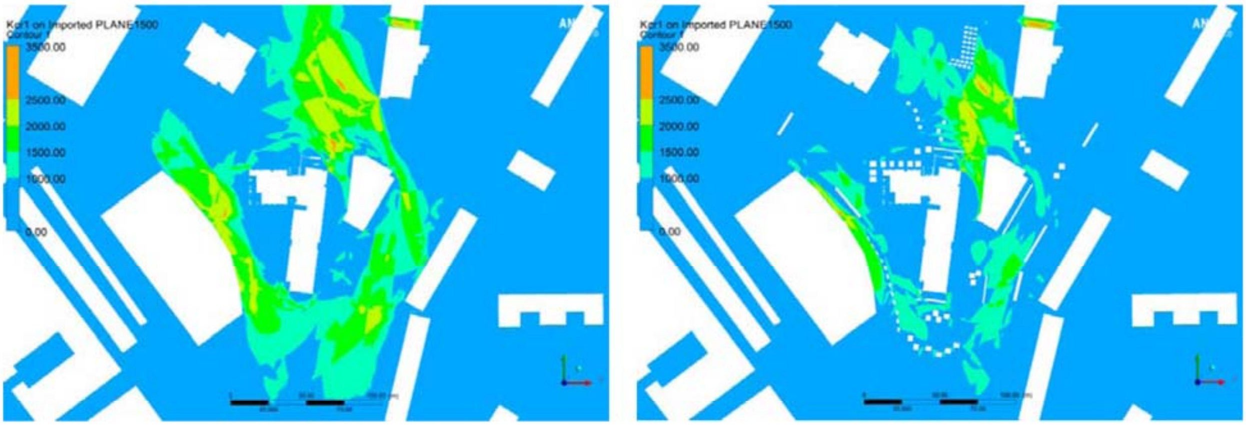


Figure 9. 1st level of pedestrian comfort V_{cr1}=6 m/s exceeding no more K_{cr1}=1000 hours per year in the pedestrian zone at a height of 1.5 m (on the left - without bushes, on the right - with bushes).

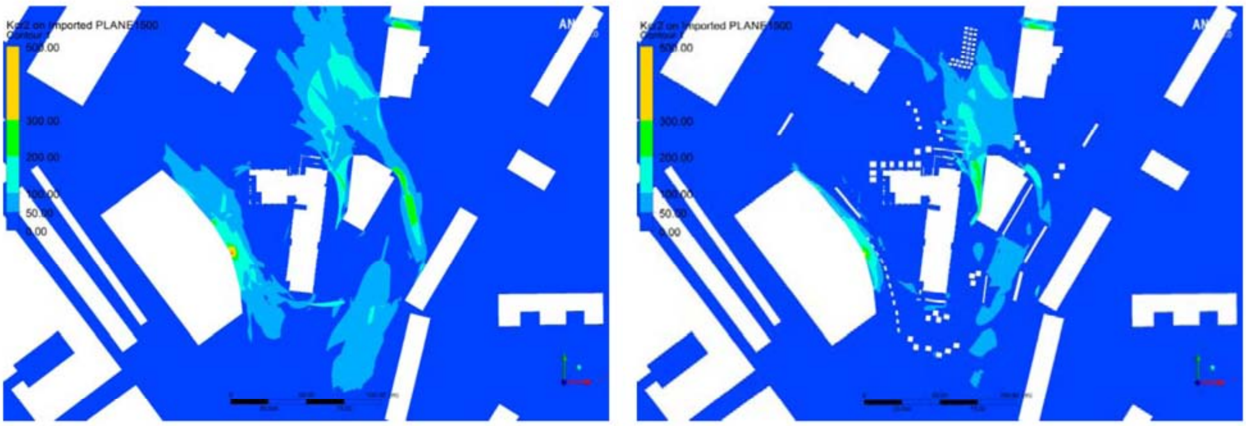


Figure 10. 2nd level of pedestrian comfort V_{cr2}=12 m/s exceeding no more K_{cr2}=50 hours per year in the pedestrian zone at a height of 1.5 m (on the left - without bushes, on the right - with bushes).

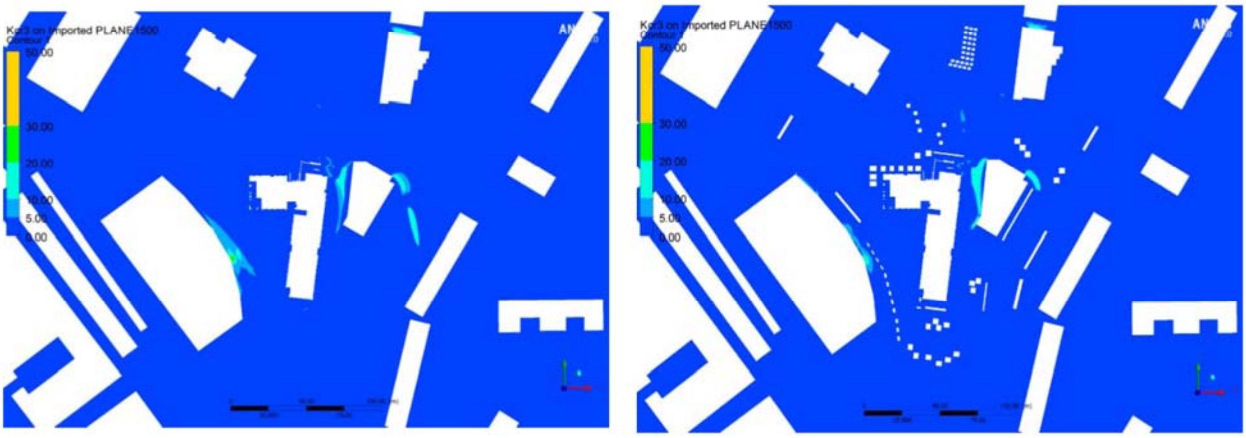


Figure 11. 3st level of pedestrian comfort V_{cr3}=20 m/s exceeding no more K_{cr3}=5 hours per year in the pedestrian zone at a height of 1.5 m (on the left - without bushes, on the right - with bushes).

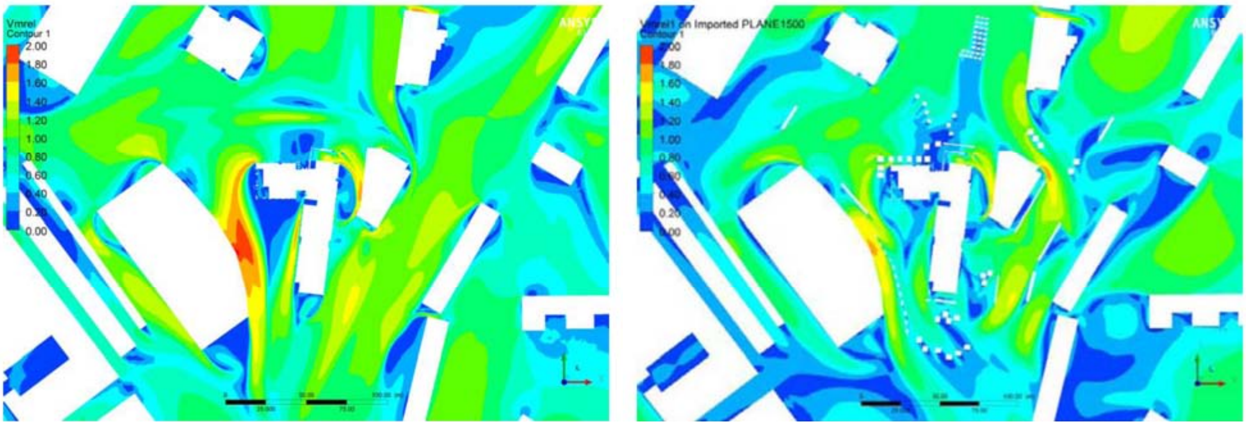


Figure 12. The meanvelocity amplifications in the pedestrian zone at a height of 1.5 m. The wind angle of attack is 0° (on the left - without bushes, on the right - with bushes).

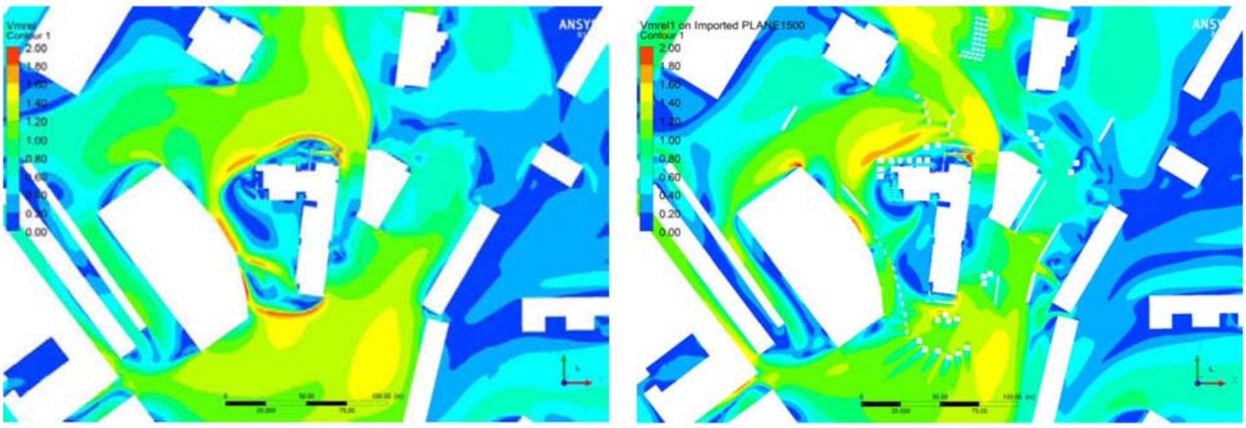


Figure 13. The meanvelocity amplifications in the pedestrian zone at a height of 1.5 m. The wind angle of attack is 90° (on the left - without bushes, on the right - with bushes).

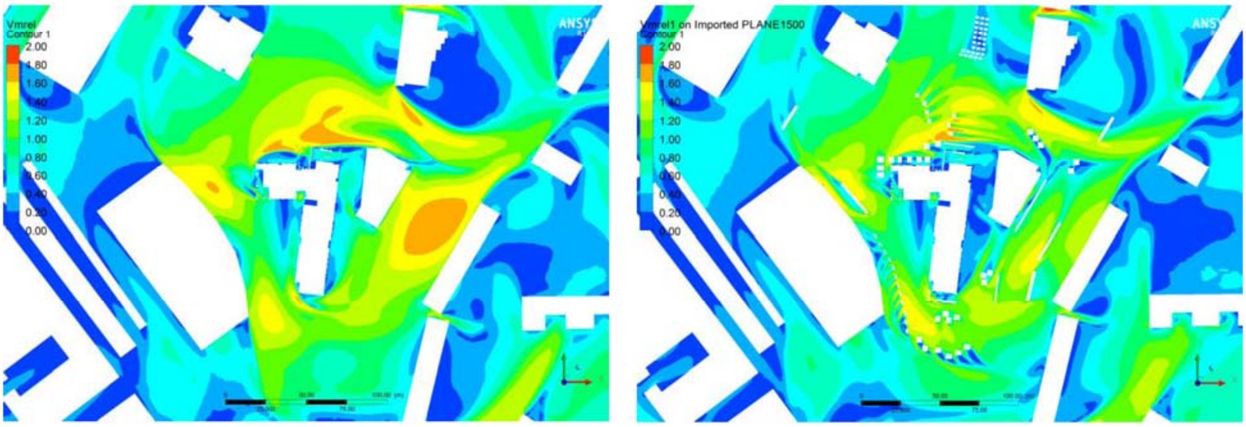


Figure 14. The mean velocity amplifications in the pedestrian zone at a height of 1.5 m. The wind angle of attack is 240° (on the left - without bushes, on the right - with bushes).

Comparison of the results of numerical modeling of the buildings aerodynamics taking into account wind chill effect in the winter season at a temperature of - 20°C for some wind directions with and without shrubs is presented below (Figure 15-18).

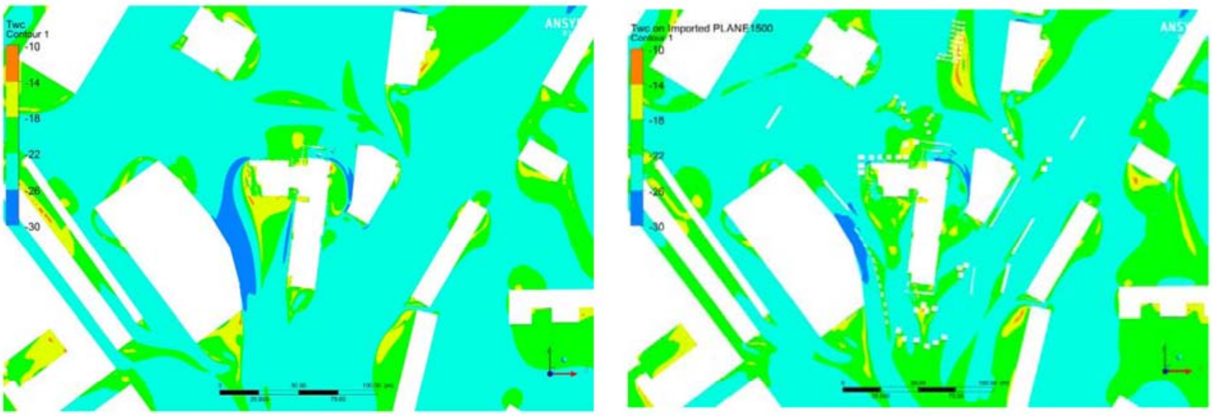


Figure 15. Comparison of the results of numerical modeling of the buildings aerodynamics taking into account wind chill effect in the winter season at a temperature of -20 °C, wind angle of attack 0° (on the left - without bushes, on the right - with bushes).

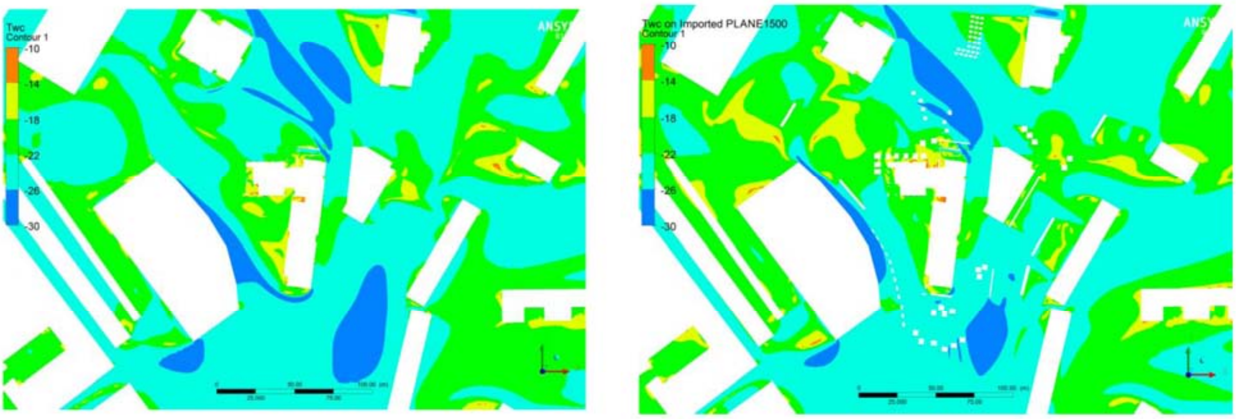


Figure 16. Comparison of the results of numerical modeling of the buildings aerodynamics taking into account wind chill effect n the winter season at a temperature of -20 °C, wind angle of attack 120° (on the left - without bushes, on the right - with bushes).

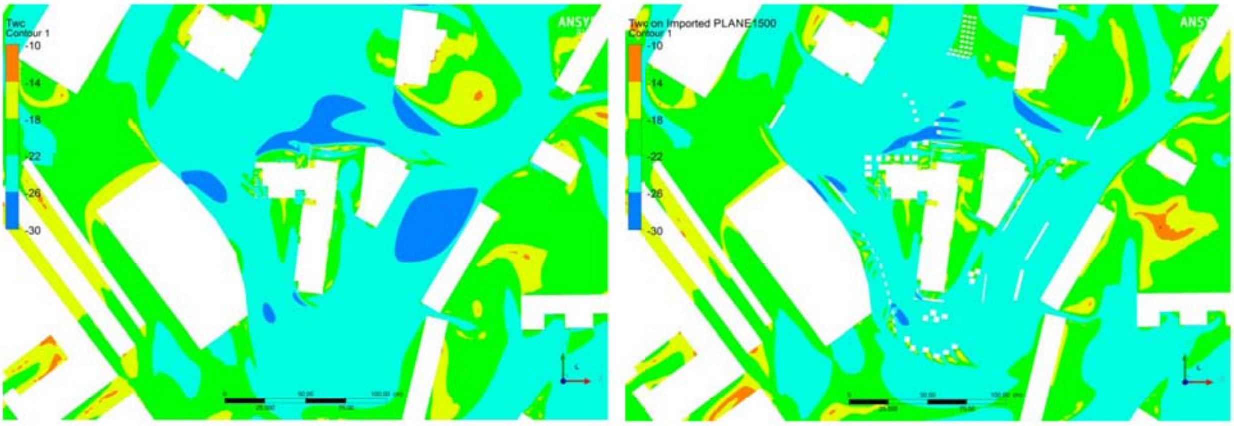


Figure 17. *Comparison of the results of numerical modeling of the buildings aerodynamics taking into account wind chill effect in the winter season at a temperature of -20 °C, wind angle of attack 240° (on the left - without bushes, on the right - with bushes).*

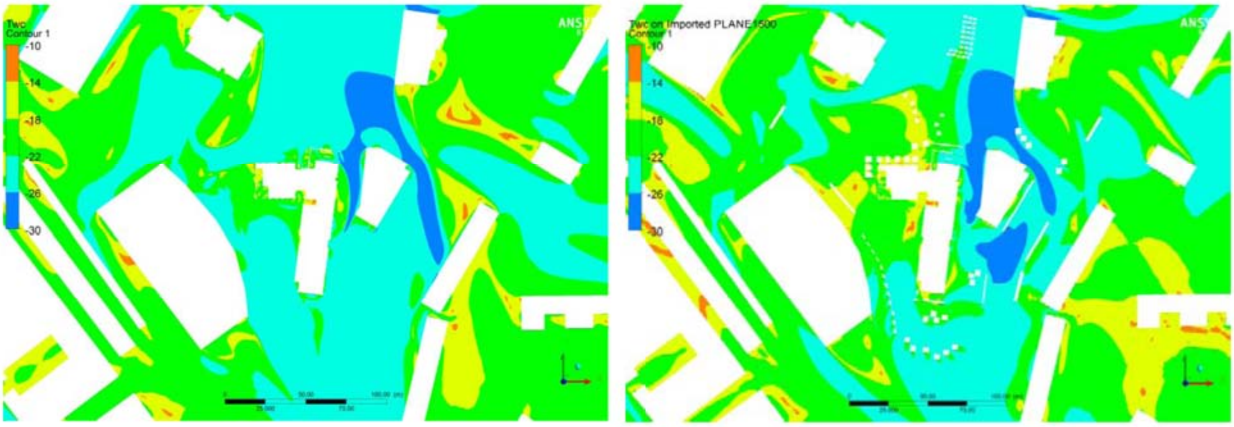


Figure 18. *Comparison of the results of numerical modeling of the buildings aerodynamics taking into account wind chill effect in the winter season at a temperature of -20 °C, wind angle of attack 300° (on the left - without bushes, on the right - with bushes).*

The results of numerical modeling of the buildings aerodynamics taking into account wind chill allow us to conclude that the human body feels the temperature 1.5 times lower than the actual temperature that equal to – 20 C. Calculations have shown that the temperature reaches the mark - 30 ° C. This gives a tangible contribution to a comfortable stay of people in these areas. The correct location of green spaces in pedestrian areas has contributed to the narrowing of areas where the minimum (minus) temperatures occur.

5. CONCLUSION

The presented results showed a wide applicability of the pedestrian comfort assessment methodology and the possibility of its adjustment by planting green spaces. The solved model problem allowed to findthe right parameters of the tree model. Comparison of the results for different numbers of windangles of attack showed that 12 angles are sufficient for obtaining the required accuracy.Further development of this methodology may include a more detailed analysis of wind flows (especially maximum velocity amplification) for each individual angle of attack, namely using the results of non-steadysimulationsobtained using more accurate (and also resource-demanding) turbulence models such as DES and LES.The results showed the practical importance of conducting suchkind of research, and therefore there is a need to include amethodology for pedestrian comfort assessment in Russian building codes.

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