Numerical investigation of the aerodynamic coefficients for the steelmaking shop

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Abstract. The wind load on the building depends on its shape and size, type of terrain, climatic region and a number of other factors. In accordance with Russian standards for buildings with a high level of responsibility, it is required to determine the wind load either experimentally in a wind tunnel, or using numerical simulation by solving three-dimensional problems of fluid dynamics. The article presents the results of the numerical determination of aerodynamic coefficients for the building of the steelmaking shop, made using the Abaqus software package. The steelmaking shop has a complex shape in plan and uneven in height, it is a particularly dangerous production facility and refers to structures with a high level of responsibility. The aerodynamic coefficients on the walls and roof of the steelmaking shop obtained by CFD analysis are represented. The different meshes are analyzed. Regulatory method to calculate aerodynamics coefficient also may be adopted for this building. The values of the coefficients by regulatory procedure are on average greater than those numerically obtained. The wind load does not have a significant effect on the framework of the steelmaking shop, since the efforts from the wind load are not more than 10% of the maximum total effort in the elements, while the efforts from the crane load are up to 45% of the total effort, and from the technological loads up to 50% of the total effort. So, using the regulatory procedure for bearing capacity analysis of framework of the steelmaking shop is also possible.

1. Introduction
Aerodynamic forces of various directions act on a structure placed in the wind flow (drag forces, lifting forces, and sometimes torque). The wind load on a building depends on a large number of factors, these include: the climatic area of construction, the conditions of the surrounding area (the presence of neighboring buildings, their height, building density, etc.), the shape and size of the structure, the framework rigidity, natural frequencies and mode shapes of the building, etc.

Flexible structures with weak damping properties (high-rise buildings, power transmission towers, antenna towers, other tower structures) are especially sensitive to the wind exposure. For these buildings, the wind load is the main horizontal load and has a significant effect on the forces and displacements that occur in the frame elements. That is why, the correct determination of the wind
load for such structures is a very important problem for safe and economical design. Determination of the aerodynamic characteristics of the structure can be carried out experimentally on models using a wind tunnel, or by numerical methods, by solving three-dimensional problems of fluid dynamics.

Presented in the literature modern studies of wind load are mainly performed especially for high-rise buildings.

Articles [1-11] present the results of an experimental assessment of the wind load on high-rise structures made in a wind tunnel. The influence of the shape and profile (stepped, tapered, the presence of curves or chamfers of corners) of the structure on the distribution of wind load is studied.

It was shown [6, 7] that the shape of the building in plan, the plan aspect ratio and dimensions have an effect on the distribution of aerodynamic coefficients. So, for buildings with the same shape in plan, but with a different aspect ratio, the distribution of wind pressures on the surface is different.

In paper [10] complex plan shapes of high-rise structures (L-, T-shaped) are considered. It is shown that the distribution of wind load in this case is very different from buildings with square plan.

In the studies of Chinese authors, field measurements of wind load are carried out on existing high-rise buildings with a height of 420.5 m in Shanghai [12] and 600 m in Shenzhen [13], and model tests in a wind tunnel are also performed. The results, both in the wind tunnel and on the full-scale model - the building itself, can later be used for the design of new super-tall buildings.

However, performing full-scale measurements and experimental studies in a wind tunnel is often a rather expensive and long-term process. An alternative to such studies is the use of computational fluid dynamics (CFD) and numerical analysis [14-17].

Since the wind load has one of the main effects on a high-rise building, the reduction of this load is one of the tasks that must be performed during the design. A number of papers are devoted to aerodynamic optimization of the shape of the high-rise buildings [18-20]. Aerodynamic optimization of the building shape is carried out to reduce wind load. However, the most optimal shape of the building that allows to decrease the wind load on building may not always be implemented, due to the fact that it does not meet the architectural requirements for the building, and may also be disadvantageous in terms of cost. That is why, aerodynamic optimization should be performed taking into account these factors also [20].

2. Materials and methods

In this paper the determination of wind load on the building of the Steelmaking Shop No. 2 of Novolipetsk steel (NLMK) is considered.

The Steelmaking Shop No. 2 of NLMK is an uneven structure in height and in plan (figure 1). The total dimensions in the plan are 340x133.5 m. The maximum height is 83.25 m. Taking into account the dangers of the production processes carried out in the steelmaking shop, it refers to the construction of a high level of responsibility. The steelmaking shop is located in Lipetsk.

![Figure 1. The Steelmaking Shop No. 2 of NLMK](image-url)
results of numerical simulation of wind aerodynamics in modern verified licensed software packages using computational fluid dynamics.

The velocity head of the free undisturbed wind flow is:

\[ p = \frac{\rho v^2}{2}, \]

where \( \rho \) – air density, kg/m\(^3\); \( v \) – velocity of wind flow, m/s.

Local wind pressure on the walls and roof of the building is expressed through the velocity head of the free flow:

\[ p_{loc} = \frac{\rho v^2}{2} C_p, \]

where \( C_p \) – aerodynamic coefficient (coefficient of wind pressure).

The aerodynamic coefficient depends on the direction of wind action on the structure and on the Reynolds number \( Re \), which characterizes the dependence on air viscosity.

The Reynolds number

\[ Re = \frac{\nu d}{v}, \]

where \( d \) – characteristic size of the buildings in a direction perpendicular to the wind direction; \( \nu = \mu / \rho \) – kinematic viscosity of air; \( \mu \) – dynamic viscosity of air.

The numerical analysis was performed using the Abaqus software package, which implements the solution of the three-dimensional hydrodynamic equation (Navier-Stokes equation) based on hybrid finite-volume and finite-element method.

The provisions given in [21-24] are used to perform the numerical analysis. A task similar to testing the model in a wind tunnel was simulated.

Figure 2. Numerical model a) calculated air zone; b) mesh with the approximate global size of elements 10 m
Taken into account the maximum height of the considered steelmaking shop equal to 83.25 m to comply with the minimum dimensions of the calculated air zone \([24]\), the air zone with dimensions of 2050 m x 986 m x 510 m is simulated (figure 2).

The action of the wind on the front side of the shop is considered. Calculated wind speed is taken equal to 22 m/s.

Thus, the following boundary conditions are applied: on flow inlet velocity \(v_x = 22\) m/s; on flow outlet pressure is equal to zero \(p = 0\) Pa, no slip wall boundary conditions are assigned and velocities on top of the air zone are taken equal to zero – \(v_x = v_y = v_z = 0\).

The air temperature of 20 °C is taken in analysis. At this temperature, the air density is \(\rho = 1.205\) kg/m\(^3\); air dynamic viscosity \(\mu = 1.81 \cdot 10^{-5}\) Pa · s.

Tetrahedral (FC3D4) finite elements are used. The meshes with the following approximate global size of elements are considered: 10 m (Mesh 10), 12 m (Mesh 12), 16 m (Mesh 16) and 20 m (Mesh 20).

CFD analysis is an iterative process. Wind velocity is applied over a time period of 30 s. Time incrementation is assigned automatic. Laminar flow is considered.

The convergence of the numerical solution is evaluated. The values of maximum positive wind pressures on the wall of the shop obtained at different times of wind velocity application and their errors in comparison when the wind velocity applied in 30 s period of time are represented in table 1. The graph of wind pressures dependence on time of wind velocity application for different meshes is shown on figure 3.

![Pressure, Pa vs Time, s graph](image)

**Figure 3.** The graph of maximum positive wind pressures dependence on load application time for different meshes

As can be seen in the graph, with an increase of time of wind velocity application, the pressures asymptotically tend to a certain value. This is observed for all meshes. The errors of pressure determined at 10 seconds time intervals of applying the wind velocity compared to the pressure obtained when applying the wind velocity in 30 seconds for dense meshes (Mesh 10, Mesh 12 and Mesh 6) is not more than 1%. For Mesh 20 this accuracy is achieved in 20 seconds time of wind velocity application. Thus, good numerical analysis convergence is obtained.
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Table 1. Maximum positive wind pressures depending on load application time for different meshes

| Mesh   | Mesh 10     | Mesh 12     | Mesh 16     | Mesh 20     |
|--------|-------------|-------------|-------------|-------------|
| Time   | Pressure P, Pa | Error     | Pressure P, Pa | Error     | Pressure P, Pa | Error     | Pressure P, Pa | Error     |
| 2      | 297.7       | 2.80%       | 290.8       | 5.32%       | 286.3       | 1.92%       | 277.3       | 3.62%       |
| 4      | 292.4       | 0.97%       | 284.5       | 3.04%       | 284.8       | 1.39%       | 269.3       | 0.64%       |
| 6      | 289.5       | -0.03%      | 281.8       | 2.06%       | 282.7       | 0.64%       | 263.4       | -1.57%      |
| 8      | 288.9       | -0.24%      | 279.8       | 1.34%       | 281.2       | 0.11%       | 262.2       | -2.02%      |
| 10     | 288.8       | -0.28%      | 278.5       | 0.87%       | 280.2       | -0.25%      | 261.6       | -2.24%      |
| 12     | 288.6       | -0.35%      | 277.6       | 0.54%       | 279.6       | -0.46%      | 264.6       | -1.12%      |
| 14     | 288.6       | -0.35%      | 277.1       | 0.36%       | 279.6       | -0.46%      | 264.3       | -1.23%      |
| 16     | 288.8       | -0.28%      | 276.9       | 0.29%       | 279.7       | -0.43%      | 262.7       | -1.83%      |
| 18     | 289.4       | -0.07%      | 277.0       | 0.33%       | 280.1       | -0.28%      | 264.6       | -1.12%      |
| 20     | 289.9       | 0.10%       | 277.0       | 0.33%       | 280.4       | -0.18%      | 266.6       | -0.37%      |
| 22     | 289.9       | 0.10%       | 276.8       | 0.25%       | 280.4       | -0.18%      | 268.3       | 0.26%       |
| 24     | 289.7       | 0.03%       | 276.6       | 0.18%       | 280.4       | -0.18%      | 268.4       | 0.30%       |
| 26     | 289.7       | 0.03%       | 276.3       | 0.07%       | 280.6       | -0.11%      | 267.6       | 0.00%       |
| 28     | 289.6       | 0.00%       | 276.1       | 0.00%       | 280.7       | -0.07%      | 267.7       | 0.04%       |
| 30     | 289.6       | -          | 276.1       | -          | 280.9       | -          | 267.6       | -          |

The values of maximum wind pressures obtained for different meshes are close to each other. The average pressure for considered meshes at time 30 s is 278.55 Pa. The difference in pressures obtained with different meshes from the average pressure value is not more than 5%. Thus, the considered meshes can be used to determine wind pressures.

Analysis run time for different meshes is shown in table 2. The notebook with 2.9 GHz 4-core Intel Core i7-7820HQ CPU and 16Gb of RAM is used.

Table 2. Analysis run time for different meshes

| Mesh | Mesh 10 | Mesh 12 | Mesh 16 | Mesh 20 |
|------|---------|---------|---------|---------|
| Approximate global size of element, m | 10 | 12 | 16 | 20 |
| Number of elements | 2458747 | 1653029 | 877320 | 524725 |
| Analysis run time, s | 40780 | 20194 | 15390 | 6047 |
| Analysis run time, h | 11.3 | 5.6 | 4.3 | 1.7 |
3. Results
As a result of numerical analysis, local air pressures on the walls and roof of the steelmaking shop $p_{loc}$ are obtained.

Aerodynamic coefficients are determined as follow (see equations (1), (2)):

$$C_p = \frac{p_{loc}}{\rho v^2/2},$$  \hspace{1cm} (4)

The contour plots of local pressures on the walls and roof of the steelmaking shop and values of aerodynamic coefficients are shown on figures 4, 5.

![Contour plots of pressures (Pa) and values of aerodynamic coefficients on the walls of the steelmaking shop (a - windward wall; b - leeward wall)](image)

**Figure 4.** Contour plots of pressures (Pa) and values of aerodynamic coefficients on the walls of the steelmaking shop (a - windward wall; b - leeward wall)
Figure 5. Contour plots of pressures (Pa) and values of aerodynamic coefficients on the walls and roof of the steelmaking shop (a, b – side walls; c - roof)
As can be seen from contour plots, the aerodynamic coefficients decrease towards the top of the shop on windward side. And on the contrary in the zones of negative pressures the aerodynamic coefficients increase with the increasing height position.

4. Discussion
The determination of the wind load on buildings with a high level of responsibility in accordance with Russian standards is required to be performed on the basis of the results of an experimental wind tunnel test or numerical simulation. But quiet often industrial buildings with a high level of responsibility have a typical or close to typical shape, and their high level of responsibility is assigned due to the danger of the technological process carried out. The regulatory documents provide recommendations for determining the aerodynamic coefficients for buildings of various typical shapes.

For the considered steelmaking shop, the aerodynamic coefficients can be calculated using the recommendations of the Russian standard (SP20.13330.2016 “Loads and impacts”) as for typical scheme of rectangular building with ledges. The aerodynamic coefficients calculated by regulatory method are on average greater than those obtained by numerical calculation. Differences are observed in some local zones, and these effects should be taken into account when calculating enclosing structures in these zones, but on the entire framework of the shop this does not have a significant effect.

Besides, it should be noted that the wind load has a negligible effect on such a complex industrial structure as the steelmaking shop, in comparison with technological impacts. The effort in the main bearing structures from the wind load (columns, trusses, braces etc.) is not more than 10% of the total design effort, while the effort from the crane load is up to 45% of the total effort, and from the technological loads is up to 50% of the total effort. Thus, with sufficient accuracy for engineering calculation to ensure safe design, aerodynamic coefficients for the steelmaking shop can be assigned according to the regulatory method.

However, for unique high-rise buildings, where the wind load has one of the main effects on the framework, its correct accounting is very important and in this case, the determination of the wind load experimentally using a wind tunnel or using numerical modeling is necessary and appropriate.

So, the article [25] compares the aerodynamic drag coefficients of a building with a height of 93 m, obtained as a result of numerical simulation and calculated according to the Eurocode. Studies have shown that the values of the coefficients in the top of the building obtained numerically are smaller than those calculated by the standards. However, on average, the total moment at the base of the building by numerical calculation is greater. Thus, a certain part of wind load is underestimated in the European standards.

5. Conclusions
The aerodynamic coefficients are determined for the steelmaking shop by numerical simulation using the Abaqus software package.

Given that the contribution of wind load in total efforts arising in elements of the steelmaking shop framework is very insignificant (not more than 10% of the total effort) in comparison with technological impacts (up to 50% of the total effort), the calculation of the aerodynamic coefficients by the regulatory method may be quite sufficient for the engineering analysis of the entire framework of the shop and its safe design.

However, for analysis of the enclosed structures, fasteners of walling and roofing, for which the wind load is the main one the aerodynamic coefficients obtained by numerical methods should be used.
References

[1] Kumar H, Rajan S, Andrew A, Babu G., Naraganti S R and Jawahar J 2016 J. Civ. Eng. 17 (3) 325–33
[2] Kim Y C, Tamura Y, Tanaka H, Ohtake K, Bandi E and Yoshida A 2014 J. Wind Eng. Ind. Aerodyn. 133 191–99
[3] Kim Y C, Kand J 2013 J. Fluids Struct. 39 306–21
[4] Tanaka H, Tamura Y, Ohtake K, Nakai M and Kim Y C 2012 J. Wind Eng. Ind. Aerodyn. 107–108 179–91
[5] Kim Y and Kanda J 2010 J. Wind Eng. Ind. Aerodyn. 98(8–9) 449–65
[6] Amin J A and Ahuja A K 2014 Int. J. Adv. Struct. Eng. (IJASE) 6(3) 66
[7] Amin J A and Ahuja A K 2013 J. Struct. Article ID 176739
[8] Tanaka H, Tamura Y, Ohtake K, Nakai M and Kim Y C 2013 Int. J. High-Rise Build. (IJHRB) 2 213–88
[9] Sandeep Y, Raju V D and Kumar P R 2015 J. Mech. Civil Eng. (IOSR-JMCE) 12(5) 14–21
[10] Amin J A and Ahuja A K 2008 BBAA VI International Colloquium on Bluff Bodies Aerodynamics & Applications, Milano, Italy, July, 20-24
[11] Giappino S, Rosa L, Tomasini G and Zasso A 2016 Struct. Des. Tall Spec. Build 25(3) 139–57
[12] Li Q, Fu J Y, Xiao Y Q, Li Z N, Ni Z H, Xie Z-N and Gu M 2006 Eng. Struct. 28 1745–58
[13] Zhang J W and Li Q S 2017 Struct. Des. Tall Spec. Build. 26(17) e1385
[14] Daemei A B, Khotbehsara E M, Nobarani E M and Bahrami P 2019 Ain Shams Eng. J. 10(3) 541–48
[15] Guvernyuk S V, Egorichev O O, Isaev S A, Kornev N V and Poddaeva O I 2011 VESTNIK MGSU (Monthly J. on Const. and Architecture) 3 185–91
[16] Bairagi A K and Dalui S K 2018 Asian J Civ Eng 19 205–21
[17] Mou B, He B, Zhao D and Chau K 2017 Eng. Appl. Comput. Fluid Mech. 11(1) 293–309
[18] Xie J 2014 J. Wind Eng. Ind. Aerodyn. 130 88–98
[19] Elshaer A, Bitsuamlak G and Damatty A 2017 Eng. Struct. 136 133–148
[20] Xu Z and Xie J 2015 Wind Struct. 21(5) 505–21
[21] Dubinsky S I 2008 Int. J. of Comp. Civil and Struct. Eng. 4(2) 58–59
[22] Belostotsky A M, Dubinsky S I and Afanasyeva I N 2010 VESTNIK MGSU (Monthly J. on Const. and Architecture) 1 182–85
[23] Dubinsky S I and Bolotov P E 2011 VESTNIK MGSU (Monthly J. on Const. and Architecture) 7 276–82
[24] Dubinsky S I 2010 Numerical modeling of wind effects on tall buildings and complexes. PhD Thesis MSUCE Moscow 199 pp.
[25] Wahrhaftig A M and Silva M A 2017 Struct Des Tall Spec Build 27(3) e1442