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FEATURES OF NUMERICAL CALCULATION OF FREE-STANDING CHIMNEYS IN SOFTWARE PACKAGES (FEM ANALYSIS)

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1. Problem statement

Modern science uses a lot of calculation complexes/structures, each with its own advantages and disadvantages. An engineer seldomly takes into consideration or avoids simple analytical methods for solving problems and starts/prefers working with complex simulation programs. Sometimes this approach is justified by the results, but sometimes not. In this work we try to answer the question about the necessity and appropriateness of a «difficult/complicated» program for the calculation of structures, such as metal chimneys and give answers to the required degree of complexity.

According to the normative documents [1, 2, 7] and technical literature [5, 6, 11], metal chimneys should be calculated as cantilever beam-curved rods, fully clamped at the base. As experience shows [4] this is not always justified, especially when checking calculations are conducted/performed in the exploitation stage/phase of such structures, when different kinds of geometrical deviations in form of various dimples, burnouts, docking drawer side with eccentricity and elhptical cyhnder shells should be considered. In modern world there are separate research centers, where the behavior of structures is studied by creating design models as close as possible to the real structures. There are also new separate research centers, in which the behavior of structures is studied with the help of creating calculating schemes, which are also close to the real structures. For example, the solid modehng of buildings and structures, that takes into account additional factors which affect the performance of such structures, and, therefore, the stress-strain state. Some of these factors are: taking into account the foundation, the base, different ways of modehng and adding the stresses, using different calculation schemes and methods of computing [3, 9]. Normally, for all types of construction and calculating cases (for example, accounting for the geometrical deviations) it is necessary to define the most suitable method of calculation, because it would allow to get the stress-strain state (hereinafter SSS) model in practice, which is close to the real one.

It is necessary to check whether the given complexities are justified and allow us to determine the SSS structure more accurate, and therefore to get more precise results in comparison with simple analytical models, since these complexities always require/demand high expenses of time and knowledge.

2. The aim of the research

On the base of comparative calculation we try to determine the most rational calculation schemes and methods to determine the stress-strain state of such structures in the design phase (ideal cyhndrical shell) and in the checking phase (example of imperfect cylindrical shell with geometrical deviation in a dimple form). Therefore it is necessary to determine the impact of the base and other factors (in our case – geometrical deviation in form of a dimple) on the SSS structure.

3. Object of research

The objects of research are steel chimneys. A chimney is a tall cylindrical structure, used for exhausting gases to the outside atmosphere and for their subsequent dispersion. The steel industrial chimneys are divided into free-standing, supported by rigid braces or braces, and those with a lattice frame (extraction tower). The main types of steel chimneys are shown in Figure 1.

a) *b)* *c)*

Figure 1. The main types of steel chimneys: a) free-standing; b) supported by braces; c) with lattice frame

The main types of calculated loads on chimneys (by [10]) are divided into permanent and temporary.

Permanent loads:
- net weight of the construction;
- weight of lining and additional equipment.

Temporary loads:
- impact of wind;
- internal pressure;
- temperature effect;
- icing;
- special types of impact (seismic, emergency, chemical exposure).

In this paper the effect of geometrical variations on the SSS of steel chimneys was considered. The areas with geometrical deviations represent zones with local perturbations. The areas with edge effect (sudden change in cross-section) and those with locally applied loads (intersection joint of braces) are also considered zones with local perturbations (by [8]).

4. Main material

In this work a steel chimney with height H = 60 m, diameter D = 3.0 m and thickness of t = 10 mm was investigated.

The calculations included the self-weight of the structure, the line weight of the fireclay brick (width of brickwork b_{fut} = 144 mm, density p = 1900 kg/m^3) and the wind load with its characteristic value taken in accordance to [2] W = 600 Pa.

There were compared four calculation schemes to determine the SSS of the chimney: cantilever rod of constant cross section; spatial ideal cylindrical shell; spatial ideal cylindrical shell which includes the base and foundation; spatial imperfect cylindrical shell with a geometrical deviation in form of a dimple/a dimple form.

The methods of calculation and boundary conditions, adopted in this study to determine the SSS for the freestanding chimney, are the following:

- For the calculation scheme 1, the analytical method of calculation was adopted, the same as for the rigidly clamped cantilever rod. Determine the main characteristic of SSS – the main stresses σ_x;
- For the calculation scheme 2, according to [9, 10], linear-resilient method of calculating the shell (LA) was adopted with the definition of the primary stresses, in our case - the equivalent stress σ_{eq} (von Mises stress). The cylindrical shell is considered as ideal rigidly clamped at the base;
- For the calculation scheme 3, the same calculation method as for scheme 2 was adopted, considering in addition the effects of the fixed base connection with the foundation;
- For the calculation scheme 4, according to [9], physically and geometrically nonlinear analysis with the defects (GMNIA) was adopted together with the definition of the primary stress (von Mises stress). The cylindrical shell is considered to be imperfect, having a geometrical deviation.

4.1 Discretization of the models

The selection of the Finite Element (hereinafter FE) size for the calculation models 2-4 represented the basis for the preliminary calculation and dimensioning of FE, whereas its subsequent reduction does not affect the results of the calculation or have very little impact (up to 3%). The comparison was made in terms of equivalent stresses (σ_{eq}) and the following dimensions of FE were used:

- in the calculation schemes 2 and 3 the first 5 meters starting from the base of the computational model were divided into FE with size of *50x50 mm*, and all the rest with *200x200 mm*;
- in calculation scheme 4, the same first 5 meters were divided into FE with size of *25x25 mm*; and a FE mesh refinement (maximum size of *5x5 mm*) was provided in the zone of geometrical deviation.

4.2 Calculation scheme 1

The fixed supported cantilever of constant cross-section was adopted as calculation scheme according to [1].

The principal stress in the trunk of the steel chimney was calculated by the formula:

$$\sigma = N / F + M / W \le R_y \gamma_c \qquad (1)$$

where N is the longitudinal calculated force from vertical loads; M denotes the calculated bending moment from the horizontal loads; $A = 2\pi rt$ is cross sectional area of the chimney shell; $W = \pi r^2 t$ the section modulus of the chimney shell; r and t are radius–and thickness of the shell.

The loading scheme of this computational model is presented in Figure 2. The model is divided into 12 equal parts - each by *5 m*. Figure 2 shows the following symbols: q_h, *1* ... q_h, *12* - wind load on the section of the chimney, according to [2]; q_v, *1* ... q_v, *12* gravity load of the chimney; q_f,*1* ... q_f,*12* - line loads . The values of q_h and q_f are constant for each segment of the model.

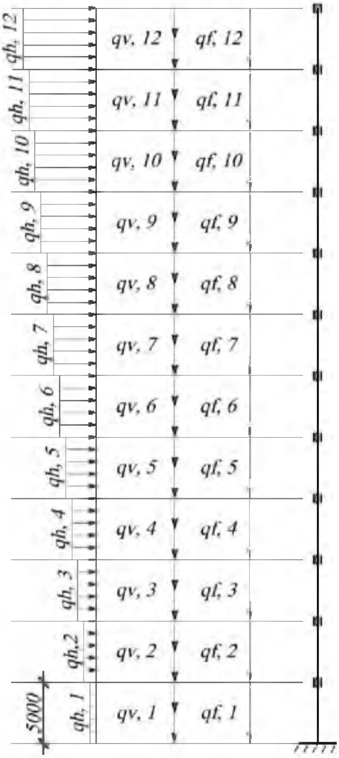


Figure 2. Calculation scheme of the chimney modeled as a cantilever rod

4.3 Calculation scheme 2

A spatial thin sheet cylindrical perfect shell is adopted as calculation scheme, modeled in the finite element software package ANSYS Workbench 14.0. The values of the equivalent stress (σ_{eq}) are defined directly in the software package by (von Mises stress):

$$\sigma_{eq} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x \sigma_y + 3\tau_{xy}^2} \qquad (2)$$

The loading scheme of this computational model is presented in Figure 3.

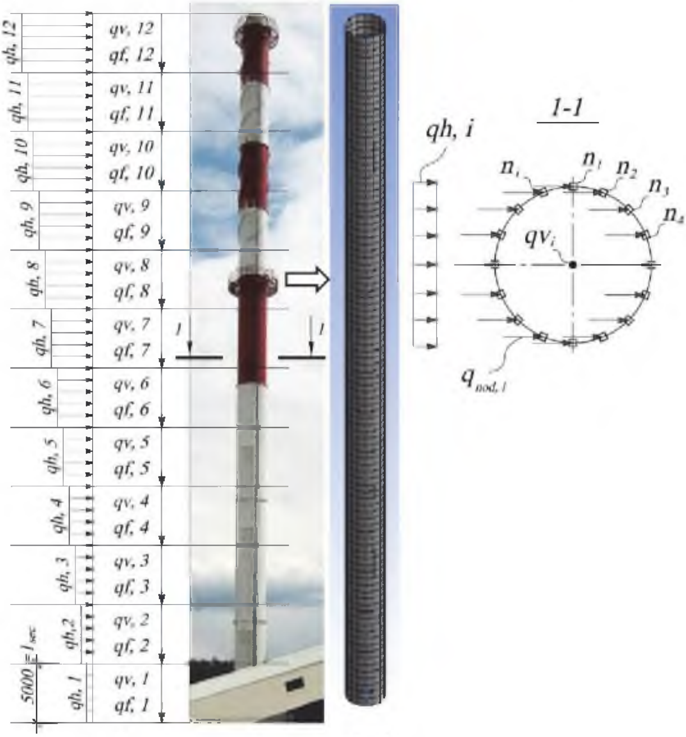


Figure 3. Calculation scheme of the pile in the PC ANSYS

The wind pressure for the calculation scheme is defined by [2] the same as for the calculation scheme 1.

The wind load is applied in the PC ANSYS model as follows (Figure 3):

- first we find qh_i, the distributed wind load in N/m, for the cantilever rod:

$$qh_i = Wm_i \cdot d \qquad (3)$$

- find the concentrated load on each node :

$$q_{nod,i} = qh_i \cdot l_{sec} / N \qquad (4)$$

where, Wm_i - wind pressure on one side in accordance with [2];
d - chimneys diameter;
l_{sec} - height of section of design model;
N - number of nodes for each side.

The counting of the number of nodes and the application of the wind load are done automatically with the help of a special macro, which was created in the programming APDL (ANSYS Parametric Design Language).

This macro allows performing calculation and application of wind loads automatically. The universality of this macro consists in determining the wind loads in all regions of Ukraine, as well as in the calculation of a chimney with any diameter and height (it is also possible to consider the conical part of chimney, the parameters of the lining); with the help of command inserts APDL, point masses are added to the model, which simulate the mass and inertial characteristics of the linear sector, considering the forces as applied to the support lining ribs.

4.4 Calculation scheme 3

A thin sheet perfect cylindrical shell modeled together with the foundation and the base was adopted in the PC ANSYS as calculation scheme following the “chimney-foundation-base” typology. The values of the equivalent stress (σ_{eq}) are defined dlrectly by the software (Formula 2).

The loading scheme and the application of the wind load on the model is similar to calculation scheme 2.

This paper examines the influence of 3 base types on the SSS structure defined by a high, medium and minimum elastic modulus (E_b), of 50 MPa, 30 MPa and 15 MPa, respectively. A general view of the calculation scheme is shown in Figure 4.

The results of comparative calculations are shown in Table 1.

This model is fully parameterized. It means that during the creation of the calculation scheme, each geometrical and physical characteristics of the chimney have been already set to a specific parameter, for example, the height of chimney - P1, the diameter of chimney - P2, and so on. When changing these values in parameter set the geometrical model of the chimney is also automatically changing, and it is important, that the whole computational model will be recalculated automatically.

The next parameters can be changed with the parameter set:

- The height, diameter, thickness and material of the chimney
  (it is also possible to take into account the cohical part and its characteristics);
- With or without lining. The material, width and height of the lining;
- Geometrical dimension and material of foundation;
- Poisson's ratio and elastic modulus of the base;
- Wind pressure in all regions of Ukraine
  (it is also possible to get any wind pressure value in *Pa*).

Table 1.

The value of σ_{eq} and the horizontal deflection at the top (f_{ch}) of the chimney.

E_b, MPa	σ_{eq}, MPa	f_{ch}, mm
15	96,0	353
30	96,0	276
50	96,0	245

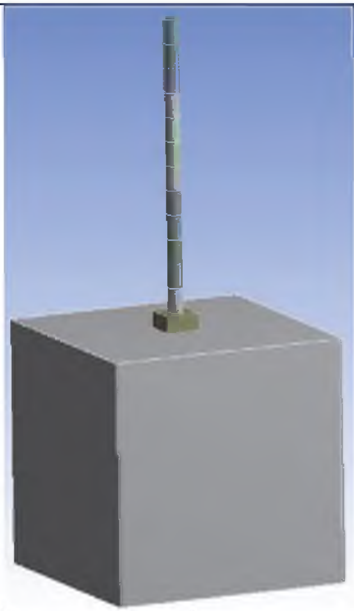


Figure 4. General view of the calculation scheme "chimney - foundation - base"

The main features of the parameterization

Creating the calculation model takes more time than in other cases, because it is important to set the parameters of major variables (height, diameter, thickness of the model, the number of edges, etc.), but the subsequent adjustment of the project takes less time and effort. The researcher spends time not on the creation of a new computational model, but on the study of the behavior of several structures by adjusting different variables of the existing model.

The creation of the parametric model will allow the following:

- calculating all interesting options of the computational model immediately;
- receiving analytical dependence (as in the two-dimensional formulation - two parameters, and in three-dimensional - the influence of two variables on the third one);
- finding the optimal construction design solutions with the parameters set (minimizing the weight or reducing the stress, applying the greatest safety factor, etc.) or a combination of them;
- performing the experimental planning and constructing/obtaining the response curves;
- performing a sensitivity analysis from various input parameters (to determine which parameters are most important to the model, and hence have the greatest influence on SSS).

4.5 Calculation scheme 4

A dimensional thin-sheet imperfect cylindrical shell, modeled with a geometric deviation as a local dimple was adopted as a calculation model. This model is similar to the calculated model 2 that includes a geometrical deviation.

The local dimple has a size of *200x200 mm* and a depth equal to the thickness of the shell (*10 mm*). The general view of the section with the dimple is shown in Figure 5.

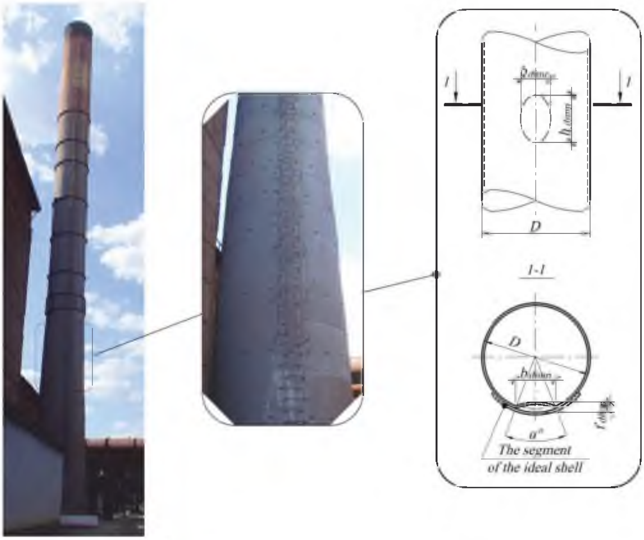


Figure 5. General view of the section with the dimple through the steel chimney.

The dimple is characterized/defined by the next parameters:

- angle of the dimple ($\alpha°$);
- width of the dimple (b_{dimp});
- height of the dimple (h_{dimp});
- depth of the dimple (f_{dimp}).

This computational model is also parameterized. In addition to various parameters of the chimney it is possible to change the size (height, width and depth), and also the location of the dimple.

The impact of the dimple location on SSS was determined by the height of the calculation model. The dimple was modeled at a distance of *0.1 to 0.5 m* from the base. The values of equivalent stresses in the shell ($\sigma_{eq,sh}$), the equivalent stresses in the dimple zone ($\sigma_{eq,dimp}$) and the concentration ratio (k_f) are shown in Table 2. The deflection at the top of the chimney is for all the calculated cases of *212 mm*.

From the results we obtain the dependence approximated by a 3rd order polynomial, as shown in Figure 6.

Table 2.

Values of σ_{eq} and k_f for different heights of the dimple.

Height from the base, mm	$\sigma_{eq.sh}$, MPa	$\sigma_{eq.dimp}$, MPa	k_f
0,1	104,9	166,4	1,6
0,2	104,9	173,9	1,7
0,3	104,9	175,7	1,7
0,4	104,9	177,1	1,7
0,5	104,9	176,1	1,7
0,6	104,9	176,9	1,7
0,7	104,9	175,7	1,7
0,8	104,9	176,4	1,7
0,9	104,9	175,4	1,7
1,0	104,9	174,8	1,7

4.6 Comparison of equivalent stresses (σ_{eq}) for four calculated schemes

The analysis of the stress-strain state of the four calculated schemes allowed identifying the maximum stress and deflection at the top of the chimney, as shown in Table 3.

Table 3.

Maximum stress and deflection at the top of the chimney for different types of calculation schemes (CS).

The rod model (PC.1)		The shell model (PC.2)		The model with a base, Eb = 50 MPa (PC.3)		The model with a dimple (PC.4) (+0,500)	
σ, MPa	fch, mm	σeq, MPa	fch, mm	σeq, MPa	fch, mm	σeq, MPa	fch, mm
92,1	214	104,9	199	96,0	245	176,1	212,2

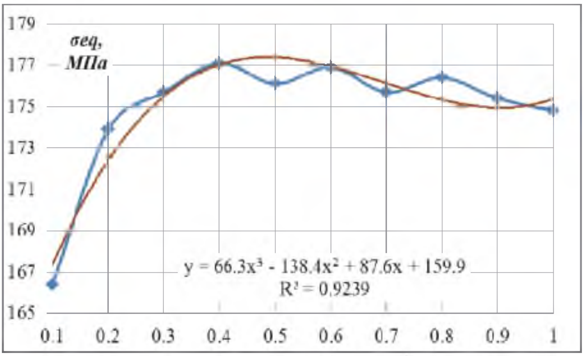
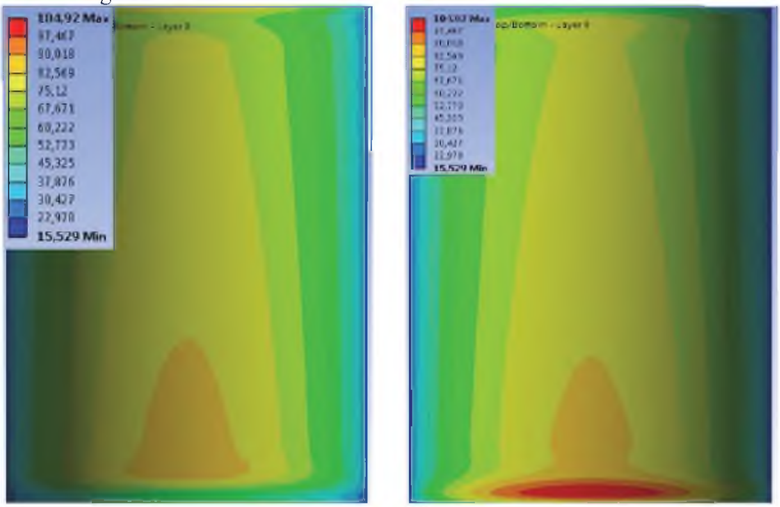


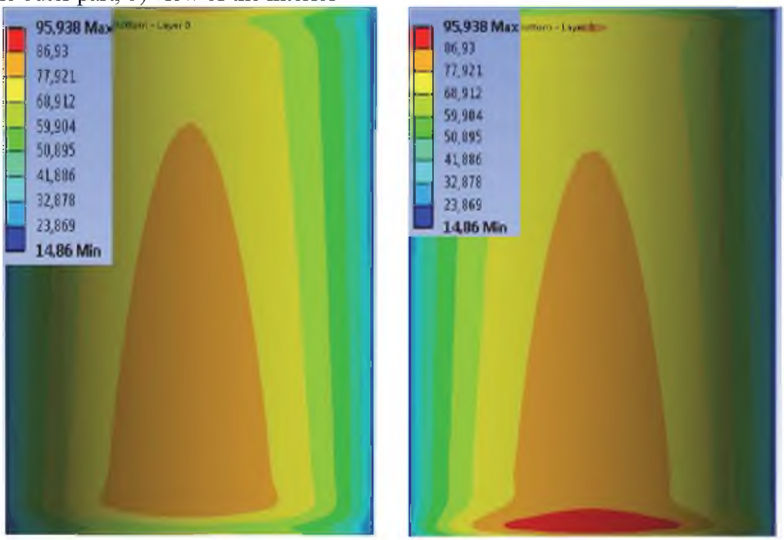
Figure 6. The influence of the location of the dimple on the SSS of the chimney, where the red line is results of calculation and the blue line comes from 3rd order polynomial.

The models with the reduced stresses distribution (AED) are shown in Figures 7-9. The height is 5 *m*.



a) *b)*

Figure 7. Distribution of σ_{eq} on the calculated shell model (PC.2): a) view of the outer part, б) view of the interior



a) *b)*

Figure 8 Distribution of σ_{eq} on the calculated shell model with the base (PC.3): a) view of the outer part, b) view of the interior.

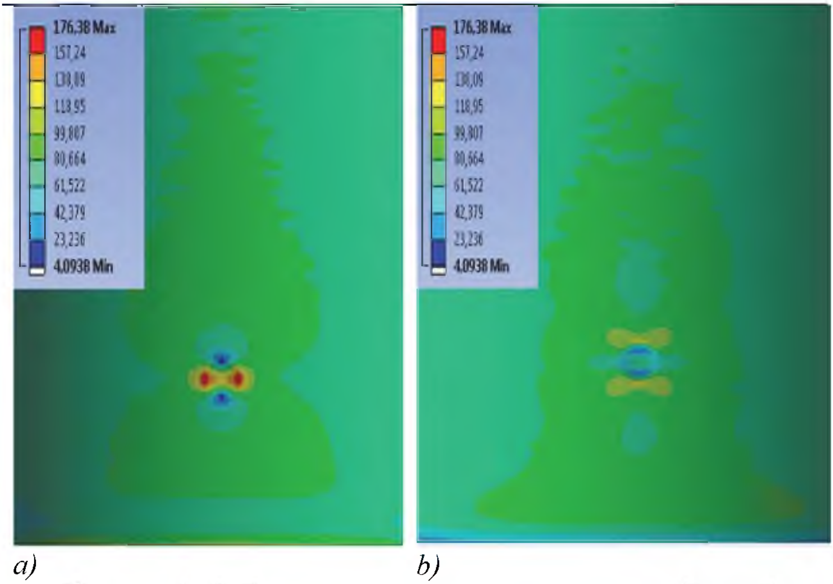


Figure 9. Distribution of σ_{eq} on the calculated shell model with the dimple (PC.4): a) view of the outer part, b) view of the interior

Conclusion

1. The analysis of chimneys according to calculation schemes 1-3 gives close values of maximum stresses. The difference between the calculated schemes 1 and 2 is 14%, and between 1 and 3 is only 4%.
2. Including the base in the calculation model, increases the deflection at the top of the chimney by 1,3 - 1,8 times in comparison with 1and 2 calculation schemes.
3. In the dimple zone a local stress disturbance occurs, which, is not considered in Ukrainian regulations or norms at the moment. To account such deviations a geometrical modeling should be performed with the help of modern software packages.
4. It seems therefore necessary to investigate the stability of the existing models of chimneys and different types of geometrical deviations.

Further ways of investigation

- Considering the chimney supported by braces model, as a "chimney supported by braces - foundation - base" calculation scheme. Determining the influence of the base on SSS for this type of structures;
- Considering different options to model the wind load for this type of structures: the same for cylindrical shells with big diameter (tanks);
- Using the hydrodynamic modeling CFX package in ANSYS to determine realistic wind load distribution on structures which permits a more precise strength calculation.

These researches will allow determining the most rational schemes to apply wind pressures on such structures, both at the protecting stage (ideal construction), and at the operation stage (design with geometric deviations). And even to get quantifying factors for the simplest schemes (calculating the chimney as a fixed cantilever rod).

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REFERENCES

1 DBN B.2.6-163:2010. The constructions of buildings and structures. The steel constructions. Norms for design, fabrication and erection. Kyiv: Ministry of Regional Development of Ukraine, 2011. 127 p. (in Ukrainian).

2 DBN B.1.2-2:2006. National Structural Rules and Regulations. The system of reliability and safety provision of constructional projects. Loads and effects. Kyiv: Minbud of Ukraine, 2006. 61 p. (in Ukrainian).

3 DIN 4133:2006-08: Schornsteine aus Stahl.

4 Gubanov, V. V.; Golikov, A. V. Calculation and gas pipes with local stresses. In: Proceeding of the Donbas National Academy of Civil Engineering and Architecture, 2009,Issue 2009-4(78): Towers: building materials, structures, processes, p. 215–220. (in Russian).

5 Elshin, A. M.; Izhorin, M. N.; Zholudov, V. S.; Ovcharenko, E. G. Edited by Satianov, S. V. Chimneys. Moscow: Stroiizdat, 2001. 296 p. (in Russian).

6 Edited by Gorev, V. V. Metal Constructions. In three volumes. Volume 3. Steel designs. Moscow: Highschool, 2002. 544 p. (in Russian).

7 SNiP 2.09.03-85. Construction rules and regulations. Structures for industrial installations. Moscow: TsITP Gosstroia USSR, 1986. 56 p. (in Russian).

8 Solodar, M. B.; Kuznetsova, M. V.; Plishkin, Yu. S. Steel designs of towers. Leningrad: Stroiizdat, 1975. 186 p. (in Russian).

9 EN 1993-1-6: Design of steel structures - Part 1-6: Strength and stability of shell structures.

10 EN 1993-3-2: Design of steel structures - Part 3-2: Towers, masts and chimneys – Chimneys.

11 Donnell LH. Beams, plates and shells. New York: McGraw Hill; 1976.