ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ СОФИЯ

Том Volume 54 | 2021 | Брой Issue 3

ANNUAL OF THE UNIVERSITY OF ARCHITECTURE, CIVIL ENGINEERING AND GEODESY SOFIA

Received: 07.05.2021
Accepted: 17.05.2021

WIND LOADS ON ROOFS ON CIRCULAR BASE

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Keywords: *vertical tank, cone and dome roofs, wind pressure, standard, FEA*

ABSTRACT

Due to the replacement of the stored product, the working conditions of a tank with a V2000 m^3 capacity and a supported cone roof will be changed. It should be checked for sufficient bearing capacity. Part of calculations includes testing for the complete displacement of an empty tank, loaded by wind and overpressure. When the conical roof is surrounded by a stream of wind, it results in forces acting from the bottom up, which, combined with the overpressure, could lead to a complete lifting of the facility.

Considered here conical roof is outside the scope of application of standards EN 1991-1-4 or Ordinance №. 3 of 2004. This enforced the author to proceed as follows:

a) to look for other standards that address the wind load on cone roof and to compare the obtained results;

b) to create computer models of the airflow around the tank, which have two types of roofs - conical and spherical. Through them he tried to determine:

- the values of wind pressure on the two types of roofs;
- is there a considerable difference in wind load on spherical and conical roofs.

From the numerical modelling and analysis of the tanks, it was found that the wind pressure was different for conical and spherical roofs, even if they have the same height.

1. Introduction

The stored product in the tank with volume 2000 m^3 and supported cone roof will be changed from petroleum to concentrated sulphuric acid. As it will change the exploitation conditions and as the facility is designed and constructed at the end of the last century, according

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to the current time rules, the facility should be checked if it has sufficient bearing capacity. One part of the check includes verification of the total displacement of the empty tank, loaded by wind and internal pressure.

When the wind flows around the conical roof that leads to appearing of uplifting forces that act down-top. These forces, in combination with overpressure, can lead to total uplifting of the facility. The wind forces acting on the roof can be determined according to БДС EN 1991-1-4 [1] or Ordinance №3 [2], but these documents contain limitations as follow:

a) according to БДС EN 1991-1-4 the roof has to be spherical;

b) according to Ordinance №3 the roof could be spherical or conical, but the last is limited to the maximum angle of inclination $\alpha \leq 5°$.

As the tank with a volume 2000 m^3 which is subject to this research has supported cone roof with an inclination $\alpha = 7{,}13° > 5°$, the facility is not in the scope of the above-mentioned documents. This led the author to proceed as follows:

a) to look for other standards that treat the wind loading on conical roofs and to compare the obtained results;

b) to create computer models of wind flow around the tanks with two types of roofs - conical and spherical. Through them are determined:

- the value of the pressure on the two types of roofs;
- is there a considerable difference in the wind load on spherical and conical roofs.

2. Analytical calculation of the wind loading of the roof

Using the methodology, shown in standard БДС EN 1991-1-4 [1], the author determined peak velocity pressure of the wind $q_p(z)$, having the following basic conditions:

a) basic speed of the wind at the height 10 m above the ground level – v_b = 33 m/s;

b) category of the field – III;

c) design heights z_e above the ground level:

- the joint of the shell with the roof, i.e. point „A“ and „C“, see fig. 1 - z_e = 12,4 m;
- the highest point of the roof, i.e. point „B“, see fig. 1 - z_e = 13,35 m;
- on the middle points between „A“ and „B“, respectively „B“ и „C“ - z_e = 12,875 m.

The wind pressure w_e, applied on the external surface of the construction is calculated according to the formula:

$$w_e = q_p(z_e).c_{pe}\,, \qquad (1)$$

where z_e is the design height of the external surface above the ground level;

$q_p(z_e)$ – the value of wind flow pressure at the height z_e;

c_{pe} – pressure coefficient when the wind flows around the surface.

In addition to the two simultaneously actual standards in Bulgaria БДС EN 1991-1-4 [1] and Ordinance №3 [2], the author obtained several foreign documents referring to the wind loading on the structures. The author used the values of the pressure coefficient c_{pe} mentioned in those documents to calculate the values of the wind pressure w_e.

2.1. Standard БДС EN 1991-1-4 of 2005

The fig. 1 shows that the methodology in the standard has to be applied for spherical domes on the circular base.

The values of the pressure coefficient c_{pe} are calculated through the correlation of h/d and f/d, see fig. 1.

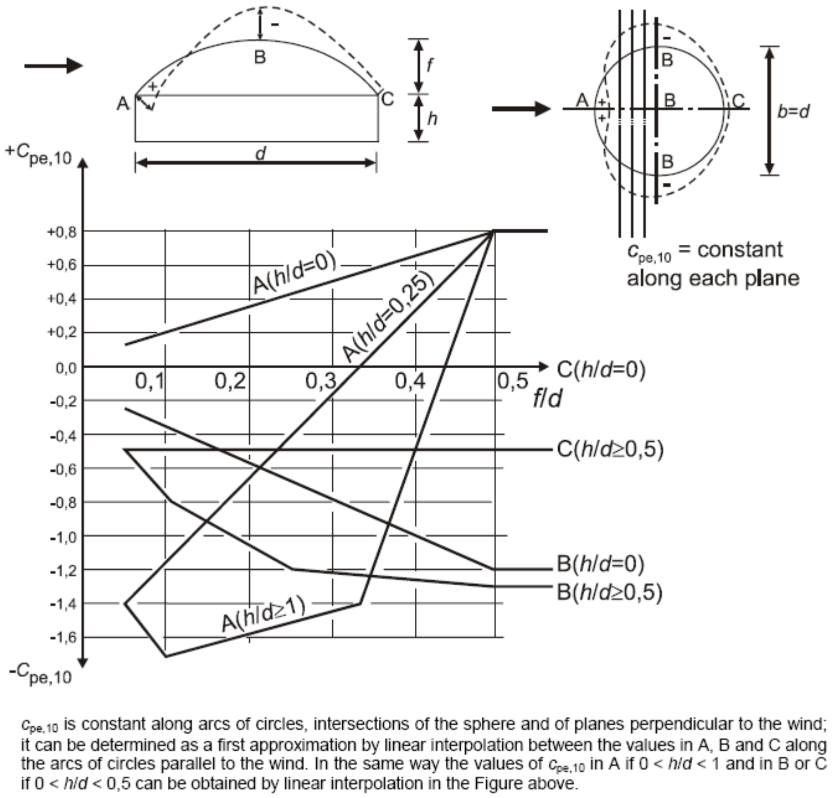


Fig. 1. External pressure coefficients $c_{pe,10}$ for domes with circular base [1]

In this concrete study, the parameters of the tank and its roof are as follows:
- the height of the tank shell h = 11,92 m;
- diameter of the tank d = 15,18 m;
- the height of the roof f = 0,95 m.

$$\frac{h}{d} = \frac{11{,}92}{15{,}18} = 0{,}785 \qquad (2)$$

$$\frac{f}{d} = \frac{0{,}95}{15{,}18} = 0{,}0626 \qquad (3)$$

Point “A”, the place of joint between roof and shell, windward side:

$c_{pe,A}$ = -1,4

$w_{e,A} = q_p(12{,}4).\ c_{pe,A}$ = 1,301.(-1,40) = -1,821 kN/m^2

Point “B”, roof’s middle:
$c_{pe,B}$ = -0,49
$w_{e,B} = q_p(13,35).\ c_{pe,B}$ = 1,333.(-0,49) = -0,653 kN/m^2

Point “C”, place of joint between roof and shell, leeward side:
$c_{pe,C}$ = -0,49
$w_{e,C} = q_p(12,4).\ c_{pe,C}$ = 1,301.(-0,49) = -0,637 kN/m^2

Point “AB”, on the middle between points „A“ and „B“:
$c_{pe,AB}$ = -0,945
$w_{e,AB} = q_p(12,875).\ c_{pe,AB}$ = 1,311.(-0,945) = -1,239 kN/m^2

Point “BC”, on the middle between points „B“ and „C“:
$c_{pe,BC}$ = -0,49
$w_{e,BC} = q_p(12,875).\ c_{pe,BC}$ = 1,311.(-0,49) = -0,642 kN/m^2

The average value of the wind pressure will be calculated according to the formula:

$$w_{e,m} = \frac{A_1}{A}\left(w_{e,A} + w_{e,C}\right) + \frac{A_2}{A}\left(w_{e,AB} + w_{e,BC}\right) + \frac{A_3}{A} w_{e,AB} =$$
$$= \frac{13,06}{181}\left(-1,821 - 0,637\right) + \frac{48,93}{181}\left(-1,239 - 0,642\right) + \frac{57}{181} \cdot \left(-0,653\right) = -0,892 \text{ kN/m}^2 \quad , \quad (4)$$

where A_1 is a horizontal projection of the roof’s area next to the points “A” or “C”;
A_2 – horizontal projection of the roof’s area around to the intermediate point “AB” or point “BC”;
A_3 – horizontal projection of the roof’s area around the middle point “B”;
$A = A_1 + A_2 + A_3$ – the whole horizontal projection of the area of the conical roof.

2.2. Ordinance №3 of 2004

The methodology used in the Ordinance №3 [2] is applicable to:
a) flat, conical roof in which the angle of inclination is $\alpha \leq 5°$;
b) spherical roof in which height f and the diameter d, see fig. 2, correspond to the correlation $f/d \leq 0,1$.

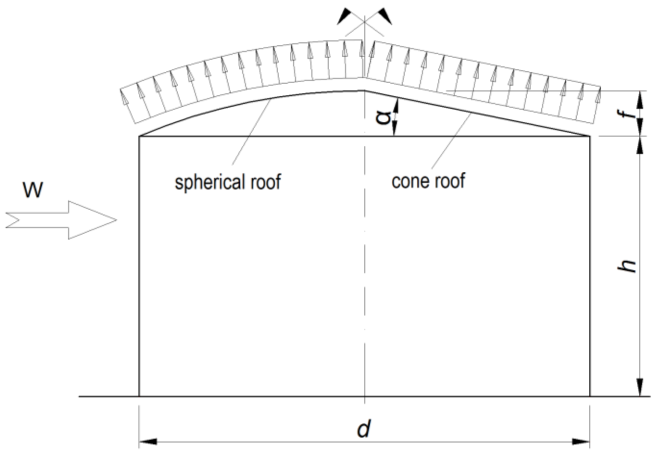


Fig. 2. Schema and dimensions of the tank

Knowing that the ratio h/d = 0,785, through linear interpolation from the table. 1 is accounted that the pressure coefficient has a value c_{pe} = - 0,735.

Table 1. Values of coefficient c_{pe}, calculated from ratio *h/d*

Type of the roof	***h/d***		
	1/6	**1/3**	**≥ 1**
Flat conical – when α ≤ 5° spherical – when $f/d \leq 0,1$	- 0,5	-0,6	-0,8

The design height above the terrain is a z_e = 12,875 m, respectively $q_p(z_e)$= 1,311 kN/m², the average value of the wind pressure on the roof is:

$$w_{e,m} = q_p(z_e).c_{pe} = 1{,}311.(-0{,}735) = -\,0{,}963 \text{ kN/m}^2 .$$

2.3. American standard ASCE7-05 of 2006

The values of the pressure coefficients c_{pe} are calculated through ratios h/d and f/d, according to the scheme, identical to the shown in fig. 1. Something is borrowing between ASCE7-05 [3] and БДС EN 1991-1-4 [1].

2.4. American standard API 650, 12th Edition, Add. 3 of 2018

In the standard API 650 [4] there is no limitation of the shape (spherical, conical) or for the values of the ratio f/d. The average wind loading on the roof is calculated according to the formula:

$$w_{e,m} = 1{,}44\left(\frac{v}{190}\right)^2 = 1{,}44\left(\frac{164{,}88}{190}\right)^2 = 1{,}084 \text{ kN/m}^2 , \quad (5)$$

where v is the wind speed at the height z_e = 12,875 m, at a 3-second averaging period, in km/h. It is calculated according to the formula:

$$v = 3{,}6\sqrt{\frac{2.q_p(z_e)}{\rho}} = 3{,}6\sqrt{\frac{2.1311}{1{,}25}} = 164{,}88 \text{ km/h} \quad , \qquad (6)$$

where ρ = 1,25 kg/m^3 is the density of the air.

2.5. Australian and New Zealand standard AS/NZS 1170.2 of 2011

The methodology in the standard AS/NZS 1170.2 [5] could be applied to the spherical and also to the conical roof, but the following limitations are valid:

- the inclination of the conical roof $\alpha < 10°$;
- the average inclination of the spherical roof $\alpha < 10°$.

The values of the pressure coefficient c_{pe} for Zone A and Zone B, see fig. 3, are shown in a table. 2:

Table 2. Pressure coefficient for the roofs of circular bins, silos and tanks, according to AS/NZS 1170.2

Zone	Zone A	Zone B
coefficient c_{pe}	-0,8	-0,5

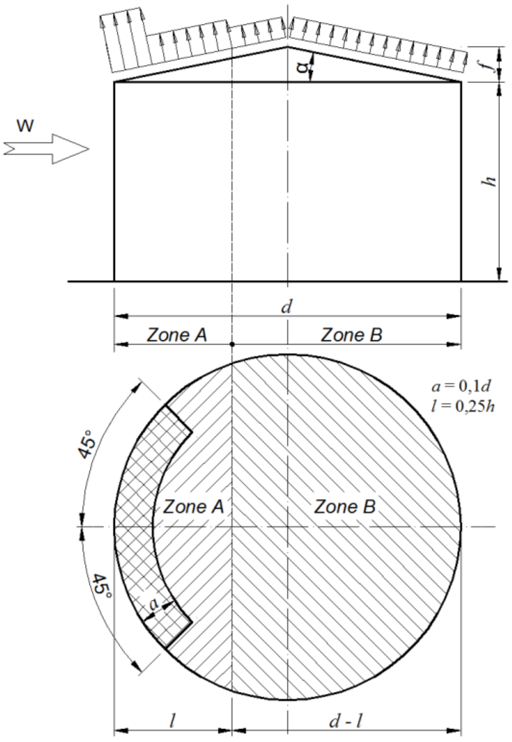


Fig.. 3. Scheme of the wind loading on the roof according to AS/NZS 1170.2

The width of edge zone in Zone A – a = 0,1d = 0,1.15,18 = 1,518 m;

The width of Zone A – l = 0,25h = 0,25.11,92 = 2,98 m.

The aerodynamic factors that determine the external wind load on building structures are determined by the expression:

$$C_{\mathrm{fig}} = c_{\mathrm{pe}}.K_{\mathrm{a}}.K_{\mathrm{l}}, \tag{7}$$

where c_{pe} is pressure coefficient, calculated in the table 2;

K_{a} – coefficient considering the dimensions of the loading area;

K_{l} – local factor of the pressure.

Aerodynamic factors for the shown on fig. 3 zones are as follow:

a) Zone A

- edge zone (zone A1)

$$C_{\mathrm{fig,A1}} = c_{\mathrm{pe,A1}}.K_{\mathrm{a,A1}}.K_{\mathrm{l,A1}} = -0{,}8.0{,}958.1{,}5 = -1{,}15 \tag{8}$$

- remaining internal surface of Zone A (zone A2)

$$C_{\mathrm{fig,A2}} = c_{\mathrm{pe,A2}}.K_{\mathrm{a,A2}}.K_{\mathrm{l,A2}} = -0{,}8.0{,}982.1{,}0 = -0{,}786 \tag{9}$$

b) Zone B

$$C_{\mathrm{fig,B}} = c_{\mathrm{pe,B}}.K_{\mathrm{a,B}}.K_{\mathrm{l,B}} = -0{,}5.0{,}8.1{,}0 = -0{,}4 \tag{10}$$

Wind loads on the roofs, for the shown on fig. 3 zones, are as follow:

a) Zone A

- edge zone (zone A1)

$$w_{\mathrm{e,A1}} = q_{\mathrm{p}}(z_{\mathrm{e}}).C_{\mathrm{fig,A1}} = 1{,}301.(-1{,}15) = -1{,}496\ \mathrm{kN/m^2}, \tag{11}$$

- remaining internal surface of Zone A (zone A2)

$$w_{\mathrm{e,A2}} = q_{\mathrm{p}}(z_{\mathrm{e}}).C_{\mathrm{fig,A2}} = 1{,}311.(-0{,}786) = -1{,}03\ \mathrm{kN/m^2}, \tag{12}$$

b) Zone B

$$w_{\mathrm{e,B}} = q_{\mathrm{p}}(z_{\mathrm{e}}).C_{\mathrm{fig,B}} = 1{,}311.(-0{,}4) = -0{,}524\ \mathrm{kN/m^2}. \tag{13}$$

The average value of the wind loading on the roof will be calculated according to the formula:

$$w_{\mathrm{e,m}} = \frac{A_{\mathrm{A1}}}{A} w_{\mathrm{e,A1}} + \frac{A_{\mathrm{A2}}}{A} w_{\mathrm{e,A2}} + \frac{A_{\mathrm{B}}}{A} w_{\mathrm{e,B}} =$$
$$= \frac{16{,}288}{181}(-1{,}496) + \frac{12{,}69}{181}(-1{,}03) + \frac{152}{181}\cdot(-0{,}524) = -0{,}647\ \mathrm{kN/m^2}, \tag{14}$$

where A_{A1} is the horizontal projection of the area of the edge zone A1 of the roof;

A_{A2} – horizontal projection of the remaining internal surface from Zone A (zone A2);

A_{B} – horizontal projection of the area of Zone B on the roof, see fig. 3.

$A = A_{\mathrm{A1}} + A_{\mathrm{A2}} + A_{\mathrm{B}}$ – the whole horizontal projection of the area of the conical roof.

2.6. Indian standard IS 875 Part 3 of 2015

The methodology in the standard IS 875 Part 3 [6] could be applied for spherical and also for conical roofs, but with the following limitations:

a) height h of the cylindrical body, see fig. 4, is within the limits $0,2d < h < 3d$;

b) angle α of the inclination of the roof corresponds to the inequity tg $\alpha < 0,2$.

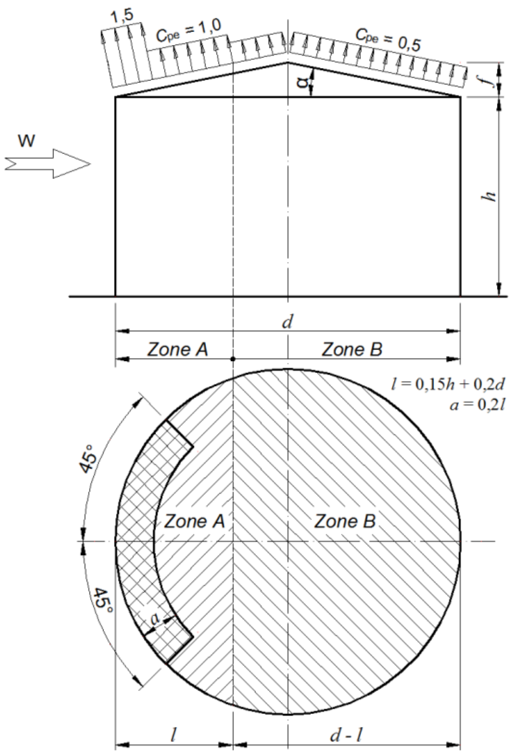


Fig. 4. Schema of loading of the roof according to IS 875 Part 3

Width of the edge zone – $a = 0,2l$ = 0,2.4,824 = 0,965 m;

Width of Zone A – $l = 0,15h + 0,2d$= 0,15.11,92 + 0,2.15,18 = 4,824 m.

The value of the pressure coefficient c_{pe} for Zone A and Zone B, see fig. 4, are shown in a table. 3:

Table 3. Pressure coefficient for the roof on the circle basement silos and tanks according to IS 875 Part 3

Zone	**Zone A**		**Zone B**
	edge zone	remaining zone	
coefficient c_{pe}	-1,5	-1,0	-0,5

When the total uplifting force F_z is calculated, the standard permits to use of the average pressure coefficient c_{pe}. Its values are shown in table 4 and depend on the ratio h/d.

Table 4. Average values of the coefficient c_{pe}, accounted by ratio *h*/*d*

Type of the roof	*h*/*d*		
	0,5	**1,00**	**2,00**
flat, conical, spherical	- 0,65	-1,0	-1,0

The above results show that the biggest wind pressure is calculated according to the standard IS 875 (Part 3):2015 [6], and the smallest - according to the AS/NZS 1170.2:2011 [5]. Standard БДС EN 1991-1-4 [1], respectively ASCE7-05 [3], give the second the lowest value of the wind loading on the roof on a circular base.

3. Numerical calculation of the wind loading on the roof

The above-mentioned standards Ordinance №3 [2], API 650 12th Edition, Add. 3 [4], AS/NZS 1170.2 [5], IS 875 Part 3 [6] do not make difference between conical and spherical roofs when the values of the wind loads are determined. Differences are inevitable. The question is whether they are small, negligible, or significant.

To find an answer to this question, the author has made a finite element analysis (FEA) of the tank in question, but with two types of roofs - conical and spherical.

3.1. Modelling

With the graphical interface Workbench of ANSYS [7] and its module Fluid Flow (CFX) are created two 3D models of the steel vertical cylindrical tank, analytically researched above. In one of the models the roof is conical, as it is executed according to the project, in the other one - spherical with height f = 0,95 m, as it is in the conical roof.

The walls of the simulated aerodynamical tunnel around the tanks are situated at the following distances:

a) fluid inlet – on 23 m;
b) fluid outlet – on 46 m;
c) sidewalls (two vertical and one horizontal) – at 26 m.

The above-shown distances are determined according to the principle that the walls of the virtual aerodynamical tunnel should not influence the airflow next to the tank [8]. At the same time to avoid heavy computer solutions and to save calculating time, the amount of the finite elements is taken into consideration. Because of it, the author observed the following limitations:

a) the inlet of the fluid and the side walls should have a distance between them not less than 1,5 times the diameter *d* of the observed object;
b) the outlet of the fluid should not be closer than 3 times the diameter *d* of the tank.

The fluid that will flow around the tank is air with a temperature of 25 °C. The speed at the inlet of the enclosure is constant by height and has a value v = 46,19 m/s, calculated according to БДС EN 1991-1-4 [1] for the height above the area z_e = 13,35 m. To optimize the mesh of the finite elements, the mesh is considerably dense in the zone around the tank and less dense in the periphery [9]. Their maximum dimension is limited to:

a) elements in direct contact with the shell and the roof of the tank – 100 mm;
b) all rest elements – 1 000 mm.

In the beginning is accepted that the model of the tank and the surrounding area will be completely smooth. After that another simulation was performed, taking into account the roughness of the tank and the surrounding terrain, as follow:

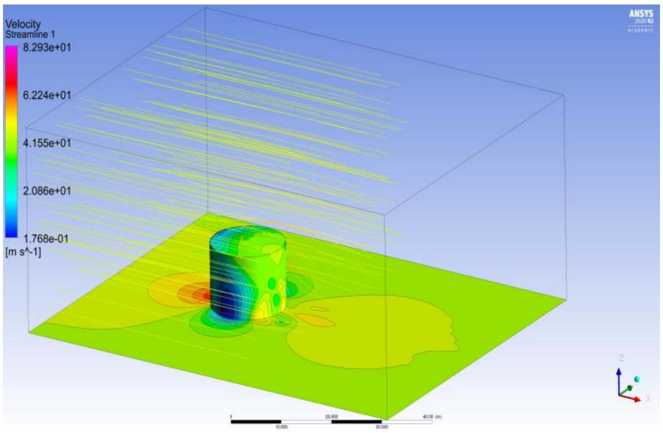
a) z_0 = 0,2 mm – for the shell and roof of the tank;

b) z_0 = 100 mm – for the area around. The author tried to simulate the around area with roughness z_0 = 300 mm, corresponding to a category III, but the programme did not permit it.

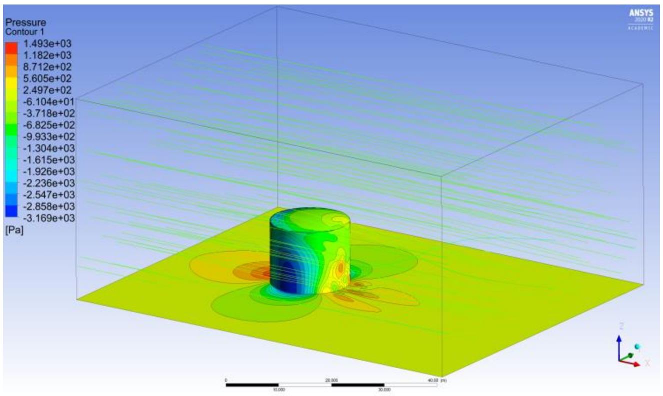
3.2. Results from finite elements analysis

3.2.1. Research of the smooth tank and area around

The flowing around the two smooth models of the tank is shown in fig. 5. Values of wind speed more than 85 m/s are accounted.



a) tank with a conical roof



b) tank with a spherical roof

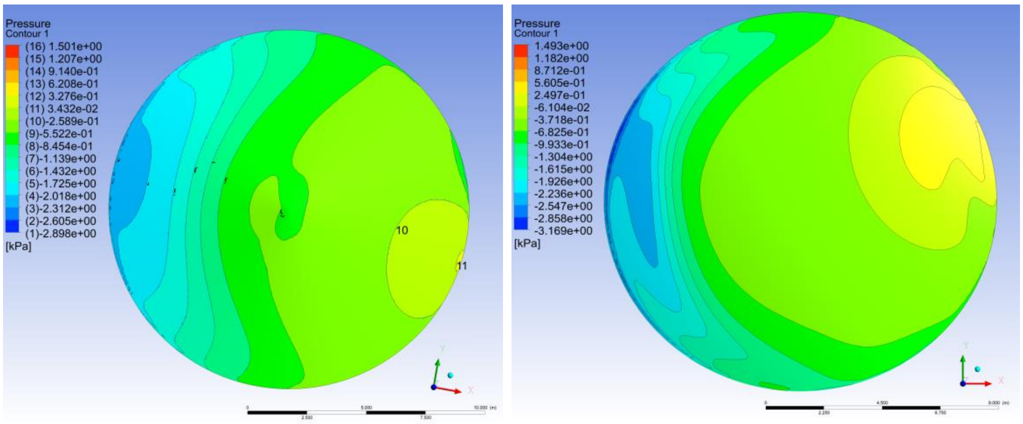
Fig. 5. Speeds and pressure of the wind flow that flows around the smooth tanks

The pressure on the smooth conical and spherical roof of the tank is shown in fig. 6. The following could be seen on them:

a) wind impact is uneven in a plane, close to the windward side it acts down-top (suction) and close to the leeward side are observed small zones in which it acts top-down (pressure);

b) unlike the research of *Verma* and *Ahuja* [10], the zones with uniform pressure on the roof are not positioned completely symmetrically toward the direction of the wind flow (axe x). This phenomenon is better expressed in the spherical roof;

c) the pressure coefficient c_{pe} is not constant on the arcs of the circles which are intersection lines of the sphere with plains, perpendicular to the wind flow, see fig. 1.



a) tank with a conical roof *b) tank with a spherical roof*

Fig. 6. Pressure on the tank' roof with smooth surface flowed around by the wind

The values of the forces that uplift the roof are measured with the help of engineer *Maria Pantusheva* and are as follow:

a) when the tank has a conical roof– F_z = 150,02 kN;

b) when the tank has a spherical proof– F_z = 145,45 kN.

Hence, the average value of the vertical component of the wind pressure on the roof is:

a) when the tank has a smooth conical roof – $w_{e,m,z}$ = 0,829 kN/m^2;

b) when the tank has a smooth spherical proof – $w_{e,m,z}$ = 0,804 kN/m^2.

The difference between the calculated values is about 3%, i.e. not so big.

Considering small inclinations of the roofs, with a minor error it can be accepted that $w_{e,m,z} = w_{e,m}$. Comparing the results calculated for the two types of roofs it is shown that the resulting force F_z, respectively average pressure $w_{e,m}$, on the smooth conical roof is bigger than on the spherical.

On the smooth roofs are accounted horizontal forces with a direction opposite to the wind flow. This effect should not be surprising, as the roof's surfaces are inclined, and in the windward zone it is observed intensive suction and in the leeward zone - suction with small intensity or pressure. The values of the horizontal forces are as follow:

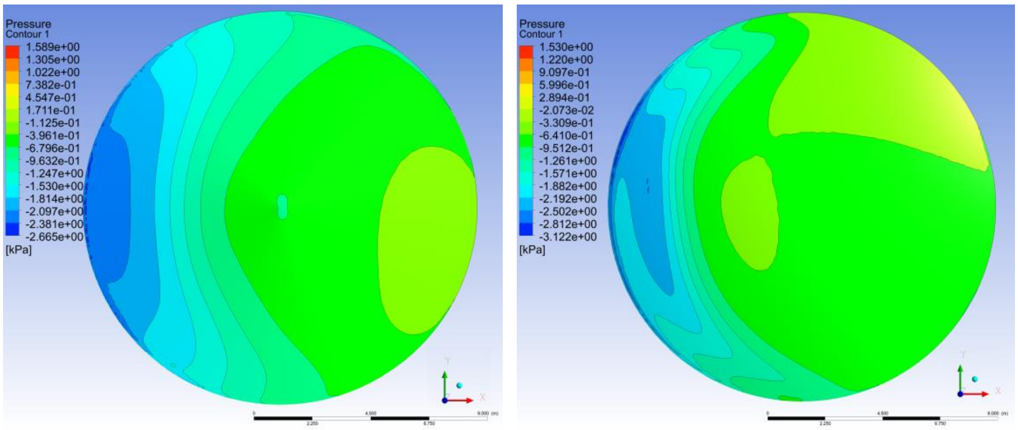
a) in the tank with a smooth conical roof – F_x = 7,52 kN;

b) in the tank with a smooth spherical roof– F_x = 11,45 kN.

3.2.2. Research of the rough tank and surrounding area

The accounted here values of the wind speed are more than 83 m/s.

The pressure on the rough conical and spherical roof on the tank is shown in fig. 7. They show the same features as described above in the smooth tanks, except the presence of zones in compression. Here on the whole surface is accounted suction.



a) tank with a conical roof *b) tank with a spherical roof*

Fig. 7. Pressure on the rough tank's roofs flowed around by the wind

The accounted forces that uplift the roofs are as follow:
a) in the tank with a conical roof– F_z = 169,7 kN;
b) in the tank with a spherical roof – F_z = 173,73 kN.

From here, the average value of the vertical component of the wind pressure on the roof is:

a) in the tank with a conical roof and rough surface – $w_{e,m,z}$ = 0,938 kN/m^2;
b) in the tank with a spherical roof and rough surface – $w_{e,m,z}$ = 0,96 kN/m^2.

The difference between the accounted values here is about 2,3%.

Considering the small inclinations of the roof here, with minor error could be accepted that $w_{e,m,z} = w_{e,m}$. Here the resulting vertical force F_z, respectively the average pressure $w_{e,m}$, on the spherical roof is bigger than on the conical roof.

The accounted here values of the horizontal forces, which direction is against the wind flow, are as follow:
a) in the tank with a conical roof – F_x = 7,476 kN;
b) in the tank with a spherical roof – F_x = 9,271 kN.

4. Results

The analytically calculated results, using the above-mentioned standards and the results, accounted by FEA, through ANSYS, are shown in the table. 5. The author underlines again that the standards do not make difference between the spherical and conical roofs.

This research shows there are considerable differences between the calculated values of wind loading on the roof. Values of the wind pressure on the roof with roughness, accounted by FEA, are between the determined through БДС EN 1991-1-4 and API 650.

Table 5. Average values of wind pressure on the roofs $w_{e,m}$, kN/m²

Method	Analytical						Numerical	
	БДС EN 1991-1-4	Ordinance №3	ASCE7-05	API 650	AS/NZS 1170.2:2011	IS 875 (Part 3): 2015	Cone roof	Dome roof
$w_{e,m}$, kN/m²	-0,892	-0,963	-0,892	-1,084	-0,647	-1,114	-0,938	-0,96

5. Conclusions

Based on the research for wind pressure on conical and spherical roofs on the circular base, the following conclusions could be done:

a) with identical initial conditions, the national standards give different values for the wind pressure on the roof. The highest values are calculated through IS 875 (Part 3):2015 [6], the lowest – according to the AS/NZS 1170.2:2011 [5]. The difference between them is more than 70%;

b) the values of wind pressure on conical and spherical roofs with roughness, calculated using numerical methods, are between by БДС EN 1991-1-4 [1] and API 650 [4];

c) from the values of the pressure on the conical and spherical roof, accounted by FEA it could be concluded that there are differences between them. The total pressure on the spherical roof with roughness is higher than the pressure on the conical roof. When the roofs are smooth, it is opposite. The accounted here differences are of the order of 2 ÷ 3%;

d) unlike the mentioned in БДС EN 1991-1-4 [1], the FEA shows that pressure coefficient c_{pe} is not constant along the arcs of the circles, representing the intersecting lines of the sphere with planes, perpendicular to the wind flow, see fig. 1.

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