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THE WIND TUNNEL STUDY OF THE INFLUENCE OF TERRAIN AND SURROUNDING STRUCTURES ON THE DISTRIBUTION OF WIND PRESSURE ON A CHIMNEY

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Abstract

The value of the total aerodynamic resistance of the structure is depended on the values of the highly variable coefficients of external pressure, the quantification of which is a typical task of aerodynamics of structures solved on a rigid model in a wind tunnel. The aim of the paper is to analyze the distribution of wind pressure on a 150 m high chimney of a nuclear power plant. Due to today's changing climate and the emergence of unwanted windstorms, it is necessary to pay increased attention to tall and slender structures, where the effects of wind play an important role. The effect of wind, the influence of the terrain and surrounding structures has a significant impact on the safety of the chimney, which is a part of the nuclear power plant, where increased safety is required not only for the chimney itself but also for buildings in its immediate vicinity. Surrounding structures can modify wind flow and cause increased chimney load. Experimental measurements were performed in the STU BLWT wind tunnel in Bratislava, where the influence of the changing terrain, as well as the influence of the surrounding objects on the external wind pressure coefficients at different altitude levels were monitored.

Keywords:

Wind load;
Wind tunnel;
Distribution of wind pressure;
Experimental measurements.

1 Introduction

The wind load depends on several factors such as wind speed and turbulence, the type of terrain, as well as the shape of the object. The structures surrounding the object also play an important role and can significantly influence and modify the wind flow and also the distribution of wind pressures on the structure. EN 1991-1-4 [1] does not take into account the influence of surrounding structures and it is therefore appropriate to objectify the external wind pressure coefficients either by CFD simulation [2, 3] or by experimental measurement in wind tunnels.

BLWT STU tunnel [4, 5] with modeled boundary layer allows repeated measurements for different wind directions and speeds.

While maintaining the similarity of flow and flow around the structures, it is possible to experimentally test the effects of wind on structures on reduced models in wind tunnels and thus determine the most unfavorable wind effects.

The distribution of external wind pressure coefficients on circular cylinders can be found in the standard EN 1991-1-4. These values take into account the effect of the free end of the structure, but there are no influences of surrounding objects, which could modify the wind flow. Actually such an isolated structure is a very rare case.

The chimney is a part of the nuclear power plant unit and is surrounded by buildings that are essential parts of the power plant. Surrounding administrative buildings also have an effect on the

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distribution of pressures and suctions on the chimney, and therefore we carried out two experiments within the experimental measurement.

In the first step, we tested the chimney and turbine hall for different terrain categories in the area, and then we added additional surrounding objects to analyze the changes that may occur in the distribution of wind pressures on the chimney. We compared the results with the standard values of the external wind pressure coefficients on vertical cylinders, as stated in the EN 1991-1-4 standard.

2 Wind load

Wind loads on structures are given by EN 1991-1-4 and National Annex EN 1991-1-4 / NA. The wind load calculation is based on the specific wind situation in the given area or specific location where the structure is built. The following factors affect the resulting wind load values:

1) site-specific wind conditions,
2) roughness of the terrain,
3) aerodynamic characteristics of the shape of the object.

The wind load is a problem of aerodynamics. Peak wind pressures are defined based on long-term meteorological measurements. In terms of the wind flow around objects, air can be considered an ideal and incompressible fluid with low resistance, where the effect of friction is limited to the area of obstruction. The character of the wind flow around the objects determines the Reynolds number

$$Re = d \cdot v/u, \tag{1}$$

where d is the characteristic size of the obstacle, v is flow velocity, $u = 1.5 \cdot 10^{-5}$ m^2/s is kinematic viscosity.

2.1 Wind velocity and pressure

The basic characteristics of turbulent wind flow are mean wind velocity, peak velocity pressure and resulting wind pressure at the area. Mean wind velocity at height z depends on terrain, and reference wind velocity

$$v_m(z,t) = \frac{1}{T}\int_0^T v(z,t)dt \ , \tag{2}$$

$$v_m(z) = 0{,}19(z/z_{0,\mathrm{II}})^{0{,}07}\, ln(z/z_0) \cdot v_b \ , \tag{3}$$

where:
v_b - reference wind velocity,
z_0 - roughness length,
$z_{0,II}$ - roughness length for terrain II.

The course of peak wind pressure $q_p(z)$ depends on the intensity of turbulence $I_v(z)$ and this varies with type of terrain category - for terrains around the chimney see Fig. 1 and [8, 9]

$$q_p(z) = [1 + 7I_v(z)] \cdot 1/2 \cdot \rho \cdot v_m^2(z) \ , \tag{4}$$

$$I_v(z) = \frac{k_I}{c_0(z) \cdot ln(z/z_0)} \ . \tag{5}$$

The distribution of the external wind pressure w_e on the circular cylinders depends on the external wind pressure coefficient c_{pe}, which can be found in EN 1991-14 for simple shapes of free-standing structures. In the case of surrounding objects, it is necessary to obtain these factors by experimental measurements in wind tunnels or CFD simulation.

$$w_e = c_{\mathrm{pe}} \cdot q_p(z). \tag{6}$$

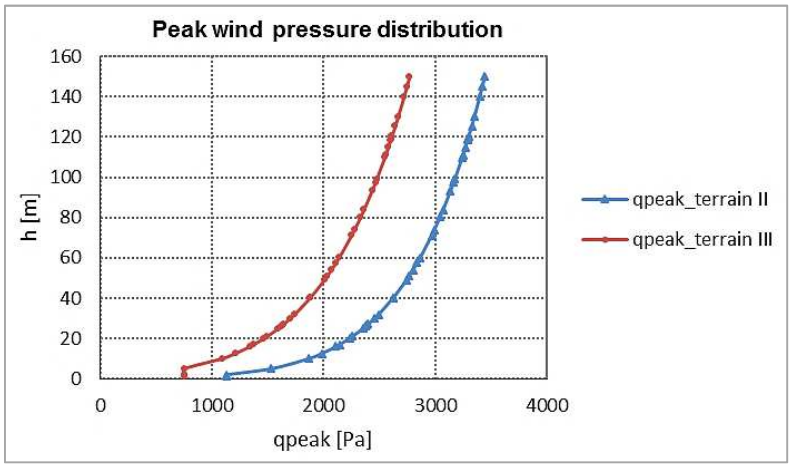


Fig. 1: Influence of terrain category on the course of peak wind pressure.

3 Experimental determinations of wind effects on the nuclear plant chimney

In the wind tunnel BLWT in Bratislava, (see Figs. 5, 6) the influence of neighboring structures on the effects of wind pressure distribution on the chimney at different speeds and wind direction have been tested in the rear measuring space according to ACSE, 1999 [7].

Given that existing standards consider wind loads only on free-standing objects and do not consider the specific effects of surrounding structures and surrounding terrain, wind loads obtained experimentally – using wind tunnel tests [10-12] can refine these values. Model wind tunnel tests can lead to a better understanding of the wind effects in individual areas.

The prevailing wind directions at the site of the tested chimney are north-west and south-east, see Fig.2.

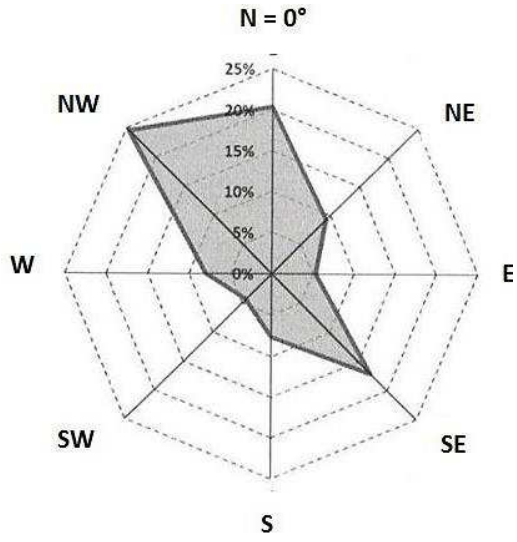


Fig. 2: Prevailing wind directions at the site, wind rose during years 1987 - 2010.

3.2 Evaluation of external wind pressure coefficients for chimney

The value of external wind pressure coefficient was calculated by Eq. (7):

$$c_{pe} = \frac{\Delta p}{p_{\mathrm{dyn}}(z_{\mathrm{ref}})} = \frac{p(t)-p_0}{1/2\cdot\rho\cdot\bar{v}^2(z_{\mathrm{ref}})}\,, \tag{7}$$

where $p(t)$ is the wind pressure in measuring point on the surface of the model and p_0 is static pressure of undisturbed flow measured by Prandtl probe at the height level 1.2 m . Dynamic pressure of the mean wind velocity p_{dyn} was considered in reference height (in our case, reference height was equal to the height of the top of examined chimney). The measurement of wind pressures Δp on the chimney was performed in six height levels. There were four sampling points in each height level of

the chimney, and in order to obtain a larger number of results, we rotated the chimney by 45°, thus obtaining 8 values at each level. The sampling points and their designation can be seen in Fig. 3.

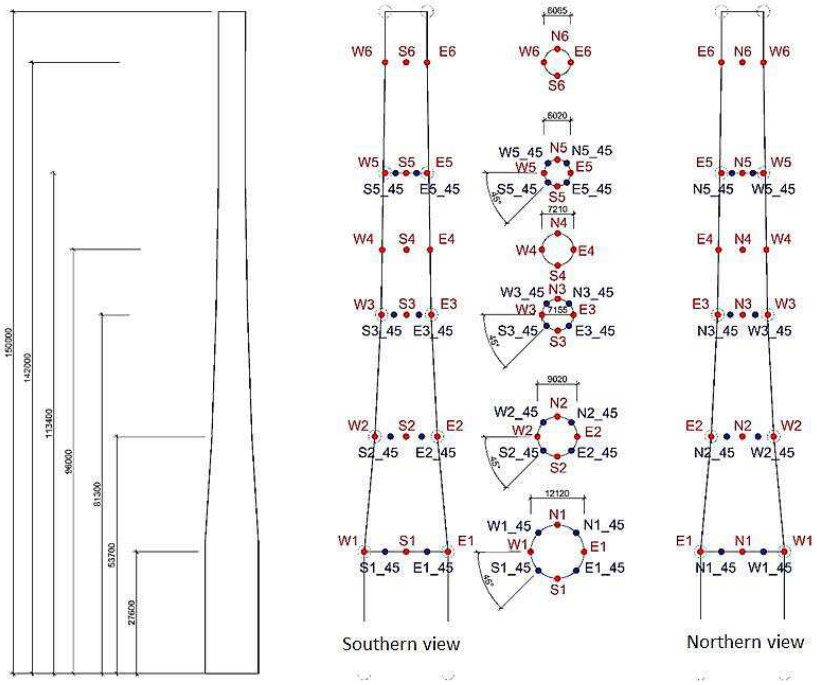


Fig. 3: Sampling points on the chimney.

In the vicinity of the nuclear power plant, we considered the terrain of categories II and III depending on the direction of wind flow, see Fig. 4. Experimental measurements were performed on the chimney only regarding the turbine hall, see Fig. 5. In the next part of the experimental measurements, also all other objects that were located within a distance of 300 m from the chimney, have been considered as it is shown in Figs. 4 and 5.

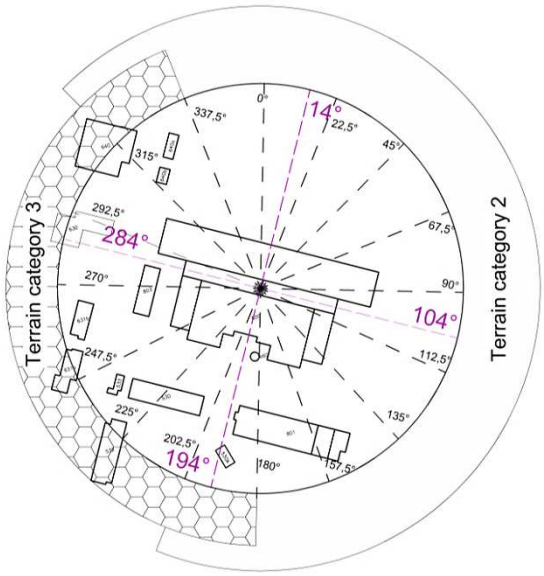


Fig. 4: Terrain categories and objects around the chimney.

The mean values of the wind flow rate were set using the LabVIEW program and ranged from 10.26 to 12.4 m/s at the top of the chimney, depending on the barometric pressure, temperature and air density. The extreme values of the external wind pressure coefficients obtained by experimental measurements are for the two variants of the surrounding objects in Tables 1 and 2.

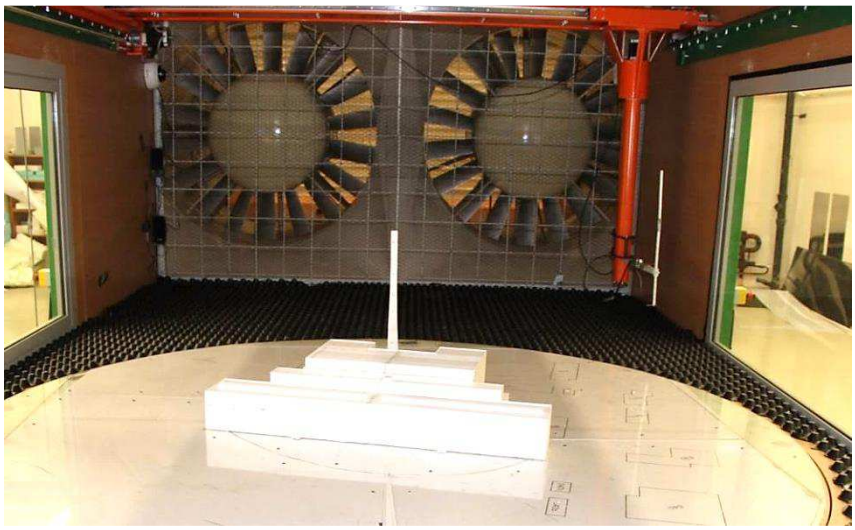


Fig. 5: Chimney with a turbine hall on a turntable in BLWT tunnel.



Fig. 6: Chimney with all surrounding buildings.

Table 1: External wind pressure coefficients c_{pe} - chimney with turbine hall.

Zone	**Windward zone wind direction 284°**		**Leeward zone wind direction 284°**		**Side zone wind direction 315°**	
Height h [m]	**points**	**c_{pe}**	**points**	**c_{pe}**	**points**	**c_{pe}**
142	W6	**1.27**	E6	**-1.23**	N6	**-1.85**
113.4	W5	1.14	E5	**-1.08**	E5	-1.29
96	W4	1.05	E4	**-1.05**	E4	-1.24
81.3	W3	0.988	E3	**-1.07**	E3	-1.23
53.7	W2	0.116	E2	**-0.78**	E2	-1.27
27.6	W1	-0.38	E1	**-0.58**	E1	-0.58

Table 2: External wind pressure coefficients c_{pe} – chimney with all surrounding objects.

Zone	**Windward zone wind direction 194°**		**Leeward zone wind direction 194°**		**Side zone wind direction 45°**	
Height h [m]	**points**	**c_{pe}**	**points**	**c_{pe}**	**points**	**c_{pe}**
142	S6	**1.22**	N6	**-1.075**	E6_45	-1.59
113.2	S5	1.16	N5	**-0.77**	E5_45	-1.51
96	S4	0.72	N4	**-1.024**	E4_45	-1.33
81.3	S3	0.99	N3	**-0.988**	E3_45	-1.308
53.7	S2	0.77	N2	**-0.706**	E2_45	**-1.736**
27.6	S1	0.39	N1	0.137	E1_45	-0.736

A comparison of the obtained external pressure coefficients for different heights and two selected wind directions with the values for free-standing circular cylinders, which is given by the EN 1991-1-4 standard, is shown in Figs. 7 - 10. When determining the external wind pressure coefficients according to EN 1991-1-4, the free end factor was also considered for the upper part of the chimney - levels 4, 5, 6.

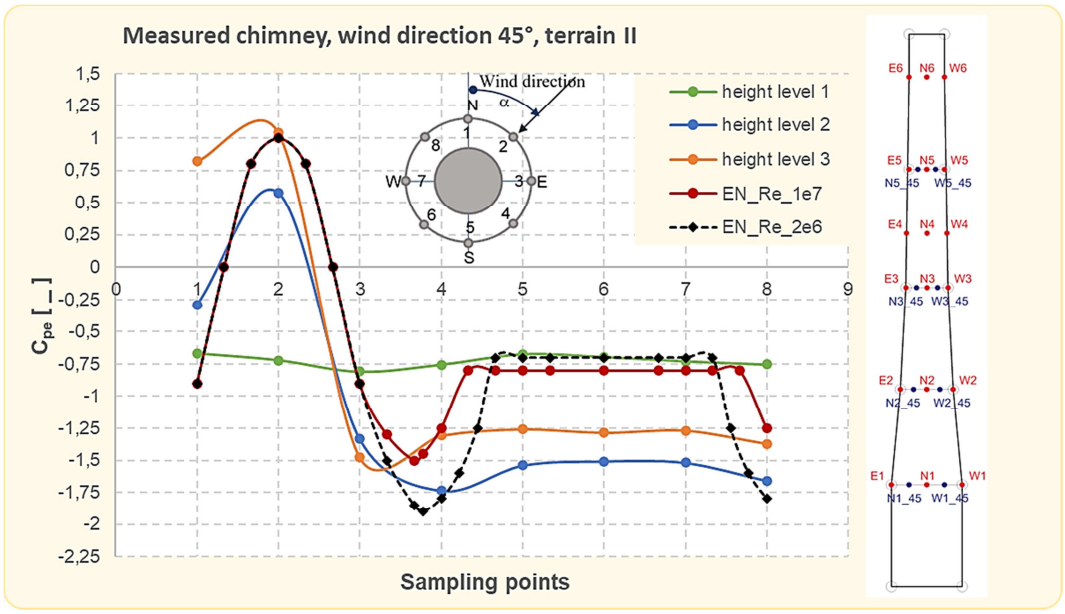


Fig. 7: External wind pressure coefficient distribution - lower part of the chimney with turbine hall, terrain II.

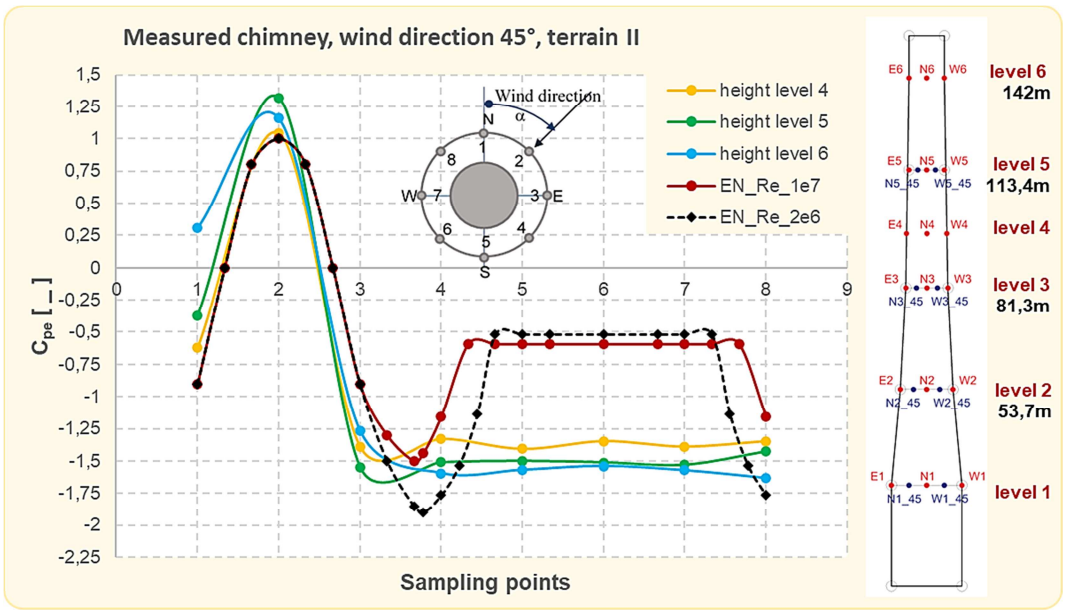


Fig. 8: External wind pressure coefficient distribution - upper part of the chimney with turbine hall, terrain II.

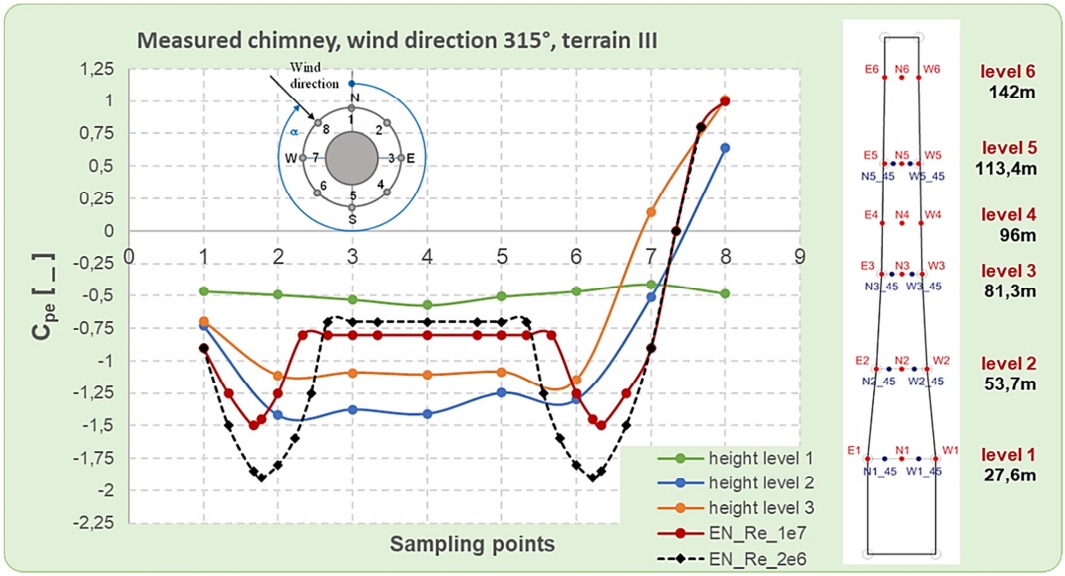


Fig. 9: External wind pressure coefficient distribution - lower part of the chimney with all surrounding buildings, terrain III.

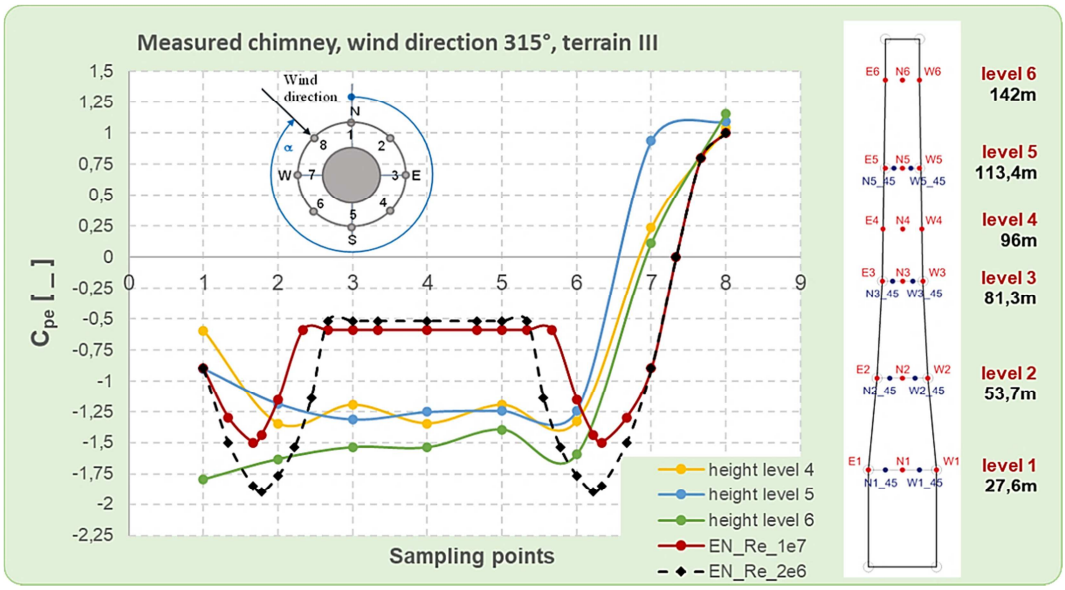


Fig. 10: External wind pressure coefficient distribution - upper part of the chimney with all surrounding buildings, terrain III.

The Reynolds number at the top of the chimney for peak wind speeds varied between $5.05 \cdot 10^6$ - $6.01 \cdot 10^6$, which is between the standard values for $Re = 2 \cdot 10^6$ and $Re = 1 \cdot 10^6$ for circular cylinders, indicates significantly higher suction in the leeward area of the chimney than stated in the standard.

4 Resume and discussion

According to the Slovak Hydrometeorological Institute the basic wind speed for a nuclear power plant with a return period of 10^4, has a value of 35.64 m/s. High resulting values of peak pressure appeared on the chimney, with the wind flow from the west, where they reached 3.5 kPa at the height of 142 m. Unfavorable values of suction occurred at the altitude of 142 m at the northwest flow of the free-standing block with chimney and reached a value of - 5.1 kPa. High value of suction was manifested when the wind passed through terrain category II - at northeast flow. Even at a chimney height of 53.7 m, the suction reached a value of - 5.98 kPa. These peak values of the suction are caused by the turbine hall, which tightly surrounds the chimney and accelerates the wind flow. Although this direction of wind flow does not prevail in the locality, it must be considered.

Based on the obtained results of peak wind pressures, it is necessary to pay increased attention to the local influence of the wind on the chimneys, especially if there are structures in the vicinity that can modify the distribution of pressures around the perimeter of the chimney.

Wind tunnels with developed atmospheric boundary layer provide a complete statistical description of the load test of the objects in the wind flow with the natural structure. Development of this transformed scientific field is conditioned by the aerodynamic quantification of structures and their elements, which can provide only specific development of wind engineering.

The distribution of wind pressure on the chimney was manifested at all height levels by increased suction in the leeward zone and the resulting wind force is higher than the values given in standard EN 1991-1-4. The experimentally obtained external wind pressure coefficients in the leeward zone were doubled in the upper part of the chimney c_{pe} = -1.5 ÷ -1.6 compared to the standard values, where the suction in the leeward zone is around c_{pe} = -0.5 ÷ -0.75, see Figs. 8 and 10. It is necessary, especially for constructions that are part of nuclear power plants and where safety is important, to monitor all types of loads.

Acknowledgements

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