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Wind loading on shell structures on example of CICIND and Eurocode standards

Obciążenie wiatrem konstrukcji powłokowych na przykładzie norm CICIND i Eurokodu

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Abstract. Paper shows problematic of calculation of wind loading on chimneys modeled as shell structures, on example of two different design codes CICIND Model Code for Chimneys and Eurocode 1. Basics of determination of wind loads and some problematic related to modeling of wind on shells are presented.

Keywords: chimneys; wind loads; FEM modeling.

Streszczenie. W artykule zaprezentowano problematykę obliczeń obciążenia wiatrem kominów przemysłowych, modelowanych jako konstrukcje powłokowe, zgodnie z dwiema normami projektowania CICIND Model Code for Concrete Chimneys oraz Eurokodem 1. Omówiono m.in. podstawy wyznaczania obciążenia wiatrem oraz problemy związane z modelowaniem wiatru na powłoki.

Słowa kluczowe: kominy; obciążenie wiatrem; modelowanie MES.

Many of being currently designed or recently built chimneys due to their geometry can be assigned to shell-like structures. This applies especially to multi-flue chimneys designed for FGD installations. In many cases such chimneys have large diameter compared with their heights. This factor has an impact on the design of this kind of structures and should reflect an appropriate wind loading. CICIND Model Code for Concrete Chimneys [5] as well as Eurocode 1 [8], give a guidance for the calculation of load effects on chimney's windshield. If a chimney windshield is modeled as a shell-like structure, wind load should be determined in a way that can be reflected in the Finite Element Model, commonly used for today's calculations.

Parameters affecting determination of wind load effects on shell structure

There are many parameters affecting wind load on structures. Beside wind speed, corresponding to the location of the structure (wind zone) some other parameters are playing a role while determining the wind load effect. The theoretical background of derivation of these parameters is widely investigated and well explained [10, 11]. The purpose of this paper is to present practical problems of modeling of the wind load on shell according to CICIND Model Code for Concrete Chimneys and Eurocode 1. There are three main parameters to be taken into account while modeling the wind load:

- distribution of the load around the horizontal cross-section;
- distribution of the load with chimney height;
- dynamic response of the structure.

Distribution of the load around horizontal cross-section

In case of traditional calculation of chimney windshields, circular shape of chimney's cross-section is taken into account, assuming drag coefficient (or shape factor) according to the code regulations. For calculations of wind actions for shell structures there is a need to determine a load distribution around chimney's circular cross-section which depends on Reynolds number, surface roughness, turbulence intensity and the ratio of chimney height to its diameter. It is important to notice that height is not constant along the chimney. Several national codes give guidance for determination of the aerodynamic pressure around circular shapes. Most of them take into account, so called end-effect factor, for finite length cylinders. This parameter makes a correction of the distribution of the pressure for different aspect ratios (h/d). Figure 1 presents the distribution of external pressure coefficient $c_p(\varphi)$ acc. to codes [3, 8, 9, 12], guideline for the structural design of cooling towers [13] and comments about the CICIND Code for Steel Chimneys [6, 7]. All diagrams presented in Figure 1 correspond to aspect ratio h/d = 10. Diagrams where mini-

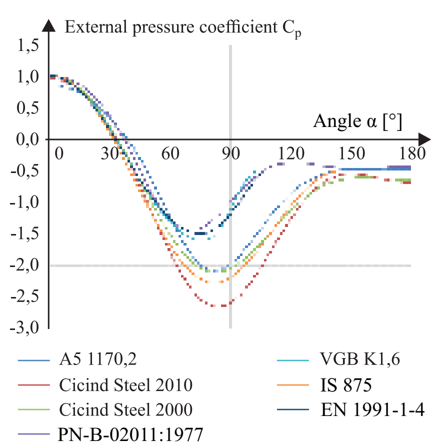

Fig. 1. Distribution of external pressure coefficient around circular shape acc. to different codes and guidelines
Rys. 1. Rozkład współczynnika ciśnienia zewnętrznego wokół przekroju kołowego (wg różnych wytycznych i norm do projektowania)

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mum pressure (maximum suction) is greater than -2.0, correspond to lower Reynolds numbers (less than $4 \cdot 10^6$). Curves with a minimum pressure around value -1.5, correspond to higher Reynolds numbers in a transcritical range (10^7 or more). Surface roughness is taken directly into account only in VGB guidelines, since in case of cooling towers, wind ribs are playing very important role for the reduction of wind pressure. The above presented VGB distribution is calculated for a pressure distribution curve K1.6 (no ribs – smooth surface). CICIND code for concrete chimneys does not give any pressure distribution formula. Calculation of wind effect is limited to beam theory and circular geometry is considered by a shape factor C_D, giving a resulting wind force at height „z". Figure 2 presents basic shape factor for concrete chimneys as a function of the h/d ratio. Eurocode 1 (PN-EN 1991-1-4) in chapter 7.9 presents two procedures of determining of external pressure coefficient and force coefficient (chapters 7.9.1 and 7.9.2 correspondingly). External pressure coefficient allows to find wind load distribution around circular cross-section depending on the angle, while force coefficient gives the total value for whole round section, like for beam model. Both methods take into account Reynolds number and end-effect factor. In addition procedure for calculation of force coefficient for circular cross section considers also surface roughness. First procedure assumes constant value of surface roughness equal to $5 \cdot 10^{-4}$.

Since the purpose of the paper is to discuss wind load effects on shell-like structure, the considered area of interest is aspects ratios equal or smaller than

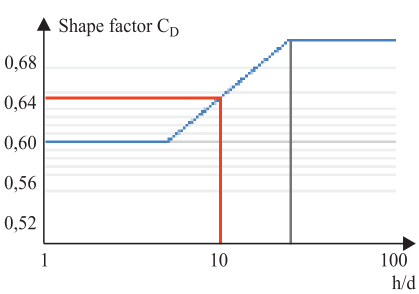

Fig. 2. Basic shape factor as a function of h/d ratio acc. to CICIND
Rys. 2. Współczynnik oporu wg CICIND jako funkcja stosunku h/d

h/d = 10, and corresponding values of shape factor between 0,60 and about 0,64, acc. to CICIND. To show the difficulties with the compatible representation of load distribution with its load effect, the table 1 presents equivalent shape factors resulting from integration of the curves from Figure 1 along the circumference. As can be seen, none of the presented values consist with the shape coefficient calculated acc. to CICIND code. Same situation can be observed when comparing force coefficients calculated acc. to Eurocode with the integrated value of external pressure coefficient (figure 3). There is a need for finding a distribution, which is in a good correlation with code requirements, but which allows to model the load on shell structures.

Table 1. Equivalent value of shape factor obtained from integration of external pressure coefficients
Tabela 1. Równoważne wartości współczynnika oporu aerodynamicznego uzyskane przez scałkowanie współczynnika ciśnienia zewnętrznego

Shape factor	AS 1170.2	Comm. for Steel Chimney Code 2010	Comm. for Steel Chimney Code 2000	PN-B-02011:1977	VGB K1.6	IS 875	EN 1991-1-4
C_D	0,63	0,63	0,70	0,52	0,46	0,50	0,52

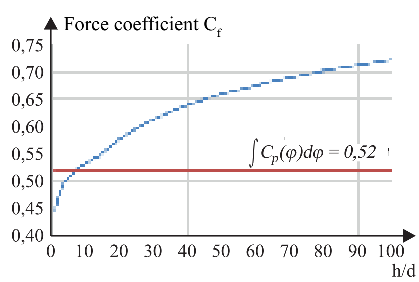

Fig. 3. Force coefficient acc. to Eurocode for different aspect ratios
Rys. 3. Współczynnik oporu aerodynamicznego wg Eurokodu w przypadku różnego stosunku h/d

Distribution of the load with chimney height

Distribution of the wind along the height of the structure depends on terrain roughness and orography of structure location. This is mostly expressed as a product of basic wind speed and corresponding exposure factor. This approach is implemented in Eurocode and is widely described in many papers. This paper focuses on a CICIND approach, because it is not very common in European standardization. Second parameter influencing calculation of the designed wind load is the determination of the wind gusts. In a classical Devenport approach mean wind speed is multiplied by the gust response factor G. In this case, calculation of the distribution of the wind along structure height is reduced to a simple multiplication of the mean load and the gust factor. CICIND model code for concrete structures gives different approach and splits total wind load into two portions: mean wind load and gust wind load. The gust wind load depends on gust factor and total bending moment corresponding to the mean wind load part. Following expressions repeat equations after the CICIND code:

w(z) = w_m(z) + w_g(z)

$$w(z) = w_m(z) + w_g(z) \quad (1)$$

where:
$w_m(z)$ – 10-minute mean wind load per unit height, calculated acc. to equation (2);
$w_g(z)$ – static equivalent of the wind load per unit height due to gusts, calculated acc. to equation (3);

$$w_m(z) = 0.5 \cdot \rho_a \cdot C_D \cdot d(z) \cdot V^2(z) \quad \text{for } z > z_{min} \quad (2)$$

$$w_g(z) = (3 \cdot (G - 1)z)/h^2 \cdot z/h \cdot \cdot \int_o^h w_m(z) \cdot z \cdot dz \quad (3)$$

Figure 4 shows an example of wind load distribution along chimney height (h = 100 m, h/d = 10, v_b = 25 m/s). The gust part of the load is linear while the

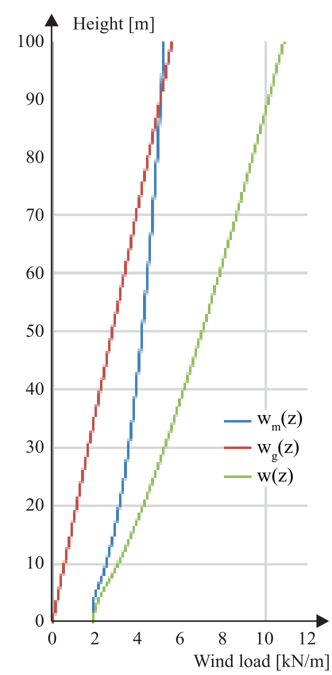

Fig. 4. Example of wind load distribution along chimney height (acc. to CICIND)
Rys. 4. Przykład rozkładu obciążenia wiatrem na wysokości komina (wg CICIND)

mean load is obtained using power low. Furthermore, the gust part for each height z is independent of the variations of diameter and shape factor. The total wind load is a combination of these two components and as a result gives a wind profile which is difficult to be expressed in a simple way for modeling of wind load on shell structures.

Dynamic response of the chimney

Dynamic response of the structure is a structural factor, not depending on loads. It depends on structural behavior to dynamic wind loading. It takes into account the reduction of the load due to the non-simultaneous loading of the whole structure and amplification of the load due to resonance with the wind. Parameters influencing this response are related to the structure size, dynamic behavior (the lowest natural frequency), shape mode of natural vibration and the structural dumping. Most of the wind load codes assume beam-like behavior of the structure and therefore they take into account first bending natural frequency (as most of chimney codes). Exception to this rule is VGB guidance, where equivalent static load is increased by multiplication by the dynamic amplification factor, calculated for the lowest natural frequency. Due to the structure type of cooling towers (typical shell structure with a low thickness to radius ratio) this vibration mode is always related to shell shape mode. CICIND code gives formulas for calculation of gust factor assuming lowest natural frequency calculated as for cantilever beam structure.

Proposal of determination of wind loading on chimney shells acc. to CICIND code

As mentioned at the beginning, many of the today's chimneys have stubby form. They have large diameters and due to today's methods of flue gas cleaning they do not require to be high. Also in many cases they are equipped with large internal flues. This implies the necessity of large openings at inlet areas. Many times such openings are too big to calculate them using typical methods, offered by chimney codes (not excluding CICIND code) and such chimneys have to be calculated using the Finite Element Methods. In order to model wind load in a FEM software, wind load needs to be calculated as a pressure acting on single shell elements. A convenient way to do this is to describe load distribution as a function of height and angle location of each element. Equation (4) allows to calculate design wind pressure at height z above grade and at angle φ around the circumference of the shell.

$$q_e(z, \varphi) = C_p(\varphi) \cdot C_e(z) \cdot q_b \qquad (4)$$

where:

$q_p(z, \varphi)$ – design velocity pressure at height z and angle φ;

$C_p(\varphi)$ – external pressure coefficient around circumference;

$C_e(z)$ – coefficient representing wind load distribution at chimney height z;

q_b – mean wind velocity pressure corresponding to mean wind velocity.

Mean velocity pressure is related to the basic 10 min wind speed as in CICIND and is calculated acc. to formula (5)

$$q_b = 0.5 \cdot \rho_a \cdot V_b^2 \qquad (5)$$

External pressure coefficient C_p, similar to a shape factor, is assumed to be constant on chimney height. The distribution of the pressure around the circumference has been assumed similar to the distribution described in Eurocode 1 [1], using cosine formulation. The basic external pressure coefficient $C_{p,0}$ is calculated as in [1], assuming end-effect factor for aspect ratio h/d equal to 10. The distribution is assumed in such a way that the resulting wind effect corresponds to the wind loading calculated using CICIND codes [4] and its shape factor C_D. Equation (6) gives the formula for calculation of the coefficient C_p assuming correction for different aspect ratios (h/d < 10):

$$C_p(\varphi) = \begin{cases} C_{p,0}(\varphi) & \text{for } C_{p,0}(\varphi) \geq 0 \\ k_\lambda \cdot C_{p,0}(\varphi) & \text{for } C_{p,0}(\varphi) < 0 \end{cases} \qquad (6)$$

Basic external pressure coefficient:

$$C_{p,0}(\varphi) = \begin{cases} (1 + 1.5/2)\cos((\varphi/80°) \cdot \pi) + 1 - 1.5/2 \text{ for } 0° \leq \varphi \leq 80° \\ (-1.5 + 0{,}5)\cos[(\varphi - 80°)/(125° - 80°)] \cdot \pi/2) - 0.5 \text{ for } 80° \leq \varphi \leq 125° \\ -0.5 \text{ for } 125° \leq \varphi \leq 180° \end{cases} \qquad (7)$$

Correction factor for different aspect ratios:

$$k_\lambda = 0.74 - 0.43\log(d/h) \qquad (8)$$

Figure 5 shows external pressure coefficient C_p for aspect ratios h/d = 4 and h/d = 10.

Coefficient C_e represents the wind load distribution along chimney height, similar to Eurocode. It can be expressed as a sum of two components. The first one is accounting for the distribution of a mean wind speed along the height, whereas the second one is representing distribution of a gust wind at different heights. The coefficient C_e can be calculated acc. to equation (9).

$$C_e(z) = C_{e,m}(z) + C_{e,g}(z) \qquad (9)$$

where:

$$C_{e,m}(z) = k(z)^2 \qquad (10)$$

$$C_{e,g}(z) = 1.29(G - 1)(z/h)C_{e,m}(h) \qquad (11)$$

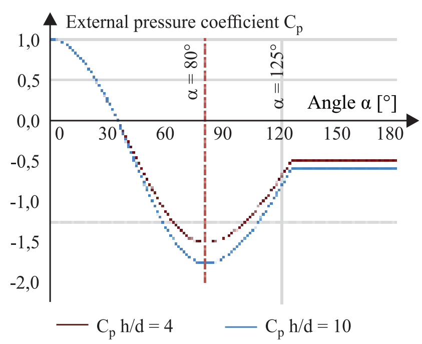

Fig. 5. External pressure coefficient for different aspect ratios

Rys. 5. Współczynnik ciśnienia zewnętrznego w przypadku różnego stosunku h/d

Height factor k(z) and gust factor G are to be calculated according CICIND model code, formulas 7.2 and chapter 7.2.3.3.2 correspondingly, with the stipulation that for the calculation of the gust factor G, first natural bending mode has to be taken. It can be easily observed that the part referred to the gust part of the wind load is linear along the height, the same as the gust wind load w_g calculated with formulas of CICIND. Coefficient C_e can be understood as an exposure factor. Figure 6 shows the same correlation between mean and gust component, the same as in case of direct wind load calculations.

Comparison of calculation results

For the purpose of comparing of the calculation procedure proposed above with the results obtained according to the formulas from CICIND, several cases have been considered. Calculations

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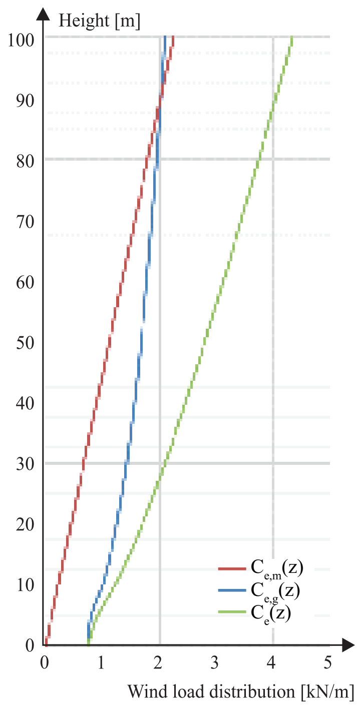

Fig. 6. Distribution of wind along chimney height (acc. to the proposed formulation)

Rys. 6. Rozkład obciążenia wiatrem na wysokości komina (zgodnie z zaproponowaną procedurą)

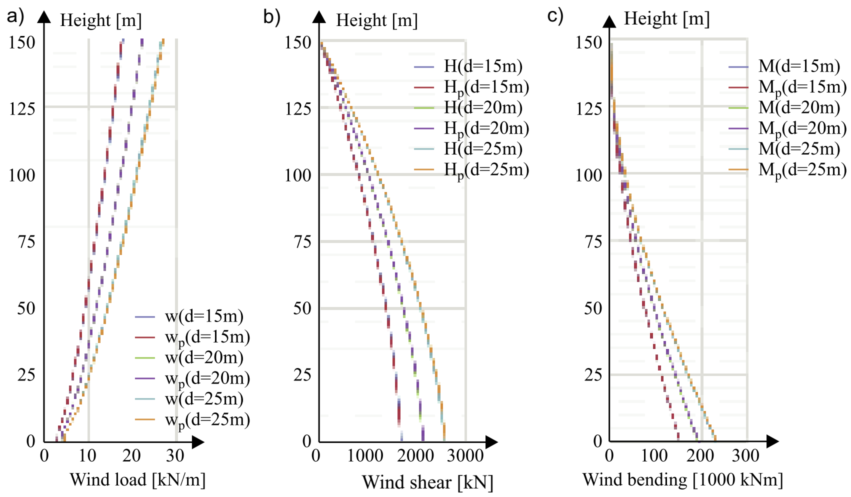

Fig. 7. Chimney h = 100 m (d = 10 m, 20 m, 25 m): wind load (a); wind shear (b); wind bending (c); p means curves acc. to the proposed formulas

Rys. 7. Komin h = 100 m (d = 10 m, 20 m, 25 m): obciążenie wiatrem (a); siła poprzeczna (b); zginanie (c); p oznacza krzywe wg zaproponowanej procedury

have been performed for seven different heights of sample chimneys (100 m up to 250 m every 25 m) and seven different diameters (10 m up to 25 m every 2.5 m). Table 2 shows considered geometries and corresponding aspect ratios. The cases taken into account are marked in yellow. Other geometries have no practical use since their small diameter compared with chimney height.

The aspect ratio of radius to wall thickness is varying and is between 10 for short chimneys with small diameter up to 25 for diameters of 25 m. Natural frequencies have been calculated with a FEM model, assuming shell elements. Figure 7 presents comparison diagrams of total wind load, wind shear force and wind bending moments for calculations acc. to CICIND and according to the above proposed procedure.

Table 2. List of analyzed cases

Tabela 2. Lista analizowanych przypadków

Height h [m]	Ratio of h/d, where d is equal to:						
	10,00	12,50	15,00	17,50	20,00	22,50	25,00
100,0	10,00	8,00	6,67	5,71	5,00	4,44	4,00
125,0	12,50	10,00	8,33	7,14	6,25	5,56	5,00
150,0	15,00	12,00	10,00	8,57	7,50	6,67	6,00
175,0	17,50	14,00	11,67	10,00	8,75	7,78	7,00
200,0	20,00	16,00	13,33	11,43	10,00	8,89	8,00
225,0	22,50	18,00	15,00	12,86	11,25	10,00	9,00
250,0	25,00	20,00	16,67	14,29	12,50	11,11	10,00

Conclusions

The paper presents the proposal of calculation of the wind load for a shell-like structures with circular cross sections, acc. to CICIND Model Code for Concrete Chimneys. The formulas provided in the paper, allow for calculation of wind in a form of pressures for different height and angle locations. The main purpose of this proposal is to provide practical and reliable method for modeling of the wind load on chimneys, which due to their geometry should be analyzed as shell-like structures. The described proposal should be understood as an invitation to the discussion about modeling of wind load in case of FEM calculations. This paper is limited to the CICIND Model Code for Concrete Chimneys, however wind loading acc. to Eurocode 1 requires also some adjustments. Both procedures of chapters 7.9.1 and 7.9.2 of EC1 are not consistent and the difference in calculations might reach 15%. Such a difference might be significant during dimensioning of the structure. The same problem can be addressed to calculation of steel chimneys acc. to CICIND and to the same calculations in case of ACI 307 [1, 2] code, where the wind loading is presented in a similar way as in CICIND standard for concrete chimneys.

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