Experimental and Numerical Investigation of In-line Standing Circular Cylinders in Steady and Turbulent Wind Flow

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Abstract. The wind pressure distribution on structures is an important parameter in terms of wind load calculation. Some wind effects, especially interference effects, are still the subject of research and experimental measurements in wind tunnels, but also in-situ. For the in-line standing circular cylinders EN standard gives only the wind force coefficient that is higher than the wind force for the stand-alone cylinder. The wind flow around in-line standing cylinders is based on distance between cylinders and their roughness and also on local wind velocities and neighboring structures. This paper deals with interference effects of air flow around the group of circular cylindrical structures. In this research, a series of parametric wind tunnel studies was carried out in BLWT Wind Tunnel in Bratislava to investigate the interference effects of in-line standing cylinders in steady and turbulent wind flow. In a steady flow in the front measurement area, we tested cylinders with smooth and rough surface at varying distance and angle of wind direction and for 10 different wind velocities from 9.6 – 19.7 m/s. The graphs of the external wind pressure distribution on the circumference of the cylinder for different wind speeds give us good information about behavior of in-line standing cylinders in steady wind flow. In a turbulent wind flow in the rear measurement area in BLWT, we tested three cylinders for different wind velocities and compared results for different positions on cylinder. Experimental results of wind pressure around cylinders were compared with CFD numerical analysis and EN 1991-1-4 standard. We chose the finite volume method implemented into program ANSYS Fluent [1], which offers several turbulence models.

1. Introduction
In the aerodynamics of structures it is necessary to determine the wind load, which is represented by a simplified set of pressures or forces for the whole structure, or for the structural parts. Characteristics of wind pressures and wind pressure coefficients were investigated recently by many authors – Strouhal, Kármán, Scruton, Davenport, Cermak, Solari, and others. Some wind effects, especially interference effects, are still the subject of research using CFD simulation and experimental measurements in wind tunnels, but also in-situ measurements.

2. Methodology
In the first phase, we tested according to [4] in the front measuring space of BLWT the smooth and rough cylinders with diameter b = 0.2m at different wind speeds and distances d between them.
In the second phase, we tested three real cylindrical structures standing in a row at a turbulent flow in nuclear power plant at different reference wind speeds. We tested the outer cylinder and the cylinder in the middle with a changing wind direction of 15°.

In the third phase, using the CFD simulation with the turbulence model SST \( k-\omega \), we obtained the distribution of the external wind pressure coefficients for in-line standing cylinders. The obtained experimental and numerical results were compared and evaluated.

3. Experimental investigation of in-line standing cylinders

Experimental measurements were made in the BLWT STU tunnel in two sectors shown in the tunnel scheme in figure 1 with steady and turbulent flow [3].

![Figure 1. BLWT STU wind tunnel scheme with two measurement sectors](image)

3.1. Experimental results in steady wind flow

In the front measuring space the smooth and rough cylinders with diameter \( b = 0.2 \text{m} \) at different wind speeds were measured. The distance between them was \( d = 0.1 \text{m} \div 0.25 \text{m} \). Position of sampling points and wind direction 0° were considered perpendicular to the longitudinal axis of the cylinder. The wind direction varied from 0° to 45°. Results of the experimental measurements - mean value of external wind pressure coefficients for different wind velocity and wind direction can be seen in table 1 and in figure 2. Comparison of the obtained values for different cylinder positions, different roughness and wind directions is shown in the graph in figure 3 for \( a/b \), where \( a = d + b \). For more detailed results from the measurement, see [6].

| \( a/b \) | Smooth cylinders wind direction 0° | Smooth cylinders wind direction 15° | Rough cylinders wind direction 0° |
| --- | --- | --- | --- |
| 1.5 | \( C_{pe} \) | \( v_{ref} \) | \( C_{pe} \) | \( v_{ref} \) | \( C_{pe} \) | \( v_{ref} \) |
| 1.75 | -3.66 | 17.02 | -3.72 | 15.92 | -2.81 | 9.68 |
| 2.0 | -3.36 | 17.02 | -3.62 | 16.02 | -2.27 | 10.74 |
| 2.25 | -3.33 | 17.22 | -3.32 | 17.14 | -2.37 | 9.77 |
| & | & | & | & | & |
3.2 Experimental results in turbulent wind flow

In the rear measuring space the smooth cylinders with diameter \(b=0.16\text{m}\), \(h=0.26\text{m}\) at different wind speeds and directions were measured in turbulent flow [7]. The distance between them was \(d=0.033\text{m}\) and \(a/b=1.2\). The external wind pressure coefficient distribution was measured for two different cylinder positions and 3 levels. The side cylinder and the cylinder in the center are shown in figure 4.

![Circular cylinders in-line](image)

**Figure 2.** External wind pressure coefficient - smooth cylinders, \(a/b = 1.5\), wind direction 0°

**Figure 3.** Comparison of mean value of external wind pressure coefficient in steady wind flow

**Figure 4.** View of the cylinders in the rear measuring space in turbulent flow. The cylinder with dark dome was measured at 3 height levels
Position of the sampling points at different levels and wind directions is visible in figure 5. The wind direction has changed by 15°. Results of the experimental measurements - mean value of external wind pressure coefficients for the largest suction on the side cylinder is shown in figure 5.

4. CFD (Computer Fluid Dynamics) simulation

For prediction of external pressure coefficients was chosen hybrid turbulence model DDES (Delayed Detached Eddy Simulation), which is part of SRS (Scale Resolving Simulations) models. From RANS (Reynolds Averaged Navier-Stokes Simulations) turbulence models was chosen SST k-ω (Shear Stress Transport) model. This model utilizes the RANS equations inside the boundary layer and an LES-like (Large Eddy Simulation) formulation for free shear flows, \([2]\).

Final volume model was created with respect to \(y^+\) approach. The \(y^+\) value is a non-dimensional distance (based on local cell fluid velocity) from the wall to the first mesh node, and is determining whether the influences in the wall adjacent cells are laminar or turbulent. In CFD often used to describe if mesh is fine or coarse. Computational domain size was set to be 6x12x1m (WxLxH) with 3m on windward side and left and right side and 9m in leeward direction. Cylinder surface elements were set to be 0.005 m. Mesh was generated under ICEM and created were 2 282 659 tetrahedron elements. Polyhedral mesh was generated under fluent solution module by converting whole domain into polyhedral mesh (see figure 6). This modification had direct influence on number of elements, which was smaller and was generated 736 628 polyhedral elements. Setup for this turbulence model simulation consists from log law velocity magnitude profile (1) and specific turbulent dissipation rate profile and turbulent kinetic energy \(k\).

\[
v(z) = \frac{v^*}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right), \tag{1}
\]

where \(v(z)\) is mean wind velocity at height \(z\), \(v^*\) is shear velocity, \(z_0\) is aerodynamic roughness height (\(z_0=0.7\)), \(\kappa\) is von Karman constant (\(\kappa = 0.42\)).

The simulation was run as transient, during time of 5s. Convergence criteria were set to \(10^{-4}\).

The wind flow around circular cylinders and the wind velocity distribution in level B are shown in figure 7. The distribution of the external wind pressure coefficient in the truncated section of the circular cylinders is shown in figure 8.
Figure 6. Detail of computer network

Figure 7. Wind velocity distribution in level B for $v_{ref} = 8.435\text{m/s}$, $\alpha = 45^\circ$

Figure 8. CFD External wind pressure coefficient in turbulent flow, a/b = 1.2, wind direction 45°
5. Results and discussions
The aim of the work was to compare the values of external wind pressure coefficients on circular cylinders standing close to each other.

Smooth cylinders, placed in low turbulence flow (at higher altitudes above ground, or in terrain category I, II where approaching flow was with turbulence intensity below 10 %) have reached suction coefficients $c_{pe} = -3.12 \div -3.72$ for Reynolds number: $2 \cdot 27 \cdot 10^5 \div 2.55 \cdot 10^5$. In the case of a rough surface, the suction values $c_{pe} = -2.26 \div -2.81$ in steady wind flow were still significantly higher than EN standard value: $c_{pe} = -2.1$ for a single cylinder.

The values obtained from the experimental measurements for smooth circular cylinders standing near each other in turbulent wind flow (near the ground in terrain category III – IV, where approaching flow was with turbulence intensity below 37.5 %) have reached $c_{pe} = -2.31$ for side circular cylinder and $c_{pe} = -2.12$ for cylinder in the middle. In the case of turbulent wind flow, a significant influence of the free end of the circular cylinder is seen at height level C - see figure 5.

Used CFD simulation showed us the same places of increased wind speed and external wind pressure coefficient on the side of the outer circular cylinder and also in the middle between cylinders, the suction value $c_{pe} = -1.43$ was lower than those obtained by experimental measurement in wind tunnel and also EN standard. In the next calculations, it will be necessary to improve the setting of turbulence parameters and boundary conditions in accordance with the experiment.

6. Conclusions
In the case of in-line standing cylinders, it is necessary to control the sidewall stresses when the structures are exposed to the wind flow with high speed and low turbulence.

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