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EXPERIMENTAL AND NUMERICAL FLUID ANALYSIS OF THE INFLUENCE OF NPP BUILDINGS TO WIND IMPACT ON THE VENTILATING CHIMNEY

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Abstract: *This paper describes the experimental and numerical analysis of the wind impact on ventilating chimneys considering the effect of surrounding buildings. Based on meteorological monitoring of the locality, the extreme load was defined for the return period 10^4 years using the Monte Carlo simulations. An overview of calculation models and methods for an analysis of the ventilating chimney in the wind flow is presented. The wind load was determined using numerical analysis in Ansys Fluent and experimentally in a wind tunnel. The results of the numerical analysis and of the experimental wind tunnel test are shown in the table.*

Keywords: Wind load, Ansys Fluent, Experiment, Wind tunnel, Eurocode.

1. Introduction

This paper deals with the analysis of the extreme wind impact on the ventilating chimney. This chimney is situated in NPP buildings and the actual wind load is different from that defined in Eurocode requirements. The international organization IAEA in Vienna (IAEA, 2003) has set design requirements for the safety and reliability of the NPP structures. Extreme environmental events (e.g., wind, temperature, snow, explosions) (NRA SR, 2011) are the important loads in terms of the NPP safety performance. Extreme wind loads are defined with the probability of mean return period equal to one per 10^4 years (SHMU, 2012). The U.S. Nuclear Regulatory Commission and Nuclear Regulatory Authority of the Slovakia have issued a set of regulatory guidelines for NPP risk analysis (NUREG/CR, 1992; NRA SR, 2011).

2. Experimental analysis of extreme wind impact

Before starting the experimental work, it was necessary to identify critical areas on the surfaces of individual objects for the placement of measuring points due to the limited possibilities of the number of scanners for measuring pressures in the wind tunnel. The extreme wind impact on NPP buildings was considered in wind tunnel of STU Bratislava (Hubová, et al, 2020). The ventilation chimney was one object near the NPP buildings with the reactor VVER 440 (Fig.1 and 2). This structure is made of reinforced concrete with the following parameters: high 125m, lower outer diameter ø 10.95 m up to a height + 30m, from a level of + 30m conically descending to an upper outer diameter of ø 5.8 m, the wall thickness at the base is 0.525m, at the top 0.2m. The models of the NPP buildings were considered without and with surrounding buildings. The objects were assembled on a 3D printer in a scale of 1: 300. The block was placed behind a modelled and experimentally verified boundary layer of terrain with a roughness length of z_0 = 0.05 (terrain II), which meets the criteria for the mean wind speed, turbulence intensity, integral turbulence length and spectral density. The solved modelled area was placed on a turntable with a diameter of d = 2.0 m, which considers the real surroundings with a diameter of 600 m. The rotary table rotated in 22.5º increments controlled by LabVIEW, which simulated a change in the direction of the wind acting on the objects. These directions were supplemented by wind directions 14º, 104º, 194º and 284º (Fig.2) to consider the perpendicular wind directions to the individual walls of the halls. From the evaluation of the measured data, we determined the most unfavorable position with the maximum values.

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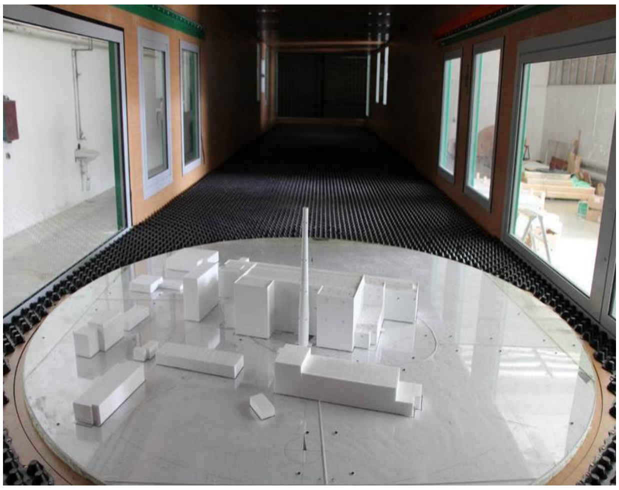

Fig. 1: Experimental model of NPP structures in the wind tunnel.

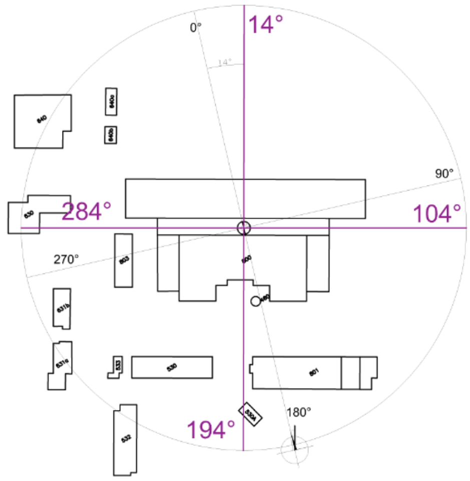

Fig. 2: Orientation of the wind impact in the wind tunnel.

The measured values of external wind pressures on the surfaces of objects for different reference speeds were averaged and converted to peak values of wind pressures using the external wind pressure factor:

$$c_{\mathrm{pe}} = \frac{p}{1/2 \cdot \rho \cdot v^2} \tag{1}$$

where p is the difference in pressure on the external surface of the model and the static pressure. In the denominator is the wind pressure corresponding to the reference wind speed at the upper level of the roof. The results from the experimental analysis were used to verify the numerical model of the NPP structures and numerical methods in software Ansys Fluent (Králik, 2020).

3. Numerical analysis of extreme wind in ANSYS-FLUENT

The computational fluid dynamics is based on the numerical solution of a system of partial differential equations that express the law of conservation of mass (continuity equation), the momentum conservation law (Navier-Stokes equations) and the law of conservation of energy (Matsson, 2021; Menter et al., 2020; Michalcová et al., 2017). This basic set of equations can be extended by others that express the transfer of impurities (gaseous liquid or solid). The whole system is then solved by one of the numerical methods, most often by the finite volume method (Michalcová et al., 2017). The model represents a flow simulation using Reynold's equations, and even with significantly lower computational complexity, it retains a sufficient solution quality (Michalcová et al, 2017). For 3D analysis, a powerful 16-processor Dell computer with 64GB of RAM was used. 3D model was created in the AutoCAD program and subsequently imported into the program Ansys-Fluent (Králik, 2020). This program has various turbulent calculation models (Spalart - Allmaras, k-ε model, and k-ω model). After considering all the influences, as well as the complexity and accuracy of individual turbulent models and previous experience with individual turbulent models (Matsson, 2021), we choose the k-ω model, which gave the best results in comparison with the experimental results. In the case of a 3D model, the following computational domain is recommended - in front of the model 5H, behind 10H, above 4H and below 5H, where H is the characteristic model dimension; the overall dimensions of the computational domain were 1172x2154x750m. A total of 14 characteristic computational models in 3D space were created. The FE model was created with 1 122 685 nodes and 6 340 840 tetrahedron elements type (Fig. 3). Subsequently, the entire domain within the "tetrahedron" elements was transformed into "polyhedral" type of elements, which represent a volume element with 12 nodes. In this way, a reduction in the number of elements to 1 193 211 was achieved, which represents a reduction of the number of elements 5.3 times. All simulations were performed with the same solver settings. It was a "Pressure-Based" model and a time-varying "transient" task. Two turbulent models, Standard k-ω and SST k-ω, were considered. During the simulation, residues were monitored, namely continuity, X-velocity, Y-velocity, Z-velocity, parameters k and ω. The convergence of the solution was defined by setting the maximum residual value. The start of the simulation took place during the first 1500-time steps with a time step of 0.03 s. This represented the first 45 seconds when a steady flow was achieved with the monitors set to 10^{-4}. Then data collection was started as part of the "transient" analysis, which took place over 4000 steps with a time step of 0.03 s. Thus, data collection took place for 2 minutes at steady flow, with the monitors set to 10^{-5}. The wind logarithmic profile that entered the simulation in the form of the UDF was defined as follows (Matsson, 2021):

$$U(z) = \frac{u_{ref} \cdot \kappa}{\kappa \cdot \ln\left(\frac{z_{ref} + z_0}{z_0}\right)} \cdot \ln\left(\frac{z + z_0}{z_0}\right) \tag{2}$$

where the reference velocity is $u_{ref} = 35.64\ \mathrm{ms}^{-1}$ (SHMÚ, 2012) for height $z_{ref} = 10$ m and terrain roughness $z_0 = 0.05$ m and von Karman constant $\kappa = 0.4$. The dissipation parameter ω is defined in the UDF model as the friction rate of a fluid (or air), which was defined in the form:

$$u^* = \frac{u_{ref} \cdot \kappa}{\ln\left(\frac{z_{ref} + z_0}{z_0}\right)} = \frac{35.64 * 0.4}{\ln\left(\frac{10 + 0.05}{0.05}\right)} = 2.688\ \frac{m}{s} \tag{3}$$

The relative profile of turbulent dissipation is considered as

$$\varepsilon(z) = \frac{u^{*3}}{\kappa \cdot (z + z_0)} \tag{4}$$

The specific profile of turbulent dissipation is

$$\omega(z) = \frac{\varepsilon(z)}{k} \tag{5}$$

where k is the kinetic energy of turbulence, defined in the form

$$k = \frac{u^{*2}}{\sqrt{C_\mu}} = \frac{2.688^2}{\sqrt{0.09}} = 24.087\ \frac{m^2}{s^2} \tag{6}$$

where $C_\mu = 0.09$ is the model constant.

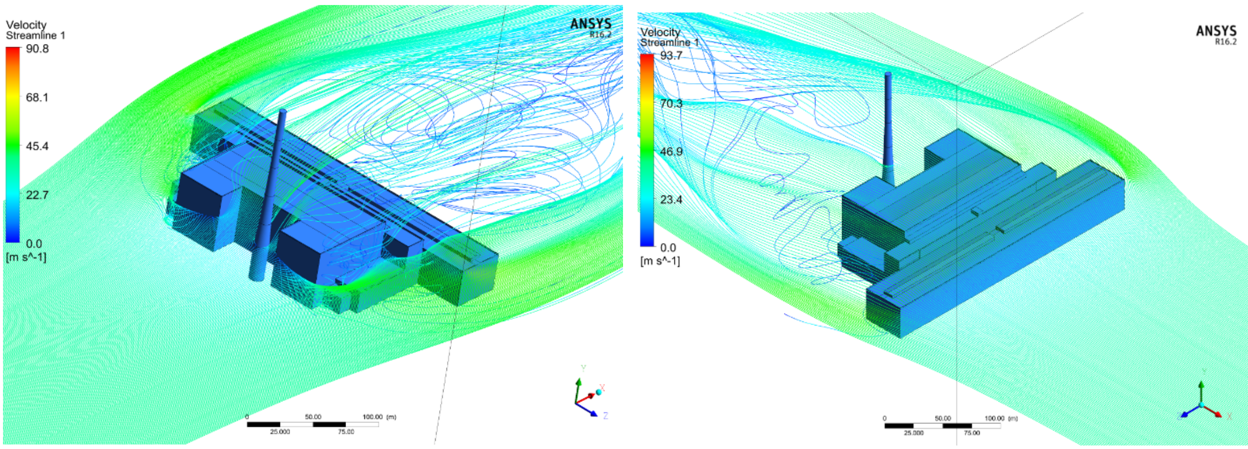

Fig. 3: The wind flow around the NPP ventilating chimney at level +15m, flow direction +X and -X.

Possible errors can also occur in defining boundary conditions as well as in computational processes during the simulation and processing of the results in the postprocessor. The resulting pressures from extreme winds were therefore considered (Tab.1) as the best estimate corresponding to the average value of the reduced peak pressures (according to the Eurocode 1) from the experiment and the values obtained by numerical simulation on a 3D model (Fig.3). We can see the differences between experimental and numerical analysis (Tab.1). The differences between the experimental and numerical results are also since in the case of the experiment, the influence of the surrounding buildings within the NPP areas was also considered.

Tab. 1: Comparison of the experimental and numerical analysis of the c_{pe} factors.

Wind impact		Methods	Level of section [m]			
Direction	Wall		27,60	53,7	81,3	113,4
South	Windward	Experiment	0,05	0,64	1,14	1,37
		Fluent	0,30	0,59	0,77	0,90
North	Leeward	Experiment	-0,46	-1,03	-1,17	-1,27
		Fluent	-0,30	-1,35	-1,49	-1,58
West	On side	Experiment	-0,77	-1,70	-1,33	-1,53
		Fluent	-0,58	-1,49	-1,62	-1,54

The wind pressure on the chimney is defined in following form

$$w_e = q_p\left(z\right).c_{pe}, \tag{7}$$

where $q_p\left(z\right)$ is the peak of the wind load defined in the standard STN EN 1991-1-4 and the factor c_{pe} is used from the Fluent analysis of the extreme wind impact to the chimney.

4. Conclusion

This paper presents the experimental and numerical analysis of the influence of NPP buildings on the wind impact on the ventilating chimney (Králik, 2020; Hubová et al, 2020). The extreme loads were defined for the mean return period equal to one per 10^4 years in accordance with the IAEA and NRA SR requirements for NPP structures. In the past, the wind loads were defined on the basis of Eurocode recommendations. Based on this new wind load, the probability analysis of the safety and reliability of the chimney was performed. The main problem of the wind resistance of NPP structures was that the actual pressures of the wind impact are indifferent in comparison of the Eurocode simple model (Králik, J. and Králik, J. jr. , 2020).

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