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Wind influence on the spent nuclear fuel safety in dry cask storage

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Abstract. This article examines the effect of wind load on the safety of spent fuel storage in a naturally ventilated building. To assess the influence of wind influences characteristic of the Akkuyu NPP site on the temperature of fuel rod cladding, a CFD model of the spent fuel storage building was developed. Reynolds-averaged governing equations of motion (RANS model) with a k-ε turbulence model were used. Computational grid included about 17 million cells. The CFD model allowed us to study different directions and intensities of wind loads, estimate the temperature around the containers and identify stagnant zones. Based on the modeling results, the dependences of the influence of wind load on the thermal fields in the building were obtained. These dependencies allowed for design decisions to be made that guaranteed safety and ensured the continuation of construction of the building.

1 Introduction

When buildings and structures that are responsible for the nuclear and radiation safety of nuclear power plants are designing, assessing the influence of site parameters on safety conditions of operating nuclear power plants and risks of accidents beginning. Based on the results of such an analysis, some initiating events, both man-made and natural, can be qualified as design basis accidents or beyond design basis accident. If such initiating events are identified, technical solutions must be adopted in the NPP design to ensure the principle of defense in depth.

One of the factors affecting the integrity of the elements of load-bearing structures is wind influences. A gust of wind, on the one hand, is a dynamic load, and on the other hand, in the case of designing buildings with venti-lation natural convection, it is a disturbance introduced into the established movement of airflow inside the building. With such a ventilation system, it is necessary to additionally evaluate the impacts on internal building envelopes and objects. At the same time, the intake of a large amount of air with physical environmental parameters over a long period of time (temperature, humidity, concentration of impurities) leads to changes in temperature conditions and air quality.

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The Akkuyu NPP spent nuclear fuel storage facility (Dry Cask Storage Facility of Spent Nuclear Fuel - SNFF) of the dry type is designed taking into account the requirements for the functioning of natural convection, which ensures cooling of containers with spent nuclear fuel. Containers with spent nuclear fuel are located in the central part of the storage facility. Air comes in SNFF through openings in the enclosing structures. The contain-ers are thick-walled cylinders with high radiation and mechanical strength and do not allow leakage of radioac-tive substances. One container holds 18 spent fuel assemblies of the VVER-1200 project. The container height is 6.2 m, the diameter is 2.5 m. Thus, air comes the building through the openings, moves towards the containers, warms up, rises up and exits through the openings in the roof. The SNFF building, airflow direction and container placement plan are shown in Figure 1.

The walls and roof of SNFF have a thickness of 1.6-1.8 m, consist of heavy concrete with a density of up to 2500 kg/m^3. SNFF maintain integrity an earthquake amplitude of up to 8 points on the Richter scale and heavy commercial aircraft and light aircraft crash. Containers do not capsize upon with corresponding fluctuations of load-bearing building structures and floor.

At the Akkuyu NPP site, measuring mast located at a height of 42 m above sea level. During the observation period from 2011 to 2013 average wind speed ranged from 1.7 m/ c to 8.9 m/s. Statistical theoretical intensive values wind gusts of 1 time in 100 years and 1 time in 10,000 years are 27 m/s and 46 m/s. The values of dynamic loads from wind are several orders of magnitude lower than the impacts associated with aircraft crashes, so the wind cannot lead to the destruction of enclosing structures and containers, which finally guarantees nuclear and radiation safety under such influences.

At the same time, the air temperature at the Akkuyu NPP site is +32.9 ℃ 88 hours per year, +44.2 ℃ is the maximum observed, +50.4 ℃ is the extreme temperature once every 10,000 years. To assess the impact on the safety of placing spent fuel in containers, the safety criterion based on the temperature of the fuel rod cladding 350 °C was used. When wind load exposed at the SNFF to for a long time, stagnant zones may form inside the SNFF, which can lead to fuel overheating.

The purpose of this research is to math modelling the external and internal airflow in the SNFF building un-der external influence of wind influences of varying intensity and direction to determine the nature of air move-ment, temperature and stagnant zones inside the SNFF.

The three-dimensional model of the SNFF and the container placement plan are shown in Figure 1.

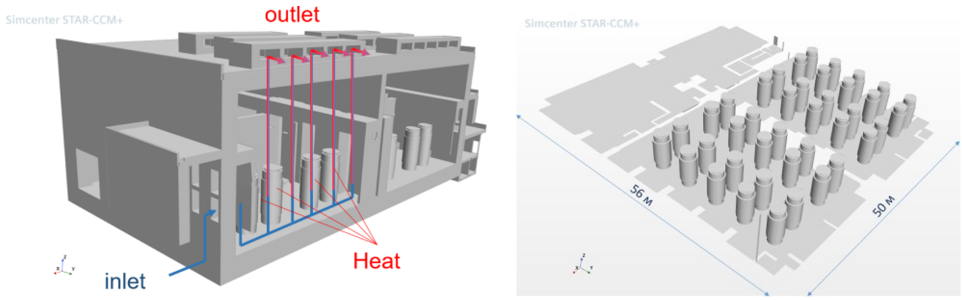

Fig. 1. SNFF 3D model on the left, container layout plan on the right.

2 Materials and methods

The calculation model was developed in StarCCM+ software. For the problem under consideration, taking into account [1-7], Reynolds-averaged governing equations of motion (RANS model) with a k-ε turbulence model were used. For an incompressible fluid, the Navier-Stokes equation is presented as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho U) = 0 \tag{1}$$

Law of impulse conservation:

$$\frac{\partial(\rho\, U)}{\partial t} + \nabla(\rho\, U \otimes U) = -\nabla p + \nabla(\tau - \rho\, \overline{u \otimes u}) + S_m \tag{2}$$

Law of energy conservation:

$$\frac{\partial \rho\, h_{tot}}{\partial t} + \nabla(\rho U\, h_{tot} + \rho\, \overline{uh} - \lambda \nabla \mathrm{T}) = \frac{\partial p}{\partial t} + S_E \tag{3}$$

Where ρ – density; t – time, U – velocity vector; u – turbulent component of velocity U; τ – molecular stresses; S_m – source term in the momentum equation; T – temperature; p – pressure; S_E – source term in the energy equation; h_{tot} – total enthalpy of air:

$$h_{tot} = h + \frac{1}{2}U^2 + k \tag{4}$$

Where h – enthalpy of air, k – kinetic turbulent energy:

$$k = \frac{1}{2}\,\overline{u^2} \tag{5}$$

In the above equations, the underscore above means averaging over time.

Reynolds stresses ($-\rho\, \overline{u \otimes u}$) is determined as follows:

$$-\rho\, \overline{u \otimes u} = -\frac{2}{3}\rho k \delta - \frac{2}{3}\mu_t \nabla U \delta + \mu_t(\nabla \mathrm{U} + (\nabla \mathrm{U})^T) \tag{6}$$

Here, δ - is a matrix with diagonal elements based on the δ - function, μ_t – is the coefficient of turbulent viscosity.

To close the presented system of equations, there are two families of models k-ε (ε - is the dissipation rate) and k-ω (ω - is the specific dissipation rate or frequency of turbulent pulsations) currently mainly use for practical calculations. Chose turbulence model is included into system, by additional equation.

The coefficient of turbulent viscosity is related to turbulent kinetic energy as:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \tag{7}$$

Where C_μ is constant, ε is energy dissipation rate.

The building openings (the presence of grilles and ventilation devices) was modeling by a porous medium model.

Containers are considered as volumetric heat sources. The internal elements of containers are not modelled. Thermal calculations of containers are a separate task of research and analysis. The boundary conditions for heat release from containers were set to 864 kW for 40 pieces. Resistance of openings is 6. A stationary formulation of the problem was used. To assess the influence of the wind load direction, the following boundary conditions were considered: [1,0,0], [0,1,0], [- 1,0,0], [0,-1,0], [1,1, 0]. The direction and location of the axes are shown in Figure 1. The wind direction [1,1,0] corresponds to the daytime breeze at the Akkuyu NPP site.

To construct a computational mesh, the built-in computational mesh generator is used. The basic cell size of 0.25 m was determined based on the analysis of the grid error with deviations in air flow and velocity in the rooms and volumetric temperature of no more than 5%. The construction of the grid model was used taking into account [8-10]. When approaching the boundary layer, the cell size decreases to 0.025 m. In the course of assessing the grid error, calculations are made using a computational grid of size from 1 million cells up to 30 million cells. The final grid size was 17 million cells. The calculation grid in the openings and around the containers is presented in Figure 2.

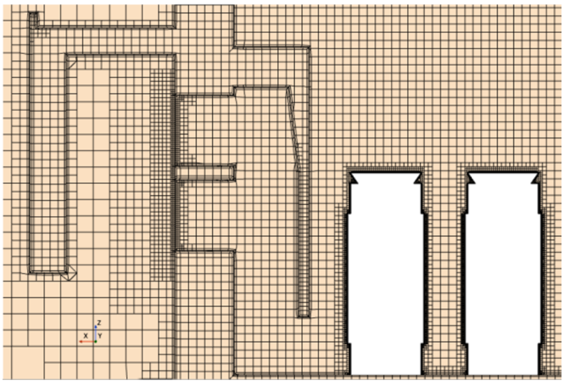

Fig. 2. Calculation grid in openings and around containers.

3 Results

The results of calculations of hydrodynamic and thermal processes during the interaction of wind with the NPP spent nuclear fuel storage facility are presented in Figures 3-7. These calculations were performed for a wind speed of 2.3 m/s, which is typical for daytime breezes.

Figures 3-4 show the distribution of air temperature at the elevation of 6 m in the area where the containers are located for wind directions [1,0,0], [0,1,0], [-1,0,0], [0, -1.0], respectively.

Figures 5-6 show the streamlines at the elevation of 6 m in the area where the containers are located for wind di-rections [1,0,0], [0,1,0], [-1,0,0], [0,-1 ,0], respectively.

Figure 7 shows the distribution of air temperature at the elevation of 6 m in the area where the containers are located and the streamlines for the wind direction [1,1,0].

Figure 8 shows the distribution of air temperature at the elevation of 6 m in the area where the containers are located and the streamlines for the case of the wind absence.

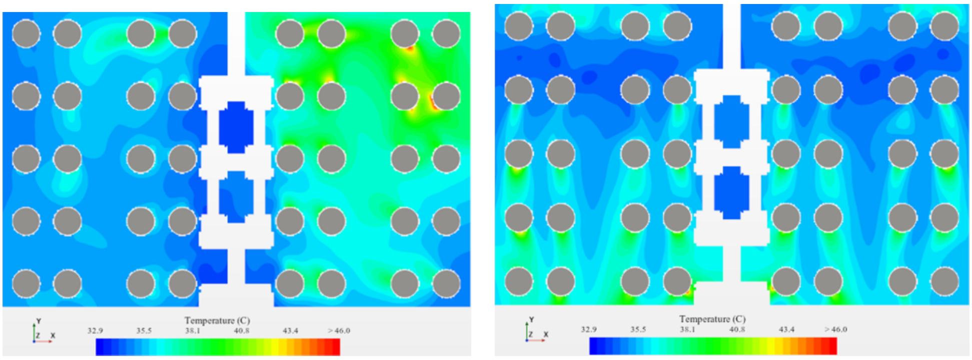

Fig. 3. Air temperature distribution at 6 m in the area where containers are placed for wind direction [1,0,0] on the left, [0,1,0] on the right (scale from 32.9℃ to 46℃).

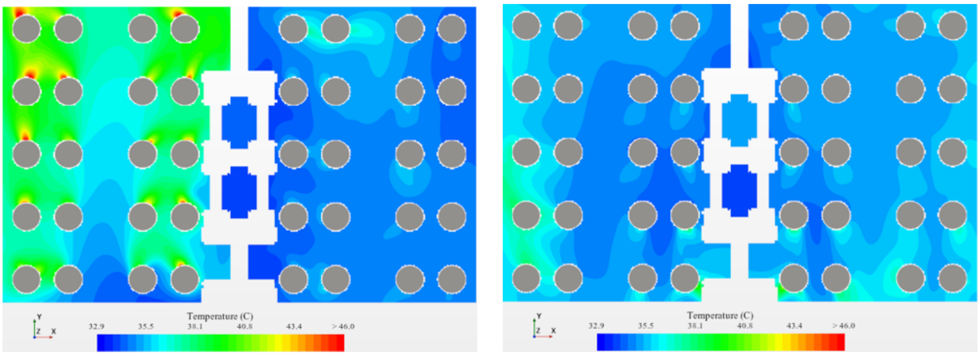

Fig. 4. Temperature distribution at 6 m in the area where containers are placed for wind direction [-1,0,0] on the left, [0,-1,0] on the right (scale from 32.9℃ to 46℃).

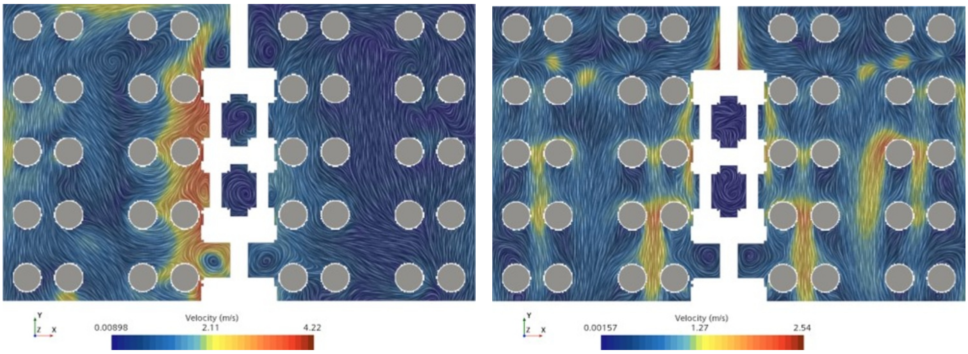

Fig. 5. Distribution of streamlines at 6 m in the area where containers are placed for wind direction [1,0,0] on the left, [0,1,0] on the right (scale from 0 m/s to 4.2 m/s on the left, from 0 to 2.5 m/s on the right).

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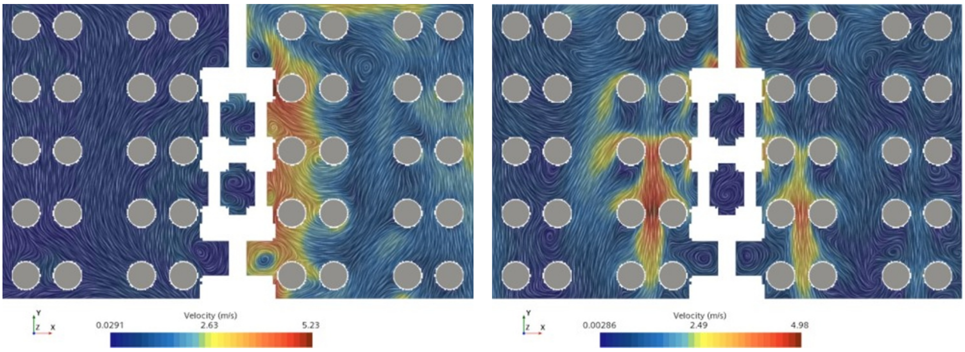

Fig. 6. Distribution of streamlines at 6 m in the area where containers are placed for wind direction [-1,0,0] on the left, [0,-1,0] on the right (scale from 0 m/s to 5.2 m/s on the left, from 0 to 5 m/s on the right).

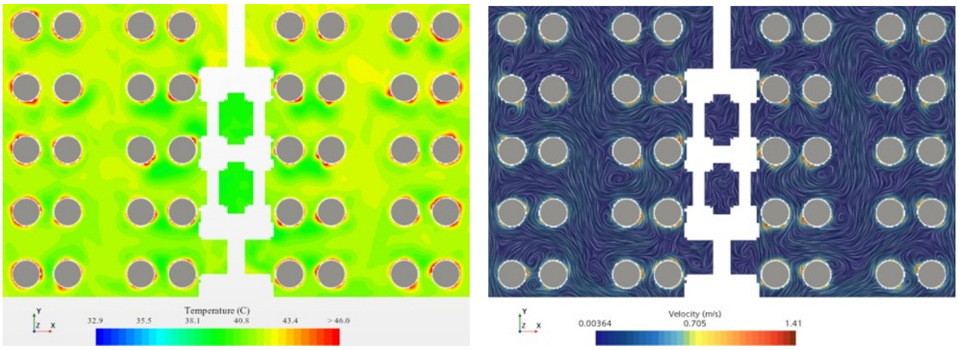

Fig. 7. Temperature distribution (left) and the distribution of streamlines (right) at 6 m in the area where containers are placed for wind direction [1,1,0] on the left. (scale from 32.9℃ to 46℃ on the left, from 0 to 1.4 m/s on the right).

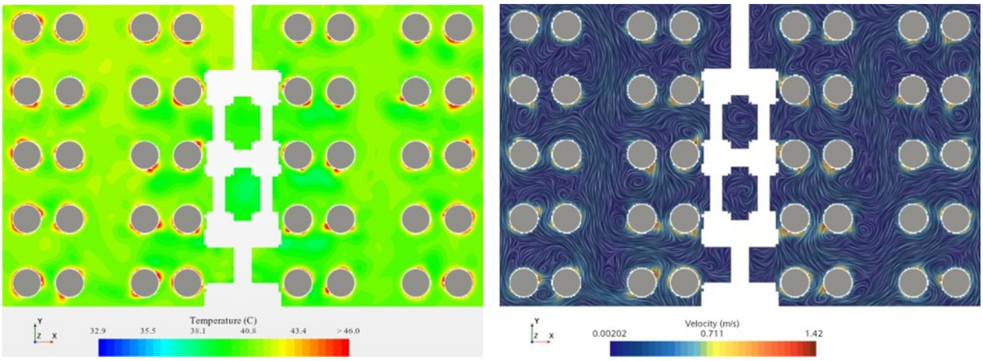

Fig. 8. Temperature distribution (left) and the distribution of streamlines (right) at 6 m in the area where containers are placed in the absence of wind load. (scale from 32.9℃ to 46℃ on the left, from 0 to 1.4 m/s on the right).

The figures presented above show the significant influence of the magnitude and direction of the wind on the air circulation inside the storage facility, which in turn determines the rate of heat removal from the containers.

Stagnant zones observed in remote areas of the building were also identified (Figures 3-6, on the left). Moreover, for such a wind direction, the local increase in air speeds along the internal wall is maximum.

Zones with the highest temperatures are formed in places with low air circulation, which indicates the cor-rectness of the calculation model.

Figures 9-10 show the dependence of the average air flow velocity in the openings of contour walls and roofs on the intensity of the wind load. Wind load direction is [1,1,0].

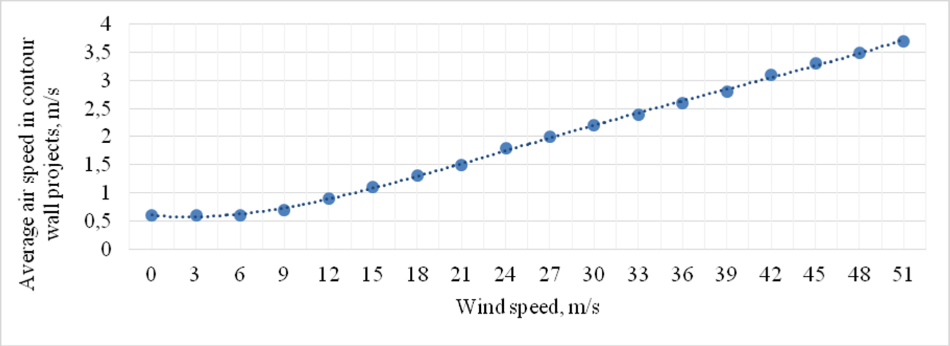

Fig. 9. Dependence of the average air flow speed in contour openings walls from the intensity of wind load.

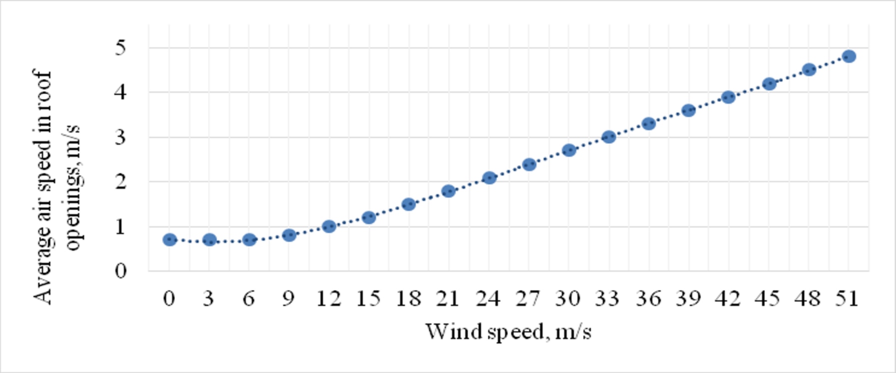

Fig. 10. Dependence of average air flow speed in roof openings on the intensity of the wind load.

In Figures 9 and 10, in the range of wind speeds from 9 m/s to 50 m/s, a linear dependence of the average air speed in the roof openings on the wind speed is observed.

4 Discussion

The results of the calculations show a dual effect of wind speed on heat transfer from containers into the air circulating between them. With different wind directions and its magnitude, it can both promote heat removal from containers and create conditions for poor heat removal.

At first glance, a heat-loaded mode should occur in the case when there is no wind load. In this case, natural convection occurs without intensification by wind. However, the calculation results show something different. In some modes with an external wind load, the heat removal from the fuel pump deteriorates due to disturbances introduced into the formed heat flows.

Also, based on the calculation results, the effect of blocking the openings was revealed, which can be seen in Figures 9 and 10. This effect is due to the presence of external and internal partitions (Figure 2). The air flow, passing in the space between the partition and the wall, becomes turbulized, the core of the flow is destroyed, resulting in the creation of a hydraulic jam. When the wind speed near the wall exceeds 6 m/s, the energy of the air flow is sufficient to overcome the barrier in the form of partitions without destroying the core of the flow.

The above findings are not affected by grid factors, since the grid-accurate model used in the calculations ensures the convergence of the numerical solution.

It should be noted that this study did not consider direct solar radiation on the roof and walls of the SNFF building. The flux of solar energy onto the roof and walls of the SNFF building can be an additional factor that impairs the heat transfer from containers. Taking into account the influence of this factor requires modification of the mathematical model and will be performed in future studies.

5 Conclusion

Based on the results of numerical modeling of the wind impact on the SNFF building of the Akkuyu NPP, it was revealed that the greatest thermal load on the containers occurs under the wind direction [1,1,0]. At the same time, this wind direction at the Akkuyu NPP site is most likely, since it corresponds to the daytime breeze. Taking into account the requirements for conservatism of boundary conditions for assessing safety criteria, in particular the temperature of the fuel element cladding, the effect of the daytime breeze must be taken into account. In this case, the wind speed must be set based on the most probable characteristic of the Akkuyu NPP construction site.

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