

COMPARISON OF THE WAKE IN FREE STREAM AND THE WAKE IN CONFINED OPEN CHANNEL OF NUCLEAR REACTOR FUEL ASSEMBLY

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Abstract

We empirically compare the wake of a streamwise-aligned cylinder – a short cylinder facing the flow (i.e. cylinder axis parallel to the flow direction) – placed in both: the free stream of a wind tunnel and in the confined channel between fuel rods of nuclear fuel assembly for pressurized water reactors VVER (i.e. with triangular symmetry of the rod arrangement). This kind of channel is special as the walls are concave (in classical pipe-flow, the walls are convex), and the channel is open to the neighboring channels. Stereo Particle Image Velocimetry (PIV) is applied to a plane perpendicular to the flow in three positions (from $2.3D$ to $11.3D$, D is the cylinder diameter) downstream of the grid holding the obstacle alone, or the fuel rods as well. As expected, the wake is completely different due to the different topology of the flow domain. When we compare the confined wake (with rods) to the unconfined wake (no rods), then the following observations are made: at early stage, the velocity deficit is deeper; later (since $z = 4.5D$) it is shallower. The area directly influenced is smaller at all stages. Fluctuations display larger values at all distances. The skewness of stream-wise velocity distribution shows a ring of negative skewness, but this ring is much weaker and it disappears completely at last explored distance ($z = 11.3D$). This is the most pronounced difference, which seems to be of principal importance. Future investigations (experiments & data analysis) are needed.

Keywords: Particle Image Velocimetry, Wind tunnel, Wake, Nuclear fuel.

1 Introduction

In recent years, increasing attention has been paid to the problem of foreign object intrusion into the primary circuit of nuclear facilities, especially in connection with their possible entrapment in the area of the fuel assembly grids [1, 2, 3, 4, 5]. This phenomenon can be of a twofold nature – on the one hand, there is a local restriction of the flow cross-section, which can affect the thermohydraulic conditions and the heat transfer from the fuel rod to the coolant.

If an obstacle is presented in the flow, then it creates a wake. The hydrodynamic community has plenty of knowledge about turbulent wakes [6, 7, 8, 9, 10] including the oscillating obstacle [11]. This knowledge is mostly on empirical basis. The wake flow often causes periodic behavior [12, 13] potentially endangering mechanical parts by vibrations.

The aim of this short conference contribution is to empirically compare the wake of a streamwise-aligned cylinder – a short cylinder facing the flow (i.e. cylinder axis parallel to the flow direction) – placed in both: the free stream of a wind tunnel and in the confined channel between fuel rods. This kind of channel is special as the walls are concave (in classical pipe-flow, the walls are convex), and the channel is open to the neighboring channels.

2 Experimental setup

Due to the limited length of this contribution, we just link the interested reader to our previous works. The wind tunnel used during this study is described in [14]. The schematic of the test setup

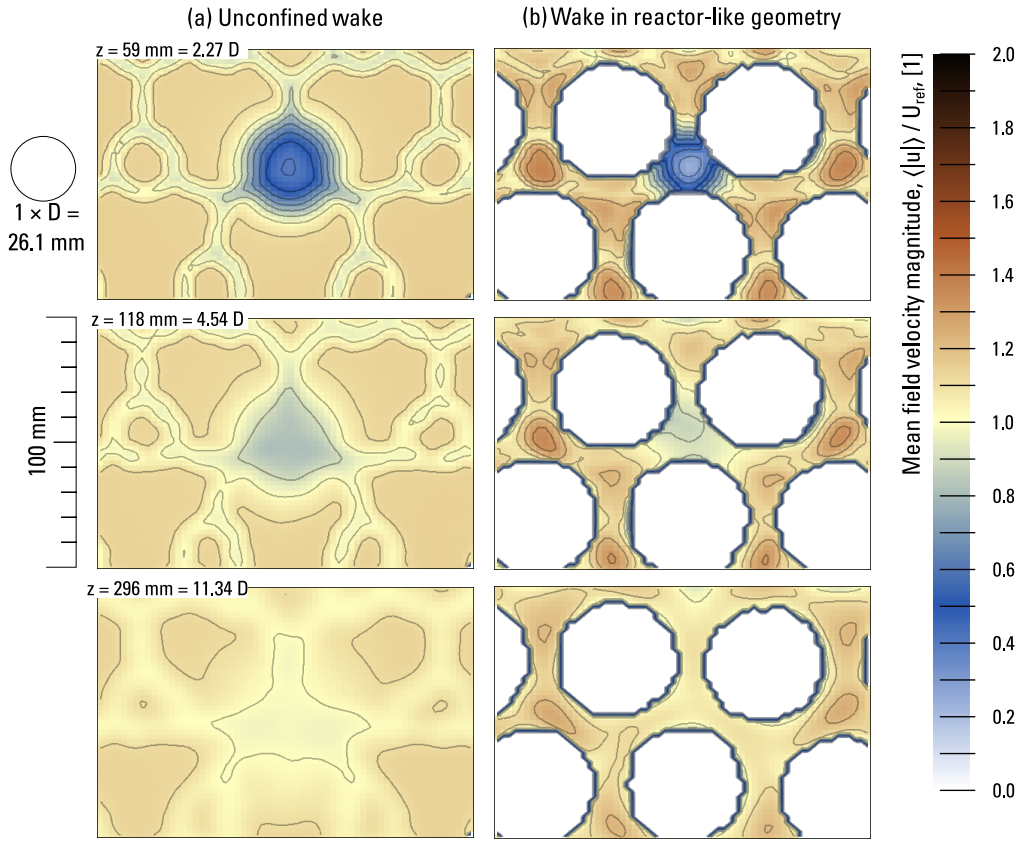


Figure 1: Magnitude of velocity of the ensemble-averaged velocity fields. Left column (a) shows the case with an obstacle mounted on a grid in free stream. Right column (b) displays the case, when there are stream-wise-oriented rods touching the obstacle; the geometry is similar to that in a nuclear reactor of pressurized water type. Lines represent different downstream distance of measuring plane from the grid with obstacle.

including positions of PIV measurement planes is described in [15], so as at the Figure 2. It is a open, low-speed wind tunnel with test section of size $0.3 \times 0.2 \times 3.0 \text{ m}^3$. The reference velocity at current experiment is set to $U_{\text{ref}} = 20 \text{ m/s}$. Note, that in the constrained case, the velocity has to be set to a smaller value of $U_{\text{tunnel}} = 10.76 \text{ m/s}$ to obtain the required U_{ref} due to the blockage effect of the fuel rods.

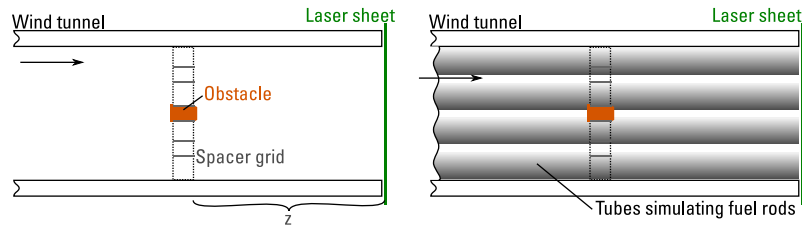


Figure 2: Simplified schematic layout of the test setup, including the position of obstacle in the spacer grid inside the wind tunnel. On the left without fuel rods, on the right with fuel rods; z - distance of the obstacle from measurement plane.

The Particle Image Velocimetry (PIV) system is introduced by [16]; our apparatus is described in works [17, 18, 19] and the algorithm used for data processing in [20]. The data are measured by using the Stereo PIV configuration, i.e. a single plane illuminated by the laser is observed by using two cameras. The plane is perpendicular to the axes of the fuel rods (i.e. axis of the wind

tunnel and the stream direction). The laser is double-pulsed and the motion of particles (fog of Safex [21]) is captured between the two pulses separated by $\Delta T = 40 \mu\text{s}$. The velocity vectors are calculated by using the built-in function *Adaptive PIV* within the software *Dantec Dynamic Studio* 6.4. The resolution of the PIV vector grid is $\Delta x = 2.4 \text{ mm}$.

The following dimensions of the model are adopted: the diameter of the obstacle $D = 26.1 \text{ mm}$, the distance of the rods (if they are used) is $M = 59.1 \text{ mm} = 2.26D$, the diameter of the rods is $D_r = 42.2 \text{ mm} = 1.62D$. The hydraulic diameter of the channel $D_h = 49.1 \text{ mm} = 1.88D$ (some studies of nuclear fuel assembly use D_h as the leading length parameter [4, 22, 23, 24, 25]). Note that the values of M , D_r and D are such, that D is the maximum inscribed circle between the rods. The D_r/M ratio corresponds to the geometry of VVER-1000 nuclear reactor. The Reynolds number based on D and on the reference velocity U_{ref} is $\text{Re}_D = 3.24 \cdot 10^4$.

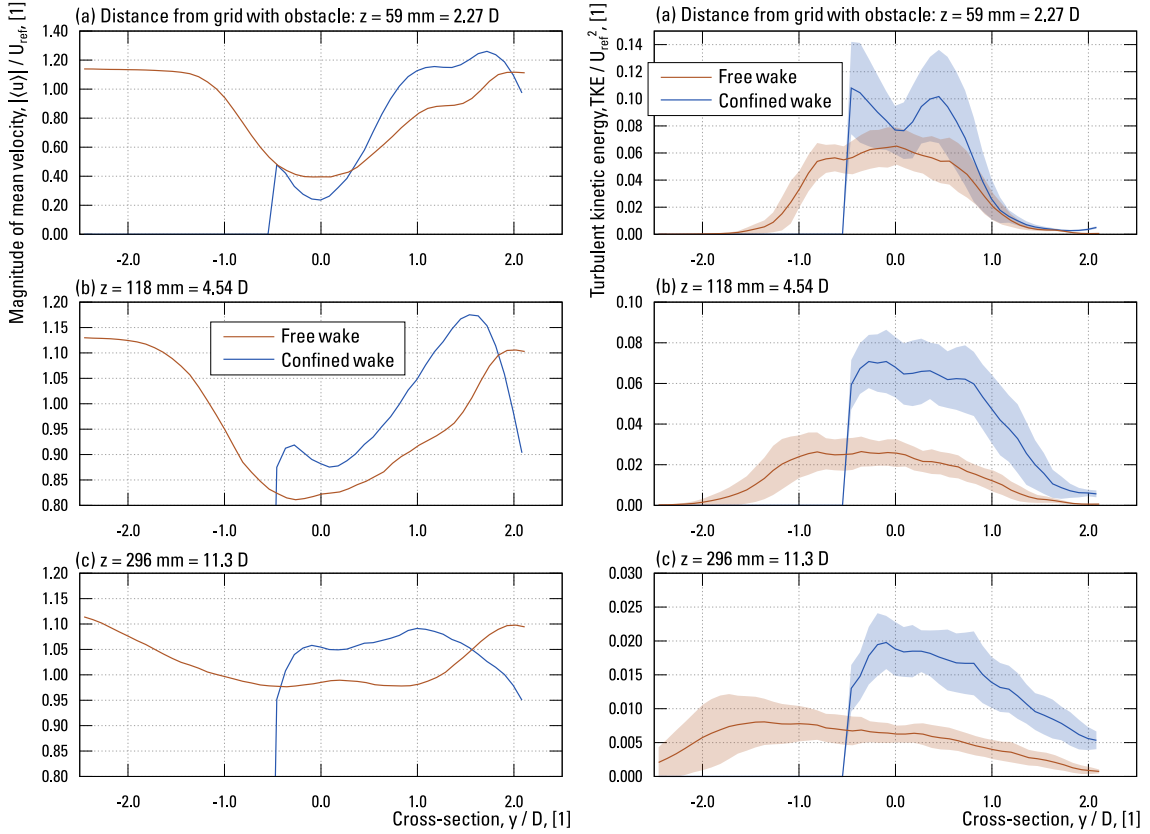


Figure 3: Sections along y -axis (vertical in Fig. 1). Left: the velocity magnitude of the ensemble-averaged velocities, $|\langle u \rangle| = \sqrt{\langle u \rangle^2 + \langle v \rangle^2 + \langle w \rangle^2}$. Right: the turbulent kinetic energy. The shaded area represents the uncertainty of the measured signal calculated as the standard deviation of the subensembles, when the full ensemble is divided into 10 subensembles.

3 Results

3.1 Mean field

The Particle Image Velocimetry plane covers the central part of wind tunnel cross-section, at the wind tunnel outlet. Figure 1 displays the magnitude of the mean velocity, $\sqrt{u^2 + v^2 + w^2}$. Note that in addition to the *shadow* of the obstacle (projected as a circle in the central part of the Field of View (FoV)), there is also the *shadow* of the grid. This grid firmly holds the obstacle in place. The fuel rods are held by this grid as well. Due to mass conservation, the free stream displays values slightly larger than 1. The obstacle produces a clear wake, which is apparent up to $11.3D$ downstream.

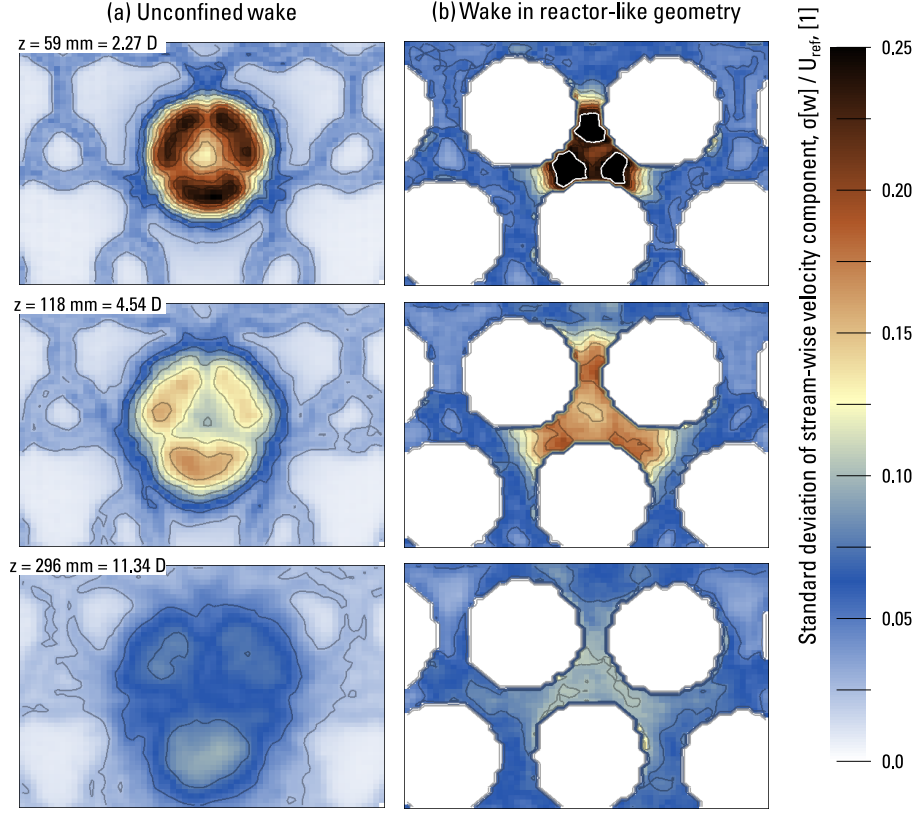


Figure 4: Spatial map of the fluctuations of stream-wise velocity component.

In the case with fuel rods (Fig. 1(right)), the wake is limited in its spreading. For a more clear comparison, see Figure 3(left), where there is the section along vertical passing trough the projected obstacle center shown. At the beginning, the velocity deficit is stronger in the confined case as there is less neighboring areas, where the wake could heal from. The velocity profile for confined case is plotted by blue and it suddenly ends at $y = -1/2D$ due to touching the fuel rods. Similarly on the other side, the velocity decreases as it approaches the edge of FoV, because there is another rod just behind the edge of the FoV. At later stages, the wake in free stream becomes significantly more dominant with both: deeper velocity deficit and larger area influenced.

3.2 Fluctuations

Fluctuations are shown via the Turbulent kinetic energy (TKE) [26] in profiles in Figure 3 or simply as the standard deviation of the stream-wise velocity component $\sigma[w]$, see Fig. 4. Note, that the stream-wise component has a dominant contribution to TKE. The standard deviation is more suitable for spatial plots than TKE, because it does not scales with second power, thus there are no such large differences in amplitude across the plot (note the numbers at axes of fig. 3).

$$\sigma[w] = \sqrt{\langle w^2 \rangle - \langle w \rangle^2} \quad (1)$$

$$TKE = \frac{1}{2} \sqrt{\sigma^2[u] + \sigma^2[v] + \sigma^2[w]} \quad (2)$$

Both Figures 3 and 4 display stronger fluctuations at the case with fuel rods. The meandering wake interact with boundary layers at the rods. It has less space to meander and, thus, less space for large-scale structures to develop; large-scale structures carry more energy [27, 28]. But, here we observe the opposite, suggesting that the meandering of the wake is stronger in the confined case, although the net amplitude is naturally limited by the rods presented, as it is apparent from the example of instantaneous snapshots displayed in Fig. 5.

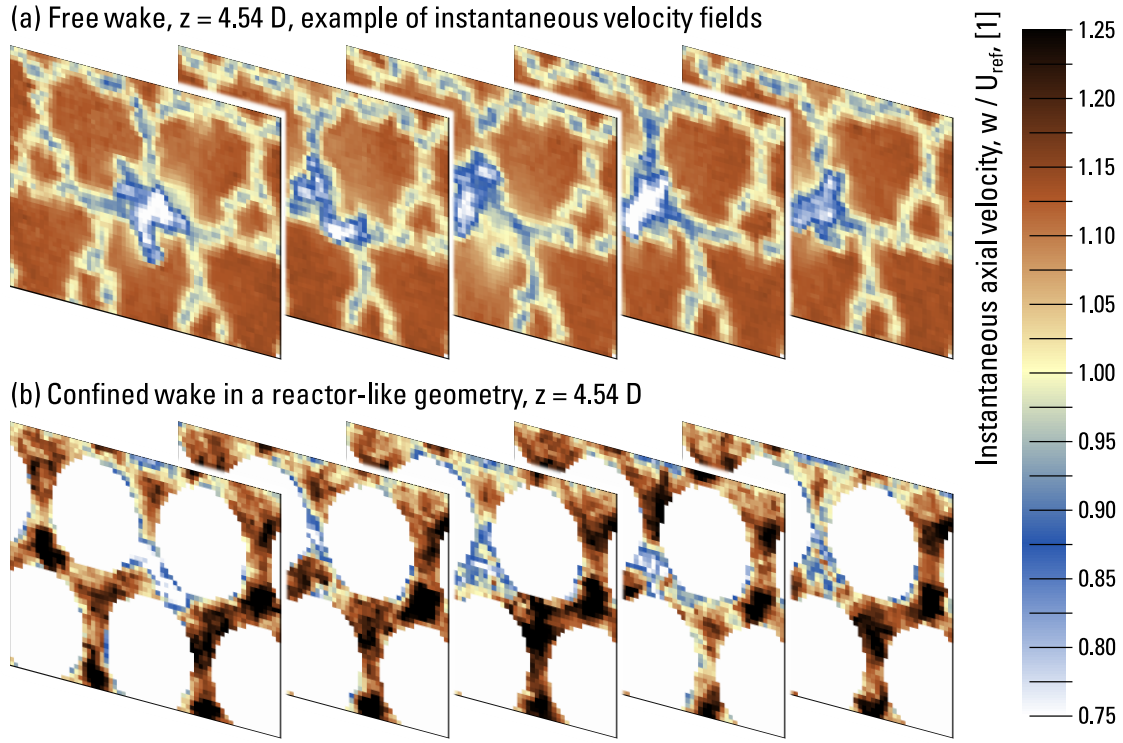


Figure 5: Example of few instantaneous velocity fields. The colorscale corresponds to the out-of-plane velocity component w . Distance past the grid with obstacle is in both cases $z = 118 \text{ mm} = 4.54 \cdot D$, where D is the obstacle diameter.

3.3 Asymmetry

The article [29] suggests, that the wake edge shall be defined as the area, where the fluctuations caused by the wake become *rare*. This is measured by using the higher statistical moments, mainly third [27, 30] one and the fourth [31] one.

In short, the *asymmetry*, of *skewness* is defined as

$$A[w] = \frac{(w - \langle w \rangle)^3}{(\sigma[w])^3} \quad (3)$$

for symmetrical distributions it reaches values around zero. Its negative value signify, that the average of probed distribution of w is shifted towards smaller values than the most probable values (median) due to the presence of stronger but rare events. In the sense of wake, this can be interpreted as follows: a rare intrusion of slower fluid from the wake into the otherwise fast fluid around the wake. The actual wake meandering is a regular event, hence it does not contribute significantly to A ; strong signal of A is caused by the turbulent events inside the wake leading to ejection of "buckets of turbulence" [32] into the surroundings.

Figure 6 displays the spatial distribution of $A[w]$. In the free, unconfined, wake we observe a typical ring of larger A as reported in [30] and [29]. Note that this ring is not fully symmetric due to the interaction with the wake past the spacer grid, which has thin walls but still contributes to the flow development (compare with Figure 1).

Very interesting is the absence of the areas of strongly skewed velocity distributions in the confined case of the wake surrounded by three rods. Respectively: at early stage ($z = 2.3D$), the ring is presented, but at slightly lower radius and with a smaller magnitude (the values are less negative) compared to the unconfined wake at the same z . At middle distance ($z = 4.5D$) the ring is still apparent, but with slightly higher radius than free case. At the last explored position ($z = 11.3D$), there is no such a structure apparent. Instead, the skewness is slightly negative across the whole observed area. This suggests, that the wake is completely destroyed at this distance,

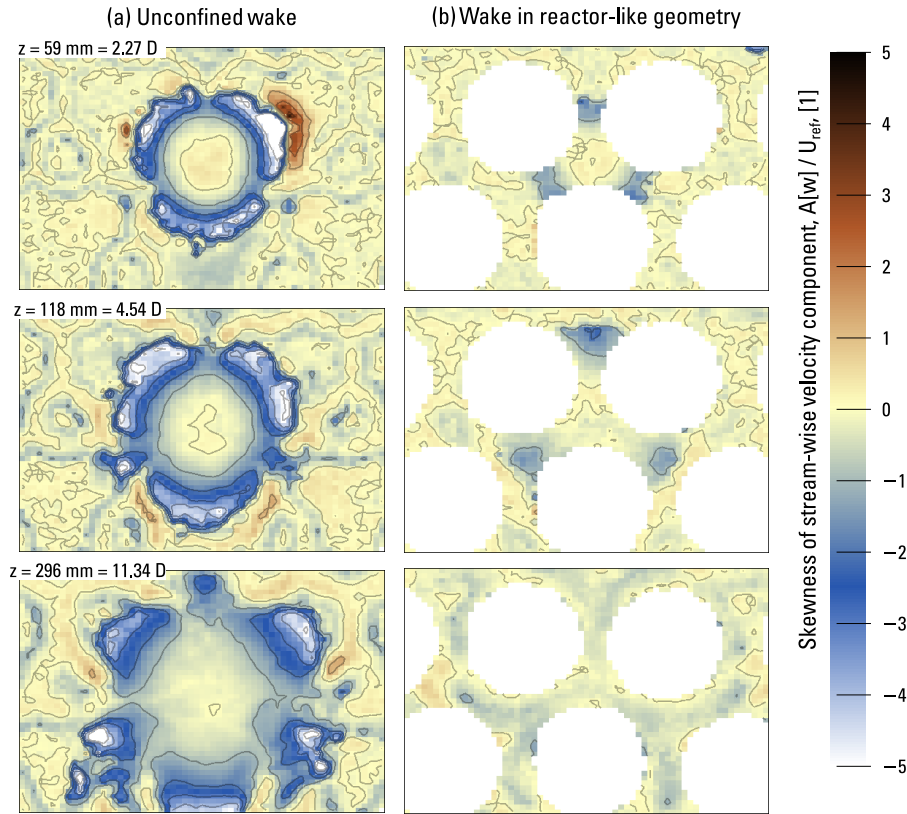


Figure 6: *Skewness or asymmetry coefficient* or just the *third statistical moment* of the stream-wise velocity component. Negative values can be interpreted as follows: the majority of values is time-to-time strongly skewed towards values much smaller than the local average, there are no opposing events of comparable strength.

although the standard deviation (Fig. 4) still reports somehow increased signal in the expected wake position. Wake without boundary is not a wake, just area of slightly increased turbulence level.

4 Conclusion

In this short and simple conference contribution we applied the standard method of Stereo PIV to the problem of a wake past a streamwise-aligned cylinder (short cylinder with axis parallel to the flow) placed in (a) empty wind tunnel with just a grid holding this obstacle and (b) test section with much larger fuel rods simulating the geometry inside a fuel assembly of pressurized water nuclear reactor of type VVER (i.e. with triangular symmetry of rod placing).

When we compare the confined wake (with rods) to the unconfined wake (no rods), then the following observations had been made: at early stage, the velocity deficit is deeper, later (since $z = 4.5D$) it is shallower. The area directly influenced is smaller at all stages. Fluctuations display larger values at all distances. The stream-wise velocity skewness shows a ring of negative values, but this ring is much weaker and it disappears completely at the last explored position ($z = 11.3D$). This is the most pronounced difference, which seems to be of principal importance.

Future investigations (experiments & data analysis) are needed. Doc. Duda suggests characterizing an instantaneous wake shape and then comparing its statistics (e.g. wake meandering). Prof. Uruba recommends using a standard method of Proper Orthogonal Decomposition (POD) to find the characteristic fluctuations. Doc. Yanovych is interested in Hot-Wire Anemometry, which would find and compare the Strouhal frequencies. But those all are only misty plans for future.

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References

- [1] T. Nguyen, L. White, R. Vaghetto, and Y. Hassan, "Turbulent flow and vortex characteristics in a blocked subchannel of a helically wrapped rod bundle," *Experiments in Fluids*, vol. 60, July 2019.
- [2] N. Todreas and M. Kazimi, *Nuclear Systems I: Thermal Hydraulic Fundamentals*. Taylor & Francis, 1993.
- [3] J. Creer, J. Bates, A. Sutey, and D. Rowe, "Turbulent flow in a model nuclear fuel rod bundle containing partial flow blockages," *Nuclear Engineering and Design*, vol. 52, p. 15–33, Mar. 1979.
- [4] T. Melsheimer, C. Menezes, D. W. Pyle, M. Kinsky, and Y. A. Hassan, "Particle image velocimetry measurements for transition flow regime through a porous blocked subchannel in a 61-pin wire-wrapped bundle," *Nuclear Engineering and Design*, vol. 424, p. 113314, Aug. 2024.
- [5] O. Bovati and Y. Hassan, "Analysis of the turbulent flow in a partially blocked wire-wrapped rod bundle using les with wall functions," *International Journal of Heat and Fluid Flow*, vol. 97, p. 109041, Oct. 2022.
- [6] I. Eames, C. Jonsson, and P. B. Johnson, "The growth of a cylinder wake in turbulent flow," *Journal of Turbulence*, vol. 12, p. N39, 2011.
- [7] R. Bardera, E. Barroso, and J. Carlos Matías, *Wingtip Vortices of a Biomimetic Micro Air Vehicle*, ch. 9. IntechOpen, 2022.
- [8] O. Sterly, "Particle image velocimetry measurement of turbulent wake past circular cylinder at reynolds numbers from $2.5 \cdot 10^3$ to $1.5 \cdot 10^4$," *MATEC Web of Conferences*, vol. 345, p. 00030, 2021.
- [9] V. Yanovych, D. Duda, and V. Uruba, "Structure turbulent flow behind a square cylinder with an angle of incidence," *European Journal of Mechanics, B/Fluids*, vol. 85, pp. 110–123, 2021.
- [10] C. H. K. Williamson, "Vortex dynamics in the cylinder wake," *Annual Review of Fluid Mechanics*, vol. 28, no. 1, p. 477–539, 1996.
- [11] G. Keulegan and L. Carpenter, "Forces on cylinders and plates in an oscillating fluid," *J. Res. Nat. Inst. Stand.*, vol. 60, pp. 423–440, 1958.
- [12] T. Von Kármán, *Aerodynamics*. McGraw-Hill paperbacks : science, mathematics and engineering, McGraw-Hill, 1963.
- [13] V. Strouhal, "Ueber eine besondere art der tonerregung," *Annalen der Physik*, vol. 241, pp. 216–251, 1878.
- [14] V. Yanovych, D. Duda, V. Horáček, and V. Uruba, "Research of a wind tunnel parameters by means of cross-section analysis of air flow profiles," *AIP Conference Proceedings*, vol. 2189, no. 020024, 2019.

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- [15] D. Duda, A. Mrázová, F. Mistre, V. Yanovych, V. Janský, V. Uruba, and K. Kovalova, “Experimental study of the debris blockage impact on the isothermal flow through the nuclear fuel assembly model,” *Nuclear Engineering and Design*, vol. 446, p. 114635, Jan. 2026.
- [16] R. Adrian, “Twenty years of particle image velocimetry,” *Experiments in Fluids*, vol. 39, pp. 159–169, 2005.
- [17] D. Duda and V. Yanovych, “Interaction of stream-wise vortices generated by swirler grid,” *Physics of Fluids*, vol. 36, no. 5, 2024.
- [18] D. Duda, J. Bém, V. Yanovych, P. Pavlíček, and V. Uruba, “Secondary flow of second kind in a short channel observed by piv,” *European Journal of Mechanics, B/Fluids*, vol. 79, pp. 444–453, 2020.
- [19] D. Duda, V. Yanovych, V. Tsymbalyuk, and V. Uruba, “Effect of manufacturing inaccuracies on the wake past asymmetric airfoil by piv,” *Energies*, vol. 15, p. 1227, 2022.
- [20] D. Duda and V. Uruba, “Spatial spectrum from particle image velocimetry data,” *ASME J of Nuclear Rad Sci.*, vol. 5, no. 030912, 2019.
- [21] V. Koschitzky, P. D. Moore, J. Westerweel, F. Scarano, and B. J. Boersma, “High speed piv applied to aerodynamic noise investigation,” *Experiments in Fluids*, vol. 50, pp. 863–876, Apr 2011.
- [22] C. F. Matozinhos, G. C. Tomaz, T. Nguyen, A. A. dos Santos, and Y. Hassan, “Experimental measurements of turbulent flows in a rod bundle with a 3-d printed channel-type spacer grid,” *International Journal of Heat and Fluid Flow*, vol. 85, p. 108674, 2020.
- [23] C. F. Matozinhos, G. C. Tomaz, T. Nguyen, and Y. Hassan, “Experimental investigation of turbulent flow characteristics in cross-flow planes of a 5×5 rod bundle with a spacer grid,” *International Journal of Heat and Fluid Flow*, vol. 87, p. 108757, 2021.
- [24] W. Qu, H. Xie, D. Shen, Z. Wang, and J. Xiong, “Experimental study of coherent structures downstream mixing vaned spacer grid of different inclination angles in a 5×5 rod bundle by tr-piv,” *Annals of Nuclear Energy*, vol. 181, p. 109516, Feb. 2023.
- [25] W. Qu and J. Xiong, “High-fidelity piv measurements of turbulent flow in reactor pressure vessel assisted by high-precision matched index of refraction technique,” *Nuclear Engineering and Design*, vol. 420, p. 112997, Apr. 2024.
- [26] R. Azevedo, L. R. Roja-Solórzano, and J. Bento Leal, “Turbulent structures, integral length scale and turbulent kinetic energy (tke) dissipation rate in compound channel flow,” *Flow Measurement and Instrumentation*, vol. 57, pp. 10 – 19, 2017.
- [27] P. Tabeling, G. Zocchi, F. Belin, J. Maurer, and H. Willaime, “Probability density functions, skewness, and flatness in large reynolds number turbulence,” *PHYSICAL REVIEW E*, vol. 53, pp. 1613–1621, 1996.
- [28] A. N. Kolmogorov, “Dissipation of Energy in the Locally Isotropic Turbulence,” *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 434, no. 1890, pp. 15–17, 1991.
- [29] D. Duda, V. Yanovych, and V. Uruba, “Wake width: Discussion of several methods how to estimate it by using measured experimental data,” *Energies*, vol. 14, no. 15, p. 4712, 2021.
- [30] C. Norberg, “Interaction between freestream turbulence and vortex shedding for a single tube in cross-flow,” *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 23, p. 501–514, Jan. 1986.
- [31] U. Frisch and A. N. Kolmogorov, *Turbulence: the legacy of AN Kolmogorov*. Cambridge university press, 1995.
- [32] D. Barkley, B. Song, V. Mukund, G. Lemoult, M. Avila, and B. Hof, “The rise of fully turbulent flow,” *Nature*, vol. 526, no. 7574, pp. 550–553, 2015.