PIV and CFD Study on the Axial and Transverse Velocity Distributions in a 19-Pin Wire-wrapped Fuel Bundle Channel

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Abstract

China initial Accelerator Driven System (CiADS) holds immense promise for transmuting nuclear wastes and enhancing the nuclear fuel's utilization rate. A study on the flow characteristics in reactor fuel assemblies is crucial for its design and safety analysis. In this study, a Visual Hydraulic ExperimentaL Platform (VHELP) was built to study the flow velocity distribution in a fuel assembly of CiADS, employing polymethyl methacrylate and a 62.932 wt% sodium iodide solutions as the material of the test section and refractive index matching fluid. Particle image velocimetry (PIV) and FLUENT were used to investigate the axial and transverse velocity distribution within the axial height of 2.25-3.25 pitches (H) and 3.75-4.75 H in 19-pin wire-wrapped fuel bundle channels. The findings reveal that the Shear Stress Transport (SST) k-ω model can accurately describe the velocity distribution in a wire-wrapped fuel assembly, and the transverse and axial periodicity of velocity distribution was one pitch. The flow velocity distribution patterns were unchanged with various Reynolds numbers. The patterns of velocity contour images on gaps 1 through 5 at 2.25-3.25 H were symmetrical to that at 3.75-4.75 H on gaps 5 through 1, respectively. The value of axial velocities and root mean square (RMS) transverse velocities proportionally increased with the increase of Reynolds numbers. Normalized transverse velocity changed in a cosine function, with a maximum value of about 40% and a peak occurring at a position slightly behind 3/4 H. The cross-flow around wire-wrap spacers enhanced and there was a deviation in the velocity direction. These results can help researchers deepen the understanding of flow velocity distribution in wire-wrapped fuel bundles, and advancing research on the cross-flow characteristics of lead-cooled fast reactors.

Full Text

Preamble

PIV and CFD Study on the Axial and Transverse Velocity Distributions in a 19-Pin Wire-Wrapped Fuel Bundle Channel

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The China Initiative Accelerator Driven System (CiADS) holds immense promise for transmuting nuclear waste and enhancing nuclear fuel utilization rates. Understanding flow characteristics in reactor fuel assemblies is crucial for its design and safety analysis. In this study, a Visual Hydraulic Experimental Platform (VHELP) was constructed to investigate flow velocity distributions in a CiADS fuel assembly, employing polymethyl methacrylate (PMMA) for the test section and a 62.932 wt% sodium iodide solution as the refractive index matching fluid. Particle image velocimetry (PIV) and FLUENT simulations were used to investigate the axial and transverse velocity distributions within axial heights of 2.25–3.25 pitches (H) and 3.75–4.75 H in 19-pin wire-wrapped fuel bundle channels. The findings reveal that the Shear Stress Transport (SST) k-ω model can accurately describe the velocity distribution in wire-wrapped fuel assemblies, with both transverse and axial periodicity of the velocity distribution equal to one pitch. The flow velocity distribution patterns remained unchanged across various Reynolds numbers. The velocity contour patterns on gaps 1 through 5 at 2.25–3.25 H were symmetrical to those at 3.75–4.75 H on gaps 5 through 1, respectively. Both axial velocities and root mean square (RMS) transverse velocities increased proportionally with Reynolds number. Normalized transverse velocity varied according to a cosine function, with a maximum value of about 40% and a peak occurring at a position slightly behind 3/4 H. The cross-flow around wire-wrap spacers was enhanced, accompanied by a deviation in velocity direction.

These results can help researchers deepen their understanding of flow velocity distributions in wire-wrapped fuel bundles and advance research on the cross-flow characteristics of lead-cooled fast reactors.

Keywords: wire-wrap spacer, bundle channel, cross-flow, refractive index matching, particle image velocimetry, subchannel

Introduction

The lead-cooled fast reactor (LFR) exhibits excellent neutronic characteristics, thermal safety features, and anti-nuclear proliferation capabilities, and has been selected as the reactor type for the China Initiative Accelerator Driven System (CiADS) [1–3]. The CiADS, designed to transmute long-lived high-level radioactive nuclear waste, comprises three main components: a linear accelerator, a spallation target, and a subcritical reactor. As a typical positioning component in lead-cooled fast reactors, wire-wrap spacers serve four primary functions: (1) maintaining spacing between neighboring fuel rods, (2) reducing vibration of fuel rod bundles, (3) enhancing transverse mixing of coolant and leveling out temperature gradients, and (4) making the reactor core more compact while reducing construction costs. Lead or lead-bismuth eutectic (LBE) operates at high temperatures and is opaque, making hydraulic experiments with LBE challenging. However, model test results can be extrapolated to prototype conditions using similarity principles and dimensional analysis, provided that the test section is properly designed and an appropriate working fluid is selected [4]. Optical velocimetry methods such as particle image velocimetry (PIV) [5–7] are commonly employed in model tests to study flow characteristics in fuel bundle channels. Research into flow characteristics within wire-wrapped fuel bundle channels is highly challenging, with difficulties including: (1) precision machining of visualization fuel assembly models; (2) imaging within narrow flow channels; (3) capturing rotational motion; (4) managing laser stray light interference; (5) limited lifespan of visualization fuel assembly models; (6) ensuring material compatibility; (7) maintaining material stability; (8) demanding high equipment performance standards; (9) addressing multidisciplinary issues; and (10) generating grid structures for the contact line region between wire-wrap spacers and fuel rods [8].

Computational fluid dynamics (CFD) is a common tool for studying flow velocity distributions due to its low cost and high accuracy. However, CFD simulation results still require validation through experimental data. Over the past few decades, numerous studies have explored flow behavior within wire-wrapped fuel bundle channels using both numerical simulations and experimental approaches.

Numerical research includes: Gajapathy et al. [9] simulated flow characteristics in 7, 19, and 37-pin wire-wrapped fuel assemblies of the Indian prototype fast breeder reactor using the standard k- model. The simulation findings were benchmarked against 91-pin experimental results and showed good agreement. Flow velocity results for the 19 and 37-pin models differed little, and the authors suggested that the velocity and temperature distributions could be applied to a 217-pin bundle fuel assembly. Rolfo et al. [10] studied 7, 19, 61, and 217-pin fuel assemblies with spiral wire-wrap spacers using both the standard k- model and second-moment closure turbulent model in 2012. They found that the main flow structure in the four fuel assemblies was almost identical, with the number of rods having little influence on CFD results. The two turbulent models agreed well with each other and with experimental correlations, particularly the Cheng and Todreas correlation [11]. Brockmeyer et al. [12] used the Shear Stress Transport (SST) k-ω model and elliptic blending k- turbulent models to study flow characteristics in 19, 37, 61, and 91-pin wire-wrapped bundles in 2017. The CFD results were validated against Large Eddy Simulation (LES) results. Their study indicated that while main flow velocity in central subchannels changed with the number of rods, some flow characteristics such as vortices and transverse velocities were independent of the number of rods. Zhao et al. [13] performed CFD simulations of a 7-pin wire-wrapped fuel assembly with different duct wall shapes using the SST model (which can switch to the k- model). The results compared well with LES data from Argonne National Laboratory and experimental data. They also found that duct wall shape can affect flow characteristics in subchannels. Overall, CFD numerical simulations have validated the coherence and similarity of flow characteristics in 7, 19, 37, 61, and even 217-pin wire-wrapped fuel assemblies, which can help simplify experimental studies. Many existing CFD studies [12–16] have recommended the use of the SST k-ω model for simulating fuel assemblies with spiral wires.

Experimental research includes: Polymethyl methacrylate (PMMA) with sodium iodide solution, and fluorinated ethylene propylene (FEP) with deionized water, are commonly used as model material and refractive index matching (RIM) fluid combinations in PIV experiments; additional RIM schemes can be found in the literature [17]. Nguyen et al. [18] performed PIV experiments in a 61-pin wire-wrap bundle model using PMMA and p-cymene in 2017. They measured flow velocity near rods and wire-wrap spacers at a Reynolds number of 19,000 and observed that large-scale structures were oriented parallel to the mean flow direction. Goth et al. [19] performed PIV measurements on the flow field distribution in multiple interior subchannels of a 61-pin wire-wrapped fuel assembly at a Reynolds number of 19,000 in 2018; these results can serve as benchmarks for CFD simulations. Wang et al. [20] executed PIV experiments in a single rod model with spiral wires, studying cross-flow in the cross-section and finding that both the velocity magnitude in cross-sections increased gradually with Reynolds number. Zhang et al. [21] conducted PIV experiments and CFD simulations in a 7-pin wire-wrapped fuel assembly at a Reynolds number of 6,500 in 2020, capturing flow distribution in the cross-section of the test section. Through experiments, they characterized the axial and transverse velocity distribution and RMS of transverse velocity fluctuations. They found that CFD simulation using the SST model could accurately predict flows in a 7-pin fuel assembly. Additionally, they observed that different locations and the number of wires in different subchannels influenced turbulent characteristics. Bovati and Hassan [22] performed LES with a wall function to study the effect of local blockage accidents in a 61-pin wire-wrapped fuel assembly at a Reynolds number of 17,000 in 2022. The mean velocity and RMS fluctuating velocity results were compared with existing PIV data, and the LES model demonstrated its capability to simulate pairs of counter-rotating vortices. Li et al. [23] conducted PIV and CFD studies in a 7-pin wire-wrapped fuel assembly for CiADS in 2023. The CFD results demonstrated the SST model's proficiency in predicting vortex formation near wire-wrap spacers in cross-sections. Similarly, Sun et al. [24] studied cross-flow in a 7-pin wire-wrapped fuel bundle using PIV and CFD methods with FEP and deionized water. They found that cross-flow exhibits obvious periodicity, with a peak ratio of transverse velocity to axial velocity of 25%. Wang et al. [25] performed PIV measurements in a 7-pin wire-wrapped bundle with FEP and deionized water in 2023. The experimental results revealed strong circulation flow in the outer region of the test section, with circulation flow velocity about 35% of the streamwise velocity. These conclusions are consistent with those reported in previous studies [8, 23].

Most previous studies have concentrated on general flow features in wire-wrapped fuel assemblies, with only limited attention to detailed local velocity distributions. This study aims to further evaluate transverse velocity in wire-wrapped fuel bundle channels and enhance the safety performance of CiADS. This will help deepen research on transverse mixing phenomena and coolant mechanisms under the influence of wire-wrap spacers, providing strong support for the design of lead-cooled fast reactors.

II. PIV Study

In this study, PMMA was selected as the material for the test section, and a 62.932 wt% sodium iodide–36.968 wt% deionized water–0.1 wt% sodium thiosulfate solution was prepared as the RIM fluid [17]. The velocity distribution in the fuel bundle channel was investigated using PIV. The CCD camera had an image resolution of 6600$×$4400 pixels, and the laser pulse energy was 200 mJ/pulse. A synchronizer controlled the CCD camera and laser to ensure they operated simultaneously. The laser was scattered into a light sheet by an optical lens, and tracer particles reflected this light sheet to be captured by the CCD camera. Two consecutive frames (frame A and frame B) were captured at a certain time interval Δt. The displacements of tracer particles were determined using an algorithm to obtain velocity vectors. The velocity distribution of tracer particles can represent that of the working liquid when the tracer particles' following capability is ensured.

A. Test Section

Fig. 1 [Figure 1: see original paper] shows a photograph of the 19-pin fuel assembly model. The bottom end plugs were made of 316L stainless steel to facilitate assembly, enhance mechanical strength, and provide corrosion resistance. In this study, SP denotes the starting point of the wire-wrap spacers, while 1R represents row 1, with similar abbreviation rules for other rows. Wire-wrap spacers were wrapped on the fuel rods using a self-designed gear-synchronized positioning device [26, 27]. The diameters of the fuel pins and wire-wrap spacers were designed to match those in CiADS. The primary parameters of the visualized fuel assembly model are shown in Table 1 .

Table 1. Primary parameters of the visualized fuel assembly.

[The table contains parameters including number of fuel rods, diameter of fuel rods (mm), length of fuel rods (mm), fuel rod arrangement, diameter of wire-wrap spacer (mm), lead pitch of wire-wrap spacer (mm), number of lead pitches, rotation direction of wire-wrap spacer, inner side length of duct (mm), outer side length of duct (mm), and length of duct (mm).]

B. Experimental Platform

As shown in Fig. 2 [Figure 2: see original paper], a Visual Hydraulic Experimental Platform (VHELP) was designed and assembled [8, 28], which included a primary loop and a secondary loop. The secondary loop regulated the temperature of the working liquid inside the primary loop. Tank 3 was the highest point of the platform, used for adding tracer particles, draining bubbles, reducing pressure fluctuations, and monitoring the liquid level. To minimize refractive index differences between the fuel bundle model and the working liquid, a sodium iodide solution was formulated with a concentration of 62.932%. This solution exhibited a refractive index of 1.491 at 25°C (identical to that of PMMA). The RIM fluid traversed the test section in an upward direction, originating from the bottom, and operated at 25 ± 1.0°C under atmospheric pressure. To accommodate different experimental conditions and enhance measurement precision, two turbine flowmeters were installed in parallel in the primary loop with measuring ranges of 1.5–15 m^3/h and 4.0–40 m^3/h, respectively. Additionally, a vortex flowmeter covering a range of 5.0–50 m^3/h was employed. Thermocouples and gauge pressure sensors were strategically installed to facilitate continuous monitoring and ensure stable physical properties of the working liquid.

The variations in refractive index, density, and dynamic viscosity of the 62.932% sodium iodide solution at 25°C were meticulously measured. The relationships are presented in equations (1), (2), and (3):

$$n_T = -1.31130 \times 10^{-4} T + 1.49530, \quad R^2 = 0.9833$$

where n_T is the refractive index and T is the temperature in °C.

$$\rho_T = -7.02779 \times 10^{-4} T + 1.88532, \quad R^2 = 0.9937$$

where ρ_T is the density in g/cm^3 and T is the temperature in °C.

$$\mu_T = -1.03047 \times 10^{-12} T^6 + 3.34261 \times 10^{-9} T^4 - 4.29940 \times 10^{-6} T^2 + 0.00423, \quad R^2 = 0.9993$$

where μ_T is the dynamic viscosity in Pa · s and T is the temperature in °C.

The density of the 62.932% sodium iodide solution at 25°C was 1.868 g/cm^3, which was similar to that of the tracer particles (density 1.7 g/cm^3 and average diameter 7 µm), ensuring the desired following behavior of the tracer particles.

Fig. 3 [Figure 3: see original paper] shows the layout of the PIV system. The laser transmitter and CCD camera were arranged in two perpendicular directions relative to the test section. The aluminum alloy support was covered with light-absorbing cloth, and the remaining zones were coated with matte paint to reduce stray light interference. The level and verticality of the electric lifting platform were adjusted, with attention paid to maintaining parallelism between the electric lifting platform and the fuel assembly.

Fig. 4 [Figure 4: see original paper] shows a top view of the channels in the xz plane. According to the position of the laser sheet along the y-axis of the fuel assembly model, the photographed flow channels were designated as gaps 1 through 5, respectively. Each gap was parallel to the xz plane and crossed the diameter of the rods and the wire-wrap spacers. The velocity distributions in the xz plane at 2.25–3.25 pitches (H) and 3.75–4.75 H were measured by PIV. A motion controller was used to adjust the light sheet and CCD camera over the height range of the fuel assembly, spanning from 2.25 to 3.25 H. Subsequently, the velocity distributions in each channel were captured under four operating conditions with Reynolds numbers of 2500, 3750, 5000, and 6250. Afterward, the CCD camera and laser light were lifted synchronously by 216 mm (1.5 H), and the velocity distributions at the 3.75–4.75 H channel were measured.

III. CFD Study

Experimental measurements typically provide limited macroscopic data, whereas numerical simulations can reveal detailed microscopic flow characteristics, further validating the applicability of CFD computational models and improving the credibility of experimental data. This research utilized FLUENT for simulating flow characteristics. FLUENT offers strong grid adaptability, contains numerous solving algorithms and rich turbulence models, and is one of the most widely applicable commercial software packages currently available.

CATIA P3 V5-6R software, developed by Dassault Systèmes, was utilized to generate the 3D model of the flow channel, as shown in Fig. 5 [Figure 5: see original paper]. The presence of line contact and sharp edges poses significant challenges for grid generation. To mitigate these difficulties, each wire-wrap spacer was indented by 0.1 mm toward its fuel rod, and a fillet radius of 0.25 mm was incorporated to simplify the grid generation process. Previous studies have shown that this geometric simplification has a negligible effect on flow characteristics in wire-wrapped fuel bundle channels [29–32].

STAR-CCM+ software, developed by CD-adapco, features powerful mesh generation tools, with its greatest advantage being the ability to produce high-quality polyhedral meshes. STAR-CCM+ 19.0 was utilized to create a polyhedral mesh, which, in contrast to a tetrahedral mesh, offers advantages such as reduced cell count and accelerated convergence rates. A base mesh size of 1.5 mm was chosen to balance accuracy and computational cost. Fig. 6 [Figure 6: see original paper] illustrates the grid distribution at the entrance of the fuel rod bundle. Four boundary layers were included in the mesh, each with a height of 0.025 mm.

FLUENT 19.2 was used to carry out numerical simulations of the fuel bundle channels. The parameter settings included: a base grid of 1.5 mm, four boundary layers on the fuel rod and wire-wrap spacer surfaces, velocity inlet and pressure outlet boundary conditions, the SST k-ω turbulence model and SIMPLE algorithm [33–35], and turbulence intensity set appropriately.

Fig. 7 [Figure 7: see original paper] shows contour images of the velocity distribution on cross-sections from 3.0 H to 3 5/6 H at intervals of 1/6 H when the Reynolds number was 5000. It can be seen that for every 1/6 H increase in axial height, the velocity distribution contour image rotates clockwise by 60°, while the magnitude remains consistent, indicating that the transverse periodicity of the velocity distribution is one H.

Fig. 8 [Figure 8: see original paper] shows the results of a mesh sensitivity analysis, demonstrating that different mesh resolutions are consistent with each other. Finally, the mesh with a base size of 1.5 mm was selected.

IV. Results and Discussion

The RMS transverse velocity can be used to assess the effective value of the transverse velocity, with its expression given as:

$$U_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} U_i^2}$$

where U_{RMS} is the RMS transverse velocity in the xz plane (m/s) and U is the transverse velocity in the xz plane (m/s).

The impact of the number of frame pairs (frames A and B) on the velocity vector during each capture was studied. Fig. 9 [Figure 9: see original paper] compares the relationship between the ratio of RMS transverse velocity to axial velocity of the fuel bundle on gap 1 and the number of captures when the Reynolds number was 5000. The number of frame pairs was varied as 1, 5, 10, 20, 40, 60, and 80 pairs, respectively. It was evident that when the number of captures exceeded 40, the ratio changed little; thus, 40 pairs of image frames were captured and post-processed each time to compute the average value, which helps reduce experimental errors.

A. Velocity Contour Images

Fig. 10 [Figure 10: see original paper] shows a comparison of experimental and simulation results for transverse velocity contour images on gap 1 in the xz plane at 2.25–3.25 H at different Reynolds numbers. The x-axis velocity is represented by U, and the z-axis velocity by W. Positive values represent flow along the positive half-axis, while negative values represent flow along the negative half-axis. It was evident that the transverse flow velocity on gap 1 increased in proportion to Reynolds number, and the flow contour images were similar under all four conditions. The flow downstream of the wire-wrap spacers changed dramatically, with micro transverse flows observed in close proximity to the wire-wrap spacers. Simultaneously, it was found that the trend of simulation results aligned closely with experimental data, and the values were generally equal, indicating that the SST k-ω model can accurately simulate the velocity distribution within wire-wrapped fuel bundle channels.

Fig. 11 [Figure 11: see original paper] shows a comparison of PIV results for transverse velocity contour images on five gaps at 2.25–3.25 H and 3.75–4.75 H at a Reynolds number of 5000. It was evident that the transverse velocity contour images of the top-half pitch and bottom-half pitch on gap 1 within 2.25–3.25 H were similar to those of the bottom-half pitch and top-half pitch on gap 1 at 3.75–4.75 H, respectively, as were those on the other four gaps. Simultaneously, the pattern of transverse velocity contour images on gaps 1, 2, 3, 4, and 5 at 2.25–3.25 H were symmetrical to those at 3.75–4.75 H on gaps 5, 4, 3, 2, and 1, respectively, with opposite values—that is, the maximum and minimum values at the same position were exchanged. This occurred because gap 1 at 2.25–3.25 H and gap 5 at 3.75–4.75 H were symmetrical about the y=0 plane, with an axial difference of half a pitch.

Furthermore, it was found that the transverse velocity contour images in the middle two channels on gaps 1, 3, and 5 were similar, with drastic changes along the flow direction, while the transverse velocity contour images in the leftmost and rightmost channels were similar, with little variation along the flow direction. The transverse velocity contour images in the leftmost and rightmost channels on gaps 2 and 4 were similar, and the magnitude and changes in the left, middle, and right channels were quite close.

Fig. 12 [Figure 12: see original paper] shows a comparison of PIV results for axial velocity contour images on five gaps at 2.25–3.25 H and 3.75–4.75 H at a Reynolds number of 5000. It can be seen that the axial velocity contour images of the top-half pitch and bottom-half pitch on gap 1 within 2.25–3.25 H were similar to those of the bottom-half pitch and top-half pitch on gap 1 at 3.75–4.75 H, respectively, and the trends on the other four gaps were similar, indicating that the axial periodicity of the velocity distribution was one pitch. Meanwhile, the pattern of axial velocity contour images on gaps 1, 2, 3, 4, and 5 at 2.25–3.25 H were symmetrical to those at 3.75–4.75 H on gaps 5, 4, 3, 2, and 1, respectively, with essentially equal values. This occurred because gap 1 at 2.25–

3.25 H and gap 5 at 3.75–4.75 H were symmetrical about the y=0 plane, with an axial difference of half a pitch. It was also found that the axial velocity contour images in the middle two channels on gaps 1, 3, and 5 were similar, with drastic changes along the flow direction, while the axial velocity contour images in the leftmost and rightmost channels alternated in magnitude. The axial velocity contour image changes in the leftmost and rightmost channels on gaps 2 and 4 were more drastic than those in the middle channel. This flow disturbance was attributable to the presence of the hexagonal duct, with a notably pronounced effect observed in the vicinity of wire-wrap spacers.

Combining Fig. 11 and Fig. 12, it can be seen that the period of both axial velocity distribution and transverse velocity distribution is one pitch.

B. RMS Transverse Velocity Distributions

This section analyzes the distribution of RMS transverse velocity with Reynolds number for quantitative analysis of cross-flow characteristics. Fig. 13 [Figure 13: see original paper] shows the variation of RMS transverse velocity with x-axis coordinates at different Reynolds numbers. It can be seen that the RMS transverse velocity increases in proportion to the rise in Reynolds number, and the PIV results were consistent with CFD data.

Fig. 14 [Figure 14: see original paper] illustrates the RMS transverse velocities on different gaps within 2.25–3.25 H and 3.75–4.75 H at a Reynolds number of 5000. It can be observed that the values on gaps 1, 3, and 5 were approximately equal, as were those on gaps 2 and 4, which is consistent with the findings in Fig. 11. Simultaneously, it was discovered that the transverse flow in the middle two channels on gaps 1, 3, and 5 was greater, while that in the leftmost and rightmost channels was smaller. The magnitude of transverse flow in the left, middle, and right channels on gaps 2 and 4 were comparable. In addition, the curves at 2.25–3.25 H and 3.75–4.75 H on these five gaps almost overlapped because the transverse velocity distribution in the top and bottom half pitches at 2.25–3.25 H was similar to that of the bottom and top half pitches at 3.75–4.75 H, respectively. The CFD results were in good agreement with the PIV data, and the position of vectors with high transverse velocity on the x-axis was basically the same. The two-peak velocity distributions observed on gaps 2 and 4 were due to the narrow gap between the two symmetric and separate parts of hexagonal ducts. The ducts were connected by a very thin layer of glue, which was a necessary processing step. This processing method has a minor effect on the PIV images.

C. Normalized Transverse Velocity Distributions

This section analyzes the distribution of normalized transverse velocity with Reynolds number and gap position. Fig. 15 [Figure 15: see original paper] shows the numbering of fuel rods and subchannels in a 19-pin wire-wrapped fuel bundle channel, comprising inner subchannels, edge subchannels, and corner subchannels.

The normalized transverse velocity at the centerline of two subchannel interfaces can be used to characterize the transverse mixing intensity between adjacent subchannels, with its expression given as:

$$U_t = \frac{U}{W_{bulk}}$$

where U_t represents the normalized transverse velocity, U is the transverse velocity at the centerline of the subchannel interface (m/s), and W_{bulk} represents the axial bulk velocity of the fuel bundle (m/s).

Fig. 16 [Figure 16: see original paper] shows the comparison of normalized transverse velocity distribution on the interface of subchannels 19# to 18# at 2.25–3.25 H at different Reynolds numbers. It was evident that the value of U_t was independent of Reynolds number, indicating that U increases proportionally with Reynolds number. As the z-axis coordinate increases, U_t varies according to a cosine function, with a maximum value of about 40% and a peak occurring at a position slightly behind 3/4 H. The cross-flow around the wire-wrap spacers was enhanced, and there was a deviation in the direction of velocity. Concurrently, the CFD results aligned well with the PIV data.

Fig. 17 [Figure 17: see original paper] shows the normalized transverse velocity distribution on the interfaces of different subchannels in the xz plane at 2.25–3.25 H and 3.75–4.75 H when the Reynolds number was 5000. It can be seen that the values of U_t at the interfaces of subchannels 19#–18# and 23#–22# were equal at 2.25–3.25 H and 3.75–4.75 H, with opposite trends. At the same time, it was found that the transverse velocity distribution of 19#–18# and 23#–22# at the same height was basically consistent, matching the conclusion from the transverse velocity contour images in Fig. 11.

V. Conclusion

In this study, PIV and FLUENT were utilized to investigate flow velocity distributions on different gaps in the xz plane at 2.25–3.25 H and 3.75–4.75 H in a 19-pin wire-wrapped fuel assembly. The axial and transverse velocity contour images of different fuel bundle gaps at various Reynolds numbers were presented. Meanwhile, RMS transverse velocity distribution and normalized transverse velocity distribution were analyzed to quantify the transverse flow characteristics and validate CFD results. The following conclusions were reached:

1. The SST k-ω model can precisely describe the velocity distribution in a wire-wrapped fuel assembly. For every 1/6 H increase in axial height from 3.0 to 4.0 H, the velocity contour image rotates clockwise by 60 degrees while maintaining its magnitude unchanged. This behavior demonstrates that both the transverse and axial periodicity of the velocity distribution is one pitch.

2. The flow velocity distribution patterns remained consistent as Reynolds numbers increased. However, the magnitude of these velocities increased in direct proportion to the rise in Reynolds number. The flow downstream of wire-wrap spacers underwent significant changes, accompanied by the emergence of micro transverse flows in their vicinity.

3. The RMS transverse velocity increased proportionally with Reynolds number. The values of U_{RMS} on gaps 1, 3, and 5 were essentially equal, as were those on gaps 2 and 4. The cross-flow in the middle two channels on gaps 1, 3, and 5 was greater, whereas that in the leftmost and rightmost channels was smaller. The magnitude of cross-flow in the left, middle, and right channels on gaps 2 and 4 were comparable. In addition, the curves on these five gaps at 2.25–3.25 H and 3.75–4.75 H almost overlapped.

4. The value of U_t remained constant regardless of Reynolds number, signifying that U increases proportionally with Reynolds number. As the z-axis coordinate increased, U_t varied according to a cosine function, with a maximum amplitude of approximately 40% and a peak occurring at a position slightly behind 3/4 H. The cross-flow around wire-wrap spacers was enhanced, and there was a deviation in the direction of velocity.

The findings and conclusions in this study can help deepen research on transverse mixing phenomena and the underlying mechanisms of coolant in the presence of wire-wrap spacers, providing strong support for safety assessments of lead-cooled fast reactors.

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Note: Figure translations are in progress. See original paper for figures.