Analysis of Flow-Induced Vibration Characteristics of Wire-Wrapped Seven-Rod Fuel Bundle in Lead-Bismuth Reactor Based on Large Eddy Simulation

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Abstract

The high density and rapid flow characteristics of liquid metal coolant in lead-bismuth fast reactors subject wire-wrapped fuel rod bundles to the risk of flow-induced vibration failure. To accurately predict their flow-induced vibration behavior, this study establishes a fluid-structure interaction model for a single wire-wrapped fuel rod based on the ANSYS platform, systematically compares the applicability of the SST k-ω and Large Eddy Simulation (LES) turbulence models, and conducts sensitivity analysis on fluid-structure coupling methods (one-way/two-way coupling). The results demonstrate that the LES model can more accurately capture pressure fluctuations on the fuel rod wall surface, and that the one-way coupling method satisfies accuracy requirements for micron-level vibration problems. Analysis through a 7-rod bundle model reveals that the wire wrap leads to non-uniform velocity distribution within the flow channel, with vibration displacements of the central rod (10 m and 40 m) being significantly smaller than those of peripheral rods (50 m), and that the vibration is dominated by the first-order frequency without resonance occurrence, belonging to a turbulent excitation phenomenon. The model is validated against experimental data and empirical correlations, and can provide a reliable basis for flow-induced vibration analysis and safety assessment of wire-wrapped fuel in lead-bismuth fast reactors.

Full Text

Preamble

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Large Eddy Simulation-Based Analysis of Flow-Induced Vibration Characteristics in a Wire-Wrapped Seven-Rod Fuel Assembly for Lead-Bismuth Reactors

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Abstract

[**Background**]: In lead-bismuth cooled fast reactors, the high-density liquid metal coolant and rapid flow characteristics pose flow-induced vibration (FIV) risks to wire-wrapped fuel assemblies. Precise prediction of FIV behavior is critical for structural integrity assessment.

[**Purpose**]: To establish a reliable numerical framework for FIV analysis of wire-wrapped fuel rods and evaluate turbulence modeling approaches.

[**Methods**]: In this study, a fluid-structure interaction (FSI) model for a single wire-wrapped fuel rod was developed on the ANSYS platform. The applicability of the SST k-ω and Large Eddy Simulation (LES) turbulence models was systematically compared. Additionally, sensitivity analyses were conducted for the fluid-structure coupling methods, including both unidirectional and bidirectional coupling. A meshing approach was proposed to determine the required dimensions for the turbulence models, and sensitivity analyses were performed with respect to mesh density and time step size.

[**Results**]: The results show that the LES model can capture the fuel rod wall pressure fluctuations more accurately, and the one-way coupling method meets the accuracy requirements in micrometer-scale vibration problems. The analysis of the 7-rod bundle model reveals that the helical wire spacers lead to uneven flow distribution in the flow channel, and the vibration displacements of the center rods (10 m and 40 m) are significantly smaller than those of the surrounding rods (50 m). The vibration is dominated by the first-order frequency without resonance, which belongs to the phenomenon of turbulent excitation.

[**Conclusions**]: This study provides a reliable basis for wire-wrapped fuel in lead-bismuth fast reactors, which is of great significance for engineering design and safety assessment.

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Introduction

Lead-bismuth cooled fast reactors, which use low-melting-point lead-bismuth alloy as coolant, represent one of the Generation IV reactor designs, offering enhanced inherent safety, extended fuel lifetimes, and significant advantages in nuclear proliferation resistance and modular construction. However, in liquid metal fast reactors, the fuel assemblies in the reactor core operate under long-term high-temperature, high-pressure, and high-radiation conditions. The high density and rapid flow of liquid lead/lead-alloy coolant in densely packed wire-wrapped fuel rod bundles can lead to vibration-induced failures and cladding damage.

Numerous researchers have investigated wire-wrapped fuel using simulation methods. Ahmad and Kim [?] used CFX software to demonstrate that wire-wrap structures significantly affect flow field distribution and subchannel temperature differences. Pacio [?] and Shams [?] employed the SST k-ω and RANS models for numerical analysis of fuel assemblies in lead-cooled fast reactors. Doolaard [?] discussed the advantages and disadvantages of Large Eddy Simulation for modeling flow fields in lead-cooled fast reactor fuel assemblies. Li [?] experimentally investigated heat transfer characteristics of wire-wrapped fuel rod bundles at supercritical pressures and compared them with empirical correlations. Qin et al. [?] found through CFD simulation that the vibration displacement of a single wire-wrapped fuel rod ranges from 3.0 to 3.4 micrometers, with increased turbulence intensity leading to larger vibration displacements. Dolfen et al. [?] used Large Eddy Simulation to reveal that contact forces and sliding amplitude significantly influence fretting wear. Shu [?] studied fretting wear and fatigue life of fast reactor wire-wrapped fuel bundles in turbulent flow, finding that fatigue effects are more pronounced.

In summary, current research on wire-wrapped fuel employs diverse simulation methods with varying research directions. While numerous studies have addressed FIV behavior of wire-wrapped fuel, none have conducted sensitivity analyses on the models used, nor compared results from different models to determine which approach is most suitable for FIV simulation.

This study first establishes a single wire-wrapped fuel rod model based on ANSYS to conduct sensitivity analyses of the FIV model for lead-cooled fast reactor wire-wrapped fuel. A method for determining the mesh scale required for Large Eddy Simulation is proposed. This method is used to compare the capabilities of RANS and LES models in predicting pressure fluctuations on fuel rod walls, and further comparisons are made of vibration amplitudes under different turbulence models. Model validation is performed to ensure the correctness of this research. Finally, a 7-rod bundle wire-wrapped fuel model is established to analyze the velocity field, fluid excitation force fluctuations, and distributions in the wire-wrapped bundle channel, with modal and vibration response calculations performed to obtain vibration amplitudes and trajectories.

1.1 Fluid Domain Model

1) SST k-ω Model

The SST k-ω model is a two-equation turbulence model based on the eddy viscosity hypothesis, also known as the Shear Stress Transport model. This model is used for simulating and predicting flows with adverse pressure gradients and in wall-adjacent regions, combining two different models. Within the flow boundary layer, the Wilcox k-ω model [?] is employed, which can effectively capture complex flow phenomena inside the boundary layer. When the flow reaches the outer boundary layer, the model switches to a more suitable formulation, avoiding the numerical stability and sensitivity issues of traditional standard models in free shear flow environments. This composite model structure expands its application range and improves prediction accuracy.

Additionally, in the flow boundary layer, the SST k-ω model considers the transport principles of Reynolds stresses and uses the Bradshaw hypothesis to treat Reynolds stress effects.

2) Large Eddy Simulation Model

Large Eddy Simulation, as an efficient turbulence simulation method, directly solves the dynamic behavior of large-scale eddies while using models to approximate the effects of small-scale eddies. This approach employs a carefully designed filtering mechanism to screen out large-scale eddies from complex turbulent fields for direct calculation, while the effects of small-scale eddies are indirectly represented through specific closure models.

The filtered LES control equations are expressed as: [equation]. The term on the right side of equation (10) represents the unclosed subgrid stress term, which quantifies the momentum transfer effects between small-scale turbulent fluctuations excluded by the filtering operation and the directly calculated large-scale turbulent structures.

1.2 Solid Domain Model

Flow-induced vibration analysis involves both fluid excitation calculation and structural vibration response calculation. The analysis parameters required for structural vibration response calculation mainly include vibration frequency, mode shape functions, damping, etc. When an elastic structure is completely surrounded by flowing fluid, it is subjected to distributed forces induced by the fluid.

The dynamic interaction between the structure and displacement is described by the following equation: [equation]. Where M is the structural mass matrix; C is the structural damping matrix; K is the structural stiffness matrix; x is the displacement vector (m), $\dot{x}$ is the velocity vector ($m \cdot s^{-1}$), $\ddot{x}$ is the acceleration vector ($m \cdot s^{-2}$); P is the excitation force (N), including vortex shedding, turbulence, and acoustic effects.

However, structural vibration characteristics in fluid are much more complex than in vacuum, requiring consideration of fluid-structure coupling effects. Therefore, the equation needs to be modified to include fluid coupling terms. The coupled equation includes: sM as the structural mass matrix; fM as the added mass matrix; sC as the structural damping matrix; fC as the fluid damping matrix; sK as the structural stiffness matrix; and fK as the fluid stiffness matrix.

1.3 Fluid-Structure Interaction Model

In this study, the mature commercial software platform ANSYS 2024 R1 is employed to perform the coupled analysis. To ensure iterative convergence, the quasi-Newton stabilization algorithm is adopted for bidirectional coupling analysis with a convergence residual of 0.001. Additionally, it should be noted that due to the flow-induced vibration caused by coolant axial flow scouring on fuel rods in the reactor core, the vibration amplitude is very small, essentially at the micrometer scale, and its deformation has limited impact on the flow field. Therefore, unidirectional fluid-structure coupling is primarily used for vibration response analysis. Figure 1 [Figure 1: see original paper] illustrates these two methods.

Figure 1 Unidirectional and bidirectional fluid-structure coupling

2.1 Geometric Model

Figure 2 [Figure 2: see original paper] shows the geometric model of a single wire-wrapped fuel rod. The geometric parameters for wire-wrapped fuel rods typically include fuel rod diameter D, wire diameter Dw, helical pitch H, and fuel rod axial length L. Table 1 provides the specific parameter values.

Table 1 Geometric parameters of the wire-wrapped fuel rod

Geometric Parameter	Value (mm)
Fuel rod diameter D	[value]
Wire diameter Dw	[value]
Helical pitch H	[value]
Axial length L	[value]

For actual operating lead-bismuth fast reactors, fuel assemblies with metal wire spacers generally contain more than 37 fuel rods. To reduce computational resources and time, this study selects a single wire-wrapped fuel rod as the analysis object. The specific geometric parameter values for the wire-wrapped fuel rod reference data from the MYRRHA reactor [?].

Figure 2 Wire-wrapped fuel assembly structure

In constructing the wire-wrapped fuel rod model, practical considerations and efficiency often require reasonable simplification of the geometry based on experience. While maintaining the geometric dimensions of the fuel rod unchanged, the distance from the wire center to the fuel rod center is reduced, changing their relationship from tangent to intersecting, with the intersecting portion filleted. This simplified form is illustrated in Figure 2, which reduces the difficulty of meshing in the contact region between the fuel rod and wire. According to Merzari et al. [?], this geometric simplification has negligible impact on the flow field near the contact point.

2.2 Boundary Conditions

This study involves calculations for both fluid and solid domains, so boundary conditions need to be specified separately for each. The fluid uses lead-bismuth alloy. To simplify calculations, temperature effects on flow field parameters are not considered, so the lead-bismuth alloy properties are constant: density of 10324.3 $\mathrm{kg \cdot m^{-3}}$ and dynamic viscosity of 0.001689 $\mathrm{Pa \cdot s}$. The fluid domain boundary conditions are: inlet velocity of 1.4 $\mathrm{m \cdot s^{-1}}$, outlet at atmospheric pressure, and no-slip walls. The solid domain boundary conditions are: both ends of the fuel rod are fully fixed [?, ?, ?], and the fuel rod and wire surface are fluid-structure coupling interfaces.

2.3 Turbulence Model Sensitivity Analysis

Since the fluid domain calculation requires analysis of pressure fluctuations near the fuel rod wall, turbulence models including RANS and LES can be selected. For near-wall analysis in RANS models, the SST k-ω model is preferred, with detailed information about this model provided in Section 1. Therefore, the analysis in this section focuses on the LES and SST k-ω models.

2.3.1 Turbulence Model Meshing

Since turbulence contains eddies of different scales, using the Large Eddy Simulation (LES) model requires constructing sufficiently fine meshes to directly simulate most eddies while employing filtering methods to treat smaller-scale eddies. To determine the mesh scale for the LES model, one approach is to estimate the minimum LES mesh resolution based on the Taylor microscale. However, at high Reynolds numbers, this method may lead to under-prediction of LES mesh resolution [?, ?]. Addad et al. [?, ?] proposed a "priori" analysis-based method for estimating the minimum LES mesh scale, which has proven effective and widely used in practice. The estimation is as follows: [equation], where l is the Taylor microscale (m) and L is the turbulent energy scale (m). The computational expressions are: [equations]. The values of l and L can be obtained from Reynolds-Averaged Navier-Stokes (RANS) model simulation results, allowing RANS calculations to estimate the mesh size for LES models.

Due to the irregular geometry, hybrid hexahedral and prism layer meshes are adopted for convenience, with hexahedral meshes used in the mainstream region. Since the LES mesh scale determines the problem' s resolved scale, once the resolution scale is determined, mesh independence analysis becomes unnecessary. However, determining the LES mesh scale requires the RANS model, whose results need to be based on an optimal mesh solution. Therefore, mesh independence analysis was performed before RANS model calculations. Four mesh sets with different quantities were generated for the fluid domain: 710,000, 1.7 million, 3.72 million, and 13.95 million cells. The pressure drop in the fluid domain was calculated for each mesh set, with results shown in Figure 3 [Figure 3: see original paper]. Considering both computational results and resources, the third mesh set (3.72 million cells) was selected for RANS model fluid calculations.

To verify mesh sensitivity on FIV results, the vibration displacement amplitudes at the fuel rod center corresponding to the four mesh sets (710,000, 1.7 million, 3.72 million, and 13.95 million cells) were further compared (Table 2). The results show that when the mesh count $\geq$ 3.72 million, the amplitude error is <3%, indicating that the third mesh set (3.72 million cells) meets the accuracy requirements for FIV analysis.

Table 2 Comparison of maximum amplitude for different mesh counts

Mesh count (ten thousand)	Maximum Amplitude (m)	Relative error (%)

For LES simulations, special attention must be paid to meshing in near-wall regions. Near-wall meshes generally need to satisfy the $y^+ < 1$ criterion, so prism layers are used to refine the near-wall boundary layer mesh. The thickness of the first boundary layer directly affects the y^+ value. However, considering computational resources, a sensitivity analysis was conducted on the maximum y^+ values corresponding to different first boundary layer thicknesses. Figure 4 [Figure 4: see original paper] shows that selecting a first boundary layer thickness of 0.0008 mm can satisfy the wall $y^+ < 1$ requirement.

Figure 4 Plot of first boundary layer thickness versus maximum wall y^+ value

Figure 5 [Figure 5: see original paper] presents the Taylor microscale and turbulent energy length scale distributions obtained from optimal mesh simulation at the axial mid-plane (z/L = 0.5). The figure shows that both the Taylor microscale and turbulent energy scale are smaller near the wire-wrap wall and larger at channel corner positions. This indicates that when using the LES model, higher mesh resolution is required in the wire-wrap wall region, while coarser meshes can be used at channel corners. The blue region in the contour plot represents the boundary layer region at the wire-wrap wall, and the mesh scale shown corresponds to the first boundary layer thickness value selected above. Considering computational resources and RANS model results, a value of 0.1 mm is adopted in this study to meet LES calculation requirements.

Figure 5 Taylor microscale and turbulent energy length scale distributions

2.3.2 Time Step Sensitivity Analysis

This study focuses on transient calculations of the fuel rod fluid domain, which involve complex dynamic processes in flow field transient simulation. The time step size has a direct impact on computational accuracy. If the time step is too large, it may lead to numerical instability; if too small, it significantly increases computational resource consumption. Therefore, a time step sensitivity analysis is conducted to determine a time step that meets computational requirements. Keeping the fluid domain mesh and other settings constant, time steps of 0.001 s, 0.0005 s, and 0.00005 s are selected for the sensitivity analysis, as shown in Figure 6 [Figure 6: see original paper].

Figure 6 Time-step sensitivity analysis

Using the three time steps mentioned above, the pressure time history at a point on the fuel rod wall at the mid-axial position (z/L = 0.5) is monitored over 0.1 s. The 0.001 s time step cannot accurately capture pressure fluctuation characteristics. When the time step is reduced to 0.0005 s, the pressure time-domain characteristics can be well captured with accuracy consistent with the 0.00005 s time step. Considering computational cost, 0.0005 s is deemed sufficient for simulation settings.

2.3.3 Solid Domain Mesh Independence Verification

The solid domain model consists of wire-wrapped fuel rods. Due to the complex structure of actual wire-wrapped fuel rods in reactors, this study neglects the fuel rod end plugs and compression springs, considering only the main components of the fuel cladding and pellets. The pellets in a single fuel rod are treated as an elastic continuum with no gap between pellets and cladding. This simplification method has been validated by De Santis and Shams [**?**], who compared the natural frequencies obtained using this approach with experimental measurements and found no differences. The cladding and wire material is 316L stainless steel, while the pellet material is UO_2. The solid domain geometric model matches the fluid domain geometric model, with cladding thickness set to the common reactor value of 0.52 mm. The treatment of the metal wire and fuel rod connection follows the method shown in Figure 2.

Similar to the fluid domain, fine meshes are required for solid analysis. Due to the irregular geometry of wire-wrapped fuel rods, structured meshing is difficult, so unstructured tetrahedral meshes are employed. Solid domain solution requires an optimal mesh, necessitating mesh independence analysis before calculation. Five mesh sets with different element counts were generated, and deformation calculations were performed under identical loading conditions for each. The mesh sensitivity analysis results are shown in Figure 7 [Figure 7: see original paper]. Considering computational resources and accuracy, the third mesh set with 640,000 elements is selected as the computational mesh for subsequent analyses.

Figure 7 Solid mesh independence analysis

2.3.4 Results Analysis

The focus of FIV analysis is fluid excitation forces, determined by monitoring the time variation of fluid excitation forces on the fuel rod and wire surface. Figure 8 [Figure 8: see original paper] compares the monitored average wall pressure fluctuations calculated by the two models. Since steady-state fluctuations are established after 0.2 s, the fluctuation curves for 0.2–0.6 s are presented. When using the SST k-ω turbulence model, the fluid excitation force load fluctuations are essentially zero and can be considered negligible over time, resulting in negligible calculated fuel rod vibration. In contrast, the LES model produces more pronounced fluctuations, exhibiting random variations on the order of tens of Pascals, demonstrating that the LES turbulence model is more suitable for capturing wall pressure fluctuations.

Figure 8 Comparison of fluid wall pressure load fluctuations for two turbulence models

Based on fluid calculations completed with both turbulence models, unidirectional fluid-structure coupling is employed for the wire-wrapped fuel rod FSI calculations. Both axial ends of the fuel rod are fully fixed, with a transient calculation time of 0.6 s. Taking the axial center position of the fuel rod, the solid vibration responses at this location calculated by the two turbulence models are obtained, with results shown in Figure 9 [Figure 9: see original paper]. When using the RANS model, the calculated vibration of the wire-wrapped fuel rod is extremely small, with maximum amplitude not exceeding 1 micrometer, making the vibration response essentially negligible. Compared with the RANS model, the vibration response calculated using the LES model is more pronounced after the transient calculation reaches stability, corresponding to the pressure fluctuations obtained from the flow field calculations. Since the LES turbulence model can more accurately capture pressure fluctuations on the fuel rod wall, it can more accurately determine the vibration response amplitude. Therefore, the LES model is more appropriate for predicting flow-induced vibration in fuel rod bundles.

Figure 9 Comparison of fuel rod vibration for two turbulence models

2.4 Fluid-Structure Coupling Model Sensitivity Analysis

This study also addresses the fluid-structure coupling model, specifically comparing unidirectional and bidirectional FSI. As introduced in Section 1.3, unidirectional FSI refers to completing the fluid domain calculation first, then passing results to the solid domain without feedback of deformation results to the fluid domain. Bidirectional FSI involves mutual data transfer between fluid and solid domains: the fluid domain transmits force results, and after the solid domain calculates deformation, it passes the deformation back to the fluid domain to update the fluid domain boundaries through dynamic meshing. Generally, when deformation is small, unidirectional FSI is employed in engineering to reduce computational resource consumption. This study considers vibration under core axial flow conditions, which is essentially a micro-motion problem with very small solid deformation and limited influence of solid domain deformation on the fluid domain. Therefore, unidirectional FSI is expected to meet computational requirements. However, specific comparative analysis is still needed. Since the LES model is more suitable than the RANS model for capturing wall pressure fluctuations, the LES model is selected based on the results in Section 2.3. Figure 10 [Figure 10: see original paper] presents the comparison results.

Figure 10 Comparison of unidirectional and bidirectional fluid-structure interaction methods

Figure 10 shows that solid domain deformation has minimal impact on the flow field in bidirectional FSI, with essentially no difference between unidirectional and bidirectional FSI results. After reaching steady state, the vibration displacement error between the two methods is negligible. This indicates little difference in vibration response results between the two methods for axial flow fuel rod FIV analysis. Considering both computational accuracy and resource consumption, the unidirectional FSI method adopted in this study meets the requirements.

3.1 Flow Field Calculation Verification

Since the 1970s, academic efforts have been devoted to developing predictive capabilities for evaluating pressure drop in hexagonal wire-wrapped rod bundles to support early deployments. Interest in Generation IV sodium-cooled fast reactors and the Belgian MYRRHA lead-cooled fast reactor over the past decade has reinvigorated this field. By 1986, approximately ten empirical correlations had been developed for pressure drop prediction in wire-wrapped bundles, with the CTD correlation being one of the most representative. The Cheng and Todreas correlation for hexagonal wire-wrapped bundles was published in 1986 [**?**]. This empirical correlation is based on friction factors for three subchannel types: interior, edge, and corner subchannels. Assuming equal pressure drop across different subchannels and neglecting inlet, outlet, and momentum losses, the subchannel friction coefficients are used to predict the average friction coefficient.

Since 2016, nine additional wire-wrapped bundle experiments have been conducted in South Korea, India, Japan, Europe, and the United States to validate design tools and empirical correlations. As researchers themselves have stated, most results show good agreement with CTD. Based on these studies, the CTD correlation is considered the most suitable method for predicting friction coefficients in wire-wrapped bundles, not only due to its prediction accuracy but also because its application range covers all flow regimes. The CTD correlation is commonly used in subchannel codes for calculating fuel bundle temperature distributions to determine subchannel friction coefficient values, though this empirical correlation can be further improved. This study employs the improved results from Chen et al. [?] in 2018 for model validation.

Based on the geometric model in this paper, numerical simulation using the LES turbulence model is performed to obtain the friction coefficient f in subchannels at different Reynolds numbers, with results compared against the CTD empirical correlation. Figure 11 [Figure 11: see original paper] shows the comparison. The error between LES model simulation results and the empirical correlation is basically within 15%, demonstrating that the LES turbulence model adopted in this study can be used for fluid simulation research in wire-wrapped bundle channels.

Figure 11 Comparison of numerical simulation results in the fluid domain with UCTD empirical correlation

3.2 Solid Domain Calculation Verification

For structural dynamics validation, this study selects experimental data from Chen and Wambsganss [?] on flow-induced vibration of a cylinder induced by water axial flow. In a water-filled flow channel with an inner diameter of 25.4 mm, the natural frequency and damping ratio of a cylindrical brass beam with a length of 1.19 m and diameter of 12.7 mm were measured. The experimental structure is simulated using ANSYS software, with the first-order modal frequency extracted. Table 3 presents the comparison of natural frequency and damping ratio results under different methods.

Table 3 Comparison of natural frequency and damping ratio results under different methods

From the results in Table 3, it can be found that this study numerically simulated cases with inlet flow velocities ranging from 10 to 40 $m \cdot s^{-1}$. Taking the first-order natural frequency for analysis, the error between the natural frequency results and experimental values is small, within 5%. For the damping ratio, the error is slightly larger than that for natural frequency, with a maximum error of 11.9%, which is still within the 20% error range and can meet engineering calculation requirements. In summary, the solid finite element model in this paper can satisfy computational requirements.

3.3 Fluid-Structure Coupling Model Verification

It is necessary to validate the fluid-structure coupling method. This section simulates the single cylinder axial flow vibration experiment in a square channel conducted by Xu et al. [?] to verify the model and method adopted in this study.

The vertical test section of the gravity water tunnel is 2 meters long with a cross-section of 0.3 m × 0.3 m. The internal water flow is driven by a motor-controlled single-stage pump with designed velocities ranging from 0.02 to 2 $m \cdot s^{-1}$. The flexible cylinder is vertically fixed on a pair of identical metal airfoil supports, with both ends rigidly connected to convex upstream supports and downstream cylindrical supports, achieving clamped-clamped boundary conditions. The ratio of cylinder diameter to hydraulic diameter in the test section is 1/12.

A turbulence grid installed above the cylinder can transform the incoming flow from laminar to turbulent state. Figures 12 [Figure 12: see original paper] and 13 [Figure 13: see original paper] show the test section and the grid structure used in the experiment. The fluid is liquid water, which passes through the grid above the flow channel to increase turbulence intensity and flows downward to scour the cylindrical rod. A laser vibrometer is used to measure the cylinder' s vibration response. The cylinder material is silicone rubber, specifically Dow Corning RTV-4230-E, identical to the material used by Paidoussis. The cylinder top is 1 m from the grid, with a diameter of 14 mm, length of 610 mm, and water at room temperature.

Four inlet flow velocities from the experimental results are selected: 0.62 $m \cdot s^{-1}$, 1.17 $m \cdot s^{-1}$, 1.7 $m \cdot s^{-1}$, and 2 $m \cdot s^{-1}$. Calculations are performed using the model and FSI method from this study to obtain cylinder amplitudes at different flow velocities. Figure 14 [Figure 14: see original paper] presents the comparison. The maximum validation error between numerically simulated amplitudes and experimental results is 15%, which is within acceptable levels. Therefore, the fluid-structure coupling method adopted in this study can be used to simulate flow-induced vibration problems under axial flow.

Figure 12 Schematic diagram of the experimental section
Figure 13 Schematic of a turbulent grid
Figure 14 Comparison of results from different methods

4 Seven-Rod Bundle Flow-Induced Vibration Behavior Analysis

The geometric model uses a 7-rod bundle wire-wrapped fuel assembly with the same dimensions as before, but with the model length L increased from 600 mm to 900 mm, as shown in Figure 15 [Figure 15: see original paper]. Flow-induced vibration analysis is conducted using the LES simulation and its meshing method.

Figure 15 Schematic diagram of rod bundle wire-wrapped fuel structure

4.1 Flow Field Calculation Results Analysis

The inlet velocity is selected as 1.8 $m \cdot s^{-1}$, with a Reynolds number of [value], inlet temperature of 580 K, no-slip and adiabatic boundary conditions on the fuel rod surface, and a heat flux of 60,000 $W \cdot m^{-2} \cdot K^{-1}$. The outlet is set as a pressure outlet at atmospheric pressure.

First, the velocity field fluctuations are analyzed. The velocity u of a fluid particle passing through a fixed point in space at a specific moment is called instantaneous velocity. According to Reynolds averaging, the time-averaged velocity is calculated as [equation], and the fluctuating velocity is calculated as [equation]. Clearly, the fluctuating velocity value can indicate the mixing intensity at a point in the flow field. Three arbitrary positions in the center channel, edge channel, and corner channel at the axial mid-plane (z/L = 0.5) are selected as monitoring points, as shown in Figure 16 [Figure 16: see original paper]. The instantaneous fluid velocity variations over time are captured at these points for statistical analysis.

Figure 16 Schematic of data extraction points for turbulent velocity fluctuation analysis

Figure 17 [Figure 17: see original paper] shows the instantaneous turbulent velocity values at each monitoring point. By comparing instantaneous velocity results in different subchannels, it can be found that velocities in the center and edge channels are smaller and very similar, while the corner channel has the highest velocity. According to Bernoulli' s principle, locations with lower velocity have higher pressure, indicating that fluid pressure in the center and edge channels is greater than in the corner channel. Regarding instantaneous velocity, after the calculation progresses to 0.3 s, the velocity basically stabilizes, with small fluctuation ranges in all three subchannel types, though the edge channel shows slightly larger instantaneous velocity fluctuations than the other two.

Figure 17 Velocity versus time at different monitoring points in channel mid-section

Flow-induced vibration arises from temporal fluctuations in fluid excitation forces at the fluid-structure interface. Three monitoring points are uniformly distributed axially on the surface of fuel rod 1 according to the helical wire distribution to monitor fluid pressure at three locations, as shown in Figure 18 [Figure 18: see original paper].

Figure 18 Time-domain results of fluid excitation force on the surface of center fuel rod 1

From the time-domain results, pressure fluctuations at axial positions are small, basically within 1 kPa. Since some fluctuations exist at the beginning of transient calculations, each figure shows variations before 0.2 s. The results after reaching steady state, marked by red lines in Figure 18 at times after 0.2 s, are the focus. As axial height increases, the pressure on the fuel rod surface gradually decreases, consistent with the pressure drop that exists during coolant flow.

To quantitatively analyze similarities and differences in pressure fluctuation characteristics at different fuel rod surface positions, pressure fluctuation frequency analysis is performed. Based on the pressure time-domain results for center fuel rod 1, Figure 19 [Figure 19: see original paper] shows the frequency domain analysis results of pressure fluctuations at different axial positions of the fuel rod.

Figure 19 Frequency domain results of fluid excitation force on the surface of center fuel rod 1

From the frequency domain results, since this is the same case, the peak frequencies at different axial points on the same fuel rod are identical, which matches expected results. Since fluid excitation force is the cause of fuel rod vibration, resonance can be determined based on the frequency of fluid excitation forces and the natural frequencies.

4.2 Vibration Response Results Analysis

The fuel rod and metal wire surface are no-slip boundaries. Fluid excitation forces obtained from fluid domain calculations are applied to perform vibration response calculations and analysis in the solid domain. First, modal frequencies under different conditions are analyzed. Both ends are fully fixed as boundary conditions, and the first 12 modal orders are analyzed, with results shown in Figure 20 [Figure 20: see original paper]. For prestressed modal calculations, the fluid excitation force at an inlet velocity of $1.8\ \mathrm{m \cdot s^{-1}}$ is applied as the load.

Figure 20 Modal frequencies corresponding to different states

The results in Figure 20 show that modal frequencies increase with mode order, with every two modal frequencies being relatively close. The radial direction is divided into X and Y directions in the calculations, but the mode shapes are essentially identical, so the frequencies are the same. The first-order wet modal frequency is lower than the dry modal frequency. The prestressed modal frequency values differ little from the dry modal frequency because the fluid loads on the wire-wrapped fuel rod surface are relatively small, so prestress values do not significantly affect modal results. Comparing with the dominant frequency of fluid excitation forces at 65.93 Hz, which does not coincide with any modal order, indicates that no resonance occurs under the conditions in this study. This is likely because the energy of turbulent excitation forces is distributed over a broad frequency band without triggering resonance.

Flow field results are loaded into the solid domain to obtain fuel rod vibration responses through FSI calculations. Since the vibration responses of fuel rods at different positions are analyzed, contact between fuel rods during vibration is not considered in the results. At an inlet velocity of 1.8 $m \cdot s^{-1}$, monitoring points are taken at the 1/4, 1/2, and 3/4 axial positions at the center of the cross-section to monitor vibration responses of center fuel rod 1 and peripheral fuel rod 4. Figures 21 [Figure 21: see original paper] and 22 [Figure 22: see original paper] present the vibration results.

Figure 21 Vibration displacement results for fuel rod 1 at center position
(a) Total vibration displacement at different axial positions
(b) Vibration displacement at axial 1/2 position

Figure 22 Vibration displacement results for fuel rod 4 at peripheral position
(a) Total vibration displacement at different axial positions
(b) Vibration displacement at axial 1/2 position

For both center rod 1 and peripheral rod 4, the maximum amplitude occurs at the axial midpoint. Since both ends are fully fixed, the vibration patterns at the 1/4 and 3/4 axial positions are essentially the same. For center rod 1, the X-direction amplitude is smaller than the Y-direction amplitude, while for peripheral rod 4, the X-direction amplitude is larger than the Y-direction amplitude. This indicates that the vibration direction of peripheral fuel rods differs from that of the center rod, which is also related to the different fluid forces acting on fuel rods 1 and 4. Comparing vibration responses between center and peripheral rods, the amplitude of peripheral rod 4 is overall larger than that of center rod 1. This is related to fuel rod 4 being located in three different subchannels and experiencing non-uniform fluid forces, which is associated not only with the wire wrap but also with different fluid loads in different subchannels. On one hand, the non-uniform flow field distribution near peripheral rod 4, with the highest velocity in the corner channel (Figure 17), leads to more intense fluid pressure fluctuations on the peripheral rod surface and increased excitation force amplitude. Additionally, due to subchannel effects, the center rod is only affected by the center subchannel flow field, while the peripheral rod is located at the junction of edge and corner subchannels where flow turbulence intensity is higher, exacerbating the vibration response. Furthermore, the helical wire structure causes larger variations in local flow channel cross-sectional area around the peripheral rod, inducing periodic vortex shedding that further amplifies vibration amplitude.

Statistical processing of vibration time-domain results is performed to analyze the distribution patterns of vibration responses at different displacement levels for fuel rods at different positions. Figure 23 [Figure 23: see original paper] shows the statistical results of vibration response at the axial 1/2 position. It can be seen that the vibration displacement of the center rod is concentrated near 10 m and 40 m, while the vibration displacement of peripheral rod 4 is mainly near 50 m. Compared with the center rod results, the vibration displacement distribution of peripheral rod 4 is more regular, with an overall distribution closer to normal distribution.

Figure 23 Statistical results of vibration displacements at the axial 1/2 position of the fuel rod
(a) Center rod 1
(b) Peripheral rod 4

PSD analysis is performed on the vibration time-domain results. The time-domain analysis results of vibration response at the axial 1/2 position for center rod 1 and peripheral rod 4 are shown in Figures 24 [Figure 24: see original paper] and 25 [Figure 25: see original paper]. The first peak frequency appearing in the frequency domain analysis results is 32 Hz for both. Comparing with the modal analysis results in Figure 20, 32 Hz is located near the first two modal frequencies. Subsequent peaks at 42 Hz, etc., are also basically consistent with the first six modes in the modal analysis, indicating that fuel rod FIV response in axial flow is primarily a superposition of the first few natural mode shapes, consistent with turbulent excitation patterns. The frequency domain vibration results for peripheral rod 4 are essentially the same as for center rod 1, with the first peak frequency also at 32 Hz, indicating that the vibration response of peripheral rod 4 is similarly dominated by superposition of low-order modal shapes.

Figure 24 Frequency domain analysis results of vibration response at axial 1/2 position of center rod 1
(a) X-direction
(b) Y-direction

Figure 25 Frequency domain analysis results of vibration response at axial 1/2 position of peripheral rod 4
(a) X-direction
(b) Y-direction

Vibration trajectories at the axial 1/2 position are plotted based on X and Y direction vibration displacements. The vibration trajectory of center rod 1 at the axial 1/2 position is shown in Figure 26 [Figure 26: see original paper]. Consistent with previous time-domain results, the position of maximum axial amplitude is at 1/2. The starting point begins near the coordinate origin and gradually approaches a stable position, with the stabilized trajectory shape being elliptical. The vibration amplitude of center fuel rod 1 in the X-direction is greater than in the Y-direction. The results indicate that fluid force fluctuations in the X-direction acting on the center position fuel rod are more intense, having a greater impact on fuel rod deformation, and the overall distribution of fluid forces is independent of different axial positions.

Figure 26 Vibration trajectory at 1/2 axial position of central rod 1

Conclusion

This study employs ANSYS software to investigate flow-induced vibration phenomena in wire-wrapped fuel assemblies for lead-cooled fast reactors. The specific research findings are summarized as follows:

1. Through sensitivity analysis, the LES model is determined to be more suitable for capturing pressure fluctuations on fuel rod surfaces, thereby enabling more accurate FIV analysis. The unidirectional fluid-structure coupling method yields results similar to the bidirectional method under axial flow, making it applicable for subsequent analyses, with simulation results consistent with experiments.
2. Metal wire wraps generate vortices in the flow channel, enhancing fluid mixing. Velocities in the center and edge channels are smaller, while the corner channel has the highest velocity. Vibration responses show that maximum amplitude occurs at the axial midpoint for both center and peripheral rods. The vibration displacement distribution of peripheral rods is more regular, primarily concentrated near 50 m, while center rod vibration displacement is concentrated near 10 m and 40 m.
3. Modal frequencies increase with mode order, with every two modal frequencies being relatively close. The first-order wet modal frequency is lower than the dry modal frequency, and the prestressed modal frequency differs little from the dry modal frequency. Under axial flow, vibration of all fuel rods is dominated by the first-order vibration frequency, characteristic of turbulent excitation phenomena.

Future research can be expanded in the following directions: Conduct multi-physics coupling analysis incorporating thermal and irradiation effects to investigate the coupled influence of temperature gradients and material irradiation swelling on vibration behavior, improving FIV prediction models under complex operating conditions. Perform experimental validation by constructing a wire-wrapped bundle vibration test platform to verify the robustness of numerical models in high-temperature, high-irradiation environments.

Author Contributions Statement

JI Xietian is responsible for proposing the research concept, establishing the computational model, performing analysis, and writing the article; GUO Hongjian provides design parameters and participates in experimental data validation; ZHANG Jing is responsible for research scheme guidance and critical review of the intellectual content; WU Yingwei provides computational guidance, research progress supervision, and article revision; HE Yanan is responsible for technical support, project process supervision, and project management; WANG Mingjun provides technical guidance and article revision; SU Guanghui is responsible for guidance and resource coordination; QIU Suizheng provides computational guidance, article review, and revision; TIAN Wenxi is responsible for overall research quality control and thesis guidance.

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