# Effect of Helical Structure on Flow and Heat Transfer in Helical Trifoil Fuel Elements

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## Abstract

Helical Tri-lobe Fuel (HTF) elements are a novel type of fuel element featuring large specific heat transfer area, strong convective heat transfer capability, and good mechanical performance, offering broad application prospects in advanced nuclear power and small nuclear reactors. This paper conducts a numerical simulation study on single-phase flow and heat transfer characteristics within HTF assemblies, calculating and analyzing key parameters such as secondary flow velocity, cross-sectional vorticity, temperature, and heat transfer coefficient in the rod bundle flow field, and obtaining the effects of parameters such as helical pitch, minimum gap spacing, and the ratio of root arc radius to tip arc radius on flow and heat transfer characteristics in the flow field. The results indicate that the helical structure of HTF elements can enhance lateral mixing of the coolant, strengthening convective heat transfer through secondary flow. Decreasing both helical pitch and minimum gap spacing can enhance the heat transfer performance of HTF elements, but a helical pitch greater than 240mm substantially increases temperature non-uniformity in both the coolant and wall surfaces.

## Full Text

## Preamble

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### Research on the Effect of Helical Geometry on Flow and Heat Transfer Characteristics of Helical Tri-lobe Fuel

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## Abstract

The helical tri-lobe fuel (HTF) element represents a novel fuel design featuring a large specific heat transfer area, strong convective heat transfer capability, and excellent mechanical properties, offering broad application prospects in advanced nuclear power systems and small modular reactors. This paper presents a numerical simulation study of single-phase flow and heat transfer characteristics within HTF assemblies, calculating and analyzing key parameters including secondary flow velocity, cross-sectional vorticity, temperature distribution, and heat transfer coefficients in the rod bundle flow domain. The influence of structural parameters such as helical pitch, minimum gap distance, and the ratio of lobe root arc to lobe tip arc radius on flow and heat transfer characteristics was systematically investigated. The results demonstrate that the helical structure of HTF elements enhances coolant lateral mixing and strengthens convective heat transfer through secondary flow effects. Both decreasing helical pitch and reducing minimum gap distance can augment heat transfer performance; however, helical pitches exceeding 240 mm substantially increase temperature non-uniformity in both the coolant and wall surfaces.

**Keywords:** Helical tri-lobe fuel; Helical geometry; Flow and heat transfer; Secondary flow

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Fuel assemblies constitute one of the core components in nuclear reactors, directly determining both economic viability and safety performance. With continuous fuel element development, helical fuel designs have been proposed for advanced nuclear power and small modular reactor applications, including wire-wrapped fuel elements, twisted tape fuel elements, helical tri-lobe fuel elements, and helical cruciform fuel elements. Among these, helical tri-lobe fuel (HTF) elements have emerged as a prominent configuration, featuring a three-lobed radial cross-section twisted along the axial direction with intimate contact between the cladding and fuel pellet. The radial tri-lobe structure increases the specific heat transfer area, while the axial helical geometry enhances inter-channel mixing within HTF assemblies, thereby strengthening core convective heat transfer capabilities. HTF elements achieve radial self-fixation through helical interlocking, eliminating the need for spacer grids, which significantly reduces flow resistance within the core and improves overall reactor safety performance.

HTF elements have undergone preliminary engineering application and demonstrated superior thermal-hydraulic performance compared to conventional rod-type fuel elements. Diakov et al. [1] initially proposed helical cruciform fuel element designs for the KLT-40 reactor core. The Petersburg Nuclear Physics

Institute (PNPI) in Russia [2] developed VVER-T reactor fuel rods characterized by triangular cross-sections with axial helical arrangement. Building upon the PNPI design, Bol'shakov et al. [3] proposed HTF elements and assemblies, experimentally validating their performance. Lightbridge Corporation [4] developed helical tri-lobe metallic fuel elements for small reactor applications, analyzing through experiments and simulations the potential for enhanced heat exchange efficiency and improved reactor safety.

The helical structure of these fuel elements induces lateral coolant mixing that strengthens surface heat transfer, prompting extensive research on flow resistance, convective heat transfer capability, and critical heat flux. Conboy [5,6], Shirvan [7], and Garusov [8] conducted experimental and numerical investigations on single-phase flow and heat transfer in helical fuel elements, analyzing the effects of helical geometry on friction coefficients and inter-channel mixing while exploring power uprate potential compared to traditional rod fuel. Koroush et al. [9] performed CFD studies on flow and heat transfer in 4$×$4 helical fuel assemblies, proposing a friction factor correlation for pressurized water reactors through comparison with experimental data. Deng et al. [10] and Cong et al. [11] conducted thermo-mechanical coupling analyses on single helical fuel rods and rod bundles to assess safety performance. Bol'shakov [3] and Fu et al. [12] experimentally investigated critical heat flux in helical tri-lobe and helical cruciform fuel rods, analyzing improvements over conventional rod bundles and developing predictive models. Tang et al. [13] compared flow and heat transfer characteristics between triangular and square arrangements for helical cruciform fuel rod bundles. Cai et al. [14] simulated the effects of helical pitch and mainstream velocity on flow and heat transfer, elucidating the influence 规律 of helical pitch.

Existing research demonstrates that HTF assemblies outperform conventional rod-type fuel assemblies in thermal-hydraulic performance; however, comprehensive understanding of how helical structural parameters affect flow and heat transfer remains insufficient. This study establishes a triangular lattice HTF assembly model and employs Fluent software to investigate flow and heat transfer characteristics, focusing on analyzing the effects of helical pitch and minimum gap distance on secondary flow velocity, temperature distribution, and heat transfer coefficients.

### 1.1 Geometric Model

Bol'shakov et al. [3] proposed an HTF element design suitable for small pressurized water reactors. This study investigates the HTF element design proposed by Bol'shakov, with its structure illustrated in [Figure 1: see original paper]. The HTF element features a tri-lobe cross-section twisted along the axis. When adjacent HTF elements align with their lobes on the same line, the minimum gap between two lobe tip arcs is designated as *d*. The fuel elements are arranged in a triangular lattice, with detailed geometric dimensions provided in .

### 1.2 Mesh Generation

This study employs hexahedral structured meshes generated using ICEM for the flow domain. Most existing helical fuel mesh generation approaches [14,15] utilize interface processing. Due to the helical and triangular arrangement characteristics of HTF elements, the flow domain is divided into a near-rod region containing the helical fuel rods and an inter-rod region without fuel rods, as shown in [Figure 2: see original paper]. Meshes are generated separately for these two regions: the near-rod region uses a 2D mesh extruded along the axial direction with rotation, while the inter-rod region employs unidirectional extrusion of a 2D mesh.

All generated meshes achieve quality metrics above 0.6, indicating high mesh quality. Five mesh sets were created with 1.43 million, 2.57 million, 3.85 million, 7.69 million, and 10.69 million cells. Since flow resistance represents a key characteristic of helical fuel assemblies, the pressure drop between inlet and outlet serves as the parameter for mesh independence verification. As shown in , when mesh counts reach 7.69 million and 10.69 million, the pressure drop becomes independent of mesh density. Considering computational efficiency, the 7.69 million cell mesh was selected for numerical analysis.

### 1.3 Turbulence Model

Cai et al. [16], Xiao et al. [17], and Cong et al. [18] validated various turbulence models against experimental data for helical fuel assembly flow resistance and mixing characteristics. The results indicate that both the SST k-$\omega$ and RSM models provide satisfactory simulation accuracy for helical fuel assemblies. Although the RSM model can deliver more detailed results, it suffers from poor convergence and computational complexity. Therefore, considering both accuracy and efficiency, this study selects the SST k-$\omega$ model for simulating coolant turbulent flow in HTF assemblies.

The SST k-$\omega$ model comprises the turbulent kinetic energy equation and the specific dissipation rate equation. The turbulent kinetic energy equation ($k$ equation) describes the transport of turbulent kinetic energy, including production, diffusion, and dissipation processes, with the general form:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ (\alpha_k + \nu_t) \frac{\partial k}{\partial x_j} \right] + P_k - \beta_k \omega k$$

where $U_j$ represents the mean velocity component, $\alpha_k$ and $\beta_k$ are model constants, $\nu_t$ is the turbulent viscosity coefficient, $\sigma_k$ is the turbulent Prandtl number, and $P_k$ is the production term.

The specific dissipation rate equation ($\omega$ equation) describes the transport of turbulent dissipation rate, including production, diffusion, and dissipation processes. The general form of the $\omega$ equation is:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\alpha_\omega + \nu_t)\frac{\partial \omega}{\partial x_j}\right] + P_\omega - \beta_\omega \omega^2$$

where $\alpha_\omega$ and $\beta_\omega$ are model constants, and $\sigma_\omega$ is the turbulent Prandtl number for the $\omega$ equation.

The SST k-$\omega$ turbulence model features an adaptive switching capability through a blending function. In regions far from walls, the model adopts the k- formulation, while near-wall regions switch to the k-$\omega$ formulation. This design ensures computational accuracy for flow phenomena within HTF assembly channels. Due to the model's stringent mesh quality requirements, the maximum y+ value in subsequent mesh generation is maintained at approximately 1 to ensure reliable near-wall results. Additionally, second-order discretization schemes are employed to enhance the accuracy of control equation discretization.

### 1.4 Boundary Conditions

Boundary conditions reference typical small pressurized water reactor IRIS design parameters [19], as summarized in . The outlet is specified as a pressure boundary at 15.5 MPa. Water serves as the coolant in the rod bundle channel, with thermophysical properties determined using the IAPWS-IF97 formulation, where density, specific heat capacity, thermal conductivity, and dynamic viscosity all vary with temperature. The inner wall surface is modeled as a uniformly heated wall with a heat flux of 300 kW/m$^2$, while the outer wall surface employs a symmetry boundary condition. The inlet is specified as a velocity boundary with 3 m/s velocity and 565 K temperature, with flow direction vertically upward.

## 2.1 Helical Pitch

Helical pitch refers to the axial distance corresponding to a 360° rotation of the HTF element helix along its axis. Simulations were conducted for fuel rod bundles with helical pitches of 120 mm, 180 mm, 240 mm, 360 mm, 720 mm, and a non-helical case.

The helical structure of HTF elements generates secondary flow as coolant sweeps over the element surface, thereby enhancing heat transfer capability. Secondary flow refers to motion perpendicular to the axial direction, typically one order of magnitude smaller than mainstream velocity but capable of significantly augmenting heat transfer without excessive flow dissipation. Proper secondary flow design can achieve substantial heat transfer enhancement with minimal flow resistance penalty.

[Figure 3: see original paper] illustrates the secondary flow velocity vectors at cross-sections z=240 mm and z=280 mm for a helical pitch of 240 mm. Due to the counterclockwise rotation of fuel rods, fluid in the near-wall region also flows counterclockwise around the rods. In the central inter-rod region, fluid flows clockwise under the influence of near-wall swirling flow. Maximum secondary flow velocities occur at the lobe root arcs, while velocities remain lower in the inter-rod region. This occurs because fluid near the lobe root arcs changes direction following fuel rod twist, experiencing enhanced mixing from the helical structure, whereas fluid in inter-rod regions is less affected by fuel rods and primarily flows axially.

To quantitatively characterize secondary flow intensity, the dimensionless absolute cross-sectional vortex flux number $J_{ABS}$ [20] is introduced, expressed as:

$$J_{ABS} = \frac{\iint |\omega_n| dA}{A}$$

where $\omega_n$ is the vorticity in the flow direction and $A$ is the cross-sectional area perpendicular to the flow direction. $J_{ABS}$ eliminates cancellation effects from opposite vortices in the cross-section, objectively reflecting secondary flow intensity.

Due to intense vorticity variations from inlet effects, $J_{ABS}$ values at z=360 mm for different configurations are analyzed. The pressure drop across the rod bundle and $J_{ABS}$ at z=360 mm are shown in Figure 4: see original paper. As helical pitch decreases, $J_{ABS}$ increases, indicating that secondary flow intensity strengthens with reduced helical pitch, with greater influence of helical structure on axial flow and enhanced mixing. However, as shown in Figure 4: see original paper, pressure drop increases from 4523 Pa to 8181 Pa as helical pitch decreases, indicating higher flow resistance and increased flow instability. Therefore, helical pitch selection requires comprehensive consideration of both mixing enhancement and flow resistance increase.

[Figure 5: see original paper] presents wall temperature variations at z=360 mm for different helical pitches. Without helical twist, wall temperature exhibits symmetric distribution with equal temperatures on both sides of each lobe. Temperature concentration occurs at lobe root arcs due to heating from adjacent helical lobes, while lobe tip arcs show decreasing wall temperatures due to more significant fluid cooling effects. The helical structure reduces wall temperature symmetry, with maximum temperatures gradually shifting leftward on individual lobes, resulting in higher left-side temperatures. As helical pitch increases, left-side temperatures rise further. This occurs because HTF elements rotate counterclockwise, causing fluid on the left side of lobes to experience greater flow resistance at subsequent moments, leading to temperature elevation.

The heat transfer coefficient directly reflects fuel assembly heat transfer efficiency. Heat transfer coefficients at z=360 mm for different helical pitches are shown in Figure 4: see original paper. As helical pitch decreases, the heat transfer coefficient increases, enhancing HTF element heat transfer capability, consistent with the overall decreasing wall temperature trend. Moreover, as helical pitch decreases, the leftward wall temperature shift diminishes, with maximum temperatures gradually moving from near lobe tip arcs toward lobe root arc centers. This occurs because reduced helical pitch creates tighter fuel rod spacing per unit length, concentrating temperature distribution toward lobe root arcs.

[Figure 6: see original paper] displays temperature field contours at various axial positions for different helical pitches. The results clearly show that inter-rod region temperatures gradually increase as helical pitch decreases, due to enhanced channel mixing and improved heat transfer in rod bundles. At H=120 mm, significant heat concentration occurs at lobe root arcs, consistent with the aforementioned wall temperature and heat transfer coefficient trends.

Although reducing helical pitch enhances secondary flow intensity and heat transfer capability, it simultaneously increases flow resistance. Therefore, HTF element design requires comprehensive evaluation of both heat transfer enhancement and flow resistance penalties associated with helical pitch reduction.

### 2.2 HTF Element Gap Distance

Simulations were performed for minimum gap distances *d* of 0.25 mm, 0.5 mm, 1 mm, and 1.5 mm. [Figure 7: see original paper] presents velocity contours at z=360 mm for different minimum gap distances. As gap distance decreases, the flow area between elements narrows. $J_{ABS}$ increases with decreasing gap distance, indicating strengthened secondary flow intensity. Additionally, as gap distance decreases, boundary layer effects become more significant at minimum gap locations, reducing flow velocity. At *d*=0.25 mm, flow becomes restricted at minimum gap locations, with velocity decreasing to 0.03 m/s.

[Figure 8: see original paper] shows temperature field contours at different positions for various minimum gap distances. Under identical wall heat flux conditions, inter-rod region temperatures increase as minimum gap distance decreases. This occurs because reduced gap distance enhances mixing effects in inter-rod regions, strengthening heat transfer between coolant and fuel rods.

[Figure 9: see original paper] illustrates surface temperature distributions for the central HTF element at z=360 mm for different minimum gap distances. Fuel rod surface temperatures generally decrease as minimum gap distance reduces, primarily due to enhanced heat transfer capability that transfers more heat to the fluid domain, lowering wall temperatures. At *d*=0.25 mm, overall wall temperature reduction occurs because boundary layer effects become more pronounced, minimizing velocity at lobe tip arcs while increasing velocity at lobe root arcs, thereby strengthening heat transfer and producing lower wall temperatures.

Pressure drop variations are shown in Figure 10: see original paper. As minimum gap distance decreases, pressure drop increases due to more compact fuel rod arrangement and greater flow resistance. As shown in Figure 10: see original paper, heat transfer coefficients increase with decreasing gap distance because, for constant fuel surface area, reduced fluid volume experiences greater helical structure influence, enhancing heat transfer capability. Furthermore, at $d$=0.25 mm, flow restriction at minimum gap locations reduces fuel rod wall temperature while increasing mainstream temperature, significantly decreasing the temperature difference between wall and mainstream, resulting in higher heat transfer coefficients despite linearly increasing pressure drop. Therefore, HTF element gap distance selection requires comprehensive consideration of both flow resistance increase and mixing enhancement, noting that laminar flow at minimum gap locations can significantly improve helical fuel heat transfer capability.

### 2.3 R2/R1 Ratio

In selecting R2/R1 values, R1 variation significantly impacts fuel loading; therefore, R2 was varied to achieve R2/R1 values of 1, 1.7, 2.5, and 3.5, as shown in [Figure 11: see original paper]. Pressure drop, heat transfer coefficient, and fuel loading at z=360 mm are presented in [Figure 12: see original paper]. Figure 12: see original paper shows that pressure drop increases with R2/R1, indicating increased flow resistance. Figure 12: see original paper demonstrates that heat transfer coefficient increases with R2/R1, showing improved HTF element heat transfer capability. However, overall variations in both pressure drop and heat transfer coefficient remain relatively small, indicating minor effects of R2/R1 changes on flow resistance and heat transfer capability.

[Figure 13: see original paper] presents HTF element surface temperature distributions for the central fuel rod at z=360 mm with different R2/R1 values. As R2/R1 decreases, surface temperatures at lobe root arcs decrease. This occurs because smaller R2/R1 provides larger heat transfer area at lobe root arcs and deeper concave profiles, intensifying temperature concentration at lobe root arcs. Based on the above analysis, R2/R1 variation has minimal impact on HTF element thermal-hydraulic characteristics; therefore, R2/R1 selection primarily considers fuel loading effects. Normalized fuel loading variations with R2/R1 are shown in Figure 12: see original paper, demonstrating that larger R2/R1 values enable higher fuel loading.

## 3 Conclusion

This study conducted numerical simulations of single-phase flow and heat transfer characteristics in HTF elements to obtain thermal-hydraulic parameters including velocity fields, temperature fields, and heat transfer coefficients. The effects of fuel rod arrangement, helical pitch, and rod gap distance on flow and heat transfer characteristics were analyzed, yielding the following conclusions:

1) Reducing helical pitch enhances secondary flow intensity in near-wall regions of HTF elements, improving heat transfer capability. However, decreasing helical pitch simultaneously increases flow resistance in coolant channels.

2) Reducing minimum gap distance between HTF elements enhances flow and heat transfer capability in coolant channels with minimal impact on temperature non-uniformity in fluid and wall surfaces. Practical designs must comprehensively consider increased flow resistance at lobe tip regions resulting from reduced gap distance.
3) Increasing R2/R1 strengthens heat transfer capability in HTF assembly coolant channels, alleviates temperature concentration at lobe root arcs, and increases coolant channel flow resistance. However, R2/R1 variation affects these parameters within a limited range; therefore, R2/R1 selection primarily considers its impact on fuel loading.

**Author Contributions:** Diao Siyu established the computational model, performed data analysis, and wrote the manuscript; Zhao Yanan conceived the research idea, reviewed and revised the manuscript; Yu Tao provided technical guidance and research funding.

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