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Research Article

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Study on Nuclear Fuel Rod Performance using Helical Rib with water and Al_2O_3 Nanofluid as Coolant

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Abstract. This study explores helical fuel rod assemblies, which exhibit a distinctive axially twisted, spacer grid-free design to enhance nuclear fuel rod thermal efficiency. The primary objective is to compare the thermo-physical properties and heat transfer characteristics of water and Al_2O_3 nanofluids at varying concentrations within a helical fuel rod bundle using different twist angles. The temperature distribution, velocity changes, and pressure drops were analyzed using CFD simulations in a 4x4 helical rod assembly. Results indicate that helical rods significantly enhance core power density and thermal performance. A 360° twist angle improves mixing and heat transfer more effectively than a 180° twist. Adding Al_2O_3 nanofluids further boosts heat transfer rates, with a 4% concentration showing the highest improvement. The study underscores the potential of helical fuel rod assemblies for superior performance in nuclear applications, particularly in optimizing reactor efficiency and safety margins.

INTRODUCTION

In the pursuit of enhancing the safety, efficiency, and viability of nuclear power systems, researchers and engineers have been exploring innovative designs and methodologies. One such significant advancement is the utilization of helical fuel rod assemblies, which deviate from traditional fuel geometries and exhibit distinctive features. Characterized by an axially twisted configuration with a three or four-petaled profile, helical fuel rods present a self-supporting and spacer grid-free assembly. This unconventional design offers several advantages over traditional fuel geometries, including a larger surface-to-volume ratio, shortened radial heat conduction paths within fuel pellets, improved mixing characteristics, and heightened core strength [1, 2]

In this paper we have tried to observe and compare the heat transfer of water and Al_2O_3 at different concentrations in a helical fuel rod bundle using different twist angles. We tried to simulate how changing in coolant properties can affect the overall heat transfer and temperature distribution in 4*4 fuel rod bundle. We have observed the temperature distribution profile in different sub channels. Velocity changes and pressure drops have been presented along different axis in the helical rod bundles.

A comprehensive literature review of helical fuel rod bundles reveals their significant_impact on flow characteristics and heat transfer performance for both water and nanofluids. Studies have shown that helical cruciform fuel (HCF) designs offer advantages such as increased power output without changing heat flux, enhanced transverse mixing, and improved heat transfer efficiency[3-5]. The unique design of helical fuel assemblies introduces significant improvements in flow and heat transfer characteristics compared to traditional cylindrical rod bundles, offering increased heat transfer area and higher critical linear heat flux, which can significantly boost core power limitations[6, 7]. Research on water with nanofluids in helical coil tubes indicates that nanoparticle volume density influences heat transfer rates, with higher concentrations leading to improved performance and efficiency[8]. Numerical investigations further demonstrate that geometric parameters, Reynolds numbers, and working fluids play crucial roles in determining heat transfer enhancements, with nanofluid solutions showing superior performance compared to traditional fluids like water[9]. These findings underscore the potential of helical fuel rod bundles in optimizing thermal-hydraulic performance in various applications.

We have designed a four petalled form helical twisted rod. Then we are trying to increase the heat transfer by using nanofluid. Nanofluid consists of Al_2O_3, CuO, Ceramics or Polymers. Nanofluid is very much stable in high heat that's why we choose it as intermediate fluid to transfer heat.

CFD MODEL APPROACH

Geometry Modeling and Boundary Conditions

The 3D geometry of the helical fuel rod bundles is created utilizing the SolidWorks application. The flow behavior within the helical fuel rod bundle was analyzed computationally through the employment of Computational Fluid Dynamics (CFD) technique using Ansys fluent 2022 R1. The primary areas of interest include the variations in temperature and pressure along the length, as well as the flow attributes among different subchannels. The geometry model utilized in the current investigation is derived from previous mixing trials involving helical fuel rod configurations as documented by Conboy [1, 2]. Within the helical fuel setup, the rods interact periodically to provide mutual support within the assembly container, obviating the necessity for a spacer grid. To ensure both the credibility and cost-effectiveness of the experiment, Conboy ultimately examines a helical fuel bundle comprising 4*4 square-arrayed rods. Therefore, the benchmark bundle utilized in this research also consists of 4*4 square-arrayed rods, with a twist pitch of 500mm. The operational parameters include atmospheric pressure, 20 °C inlet temperature, and an inlet velocity of 0.28 m/s. The simulation initiated by Ansys Fluent incorporates an initial inlet pressure, while the Reynolds number for water is calculated to be 22594.

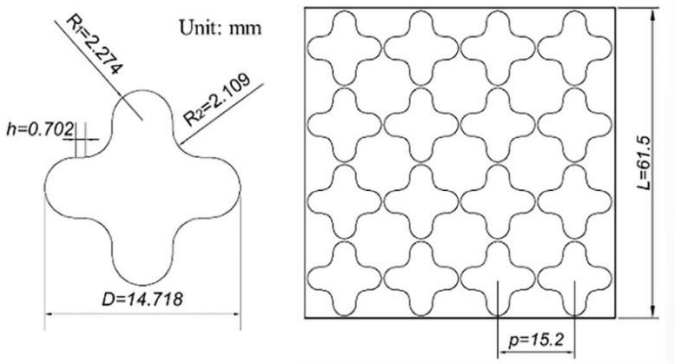
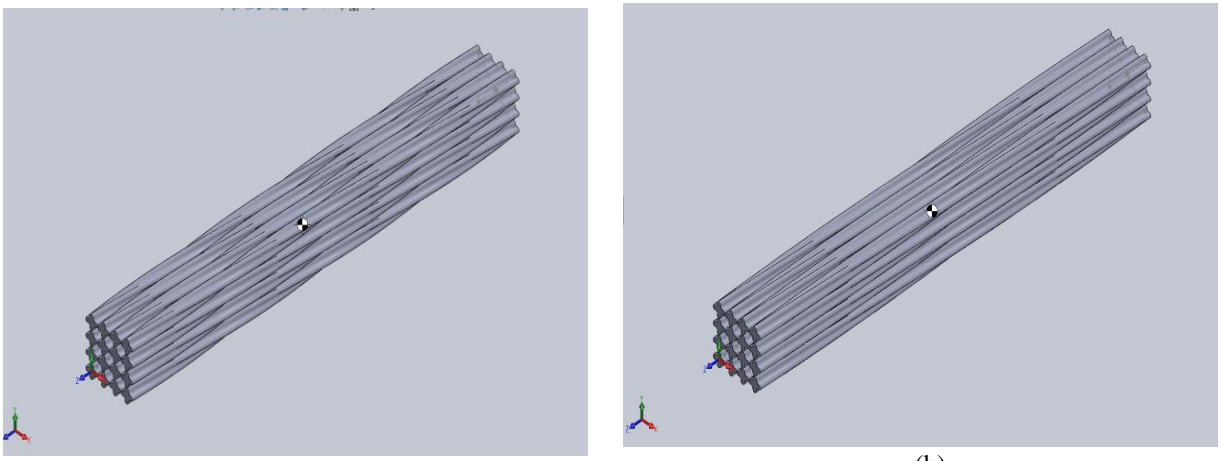


FIGURE 1. The 4×4 helical fuel rod bundle model [6]



(a) (b)

FIGURE 2. Geometry model with 180 °(a) twist and 360 °(b) twist with 500mm pitch

TABLE 1. Geometric Parameter and boundary condition

Parameters	Symbol	Value
Radius of the outer rounded corner	R_1	2.274 mm
Radius of the inner rounded corner	R_2	2.109 mm
Length of transition	h	0.702 mm
Diameter of circumcircle	D	14.718 mm
Spiral twist pitch	P_t	500 mm
Assembly array size	/	4 × 4
Rod center pitch	P_c	15.2 mm
Side length of square flow channel	L	61.5 mm
Height of rod	H	500 mm
Hydraulic diameter	D_h	8.1 mm
Boundary condition of the walls	/	Adiabatic and no-slip

FLOW PARAMETERS AND PHYSICAL PROPERTIES

Water and Al_2O_3-based nanofluid are selected as working fluids with an inlet temperature of 20°C. Two different, 1% and 4% volume concentrations of Al_2O_3-based nanofluids were selected for the simulation. A constant heat flux of 192000 W/m^2 is imposed on the fluid surface touching the helical fuel rods, while the rods and boundary walls are considered as adiabatic walls with no slip. The properties of the nanofluid are obtained [10] and inserted as the fluid property.

MESH GENERATION

The mesh is generated using Ansys mesh tool. Desired Y+ value of 30 is taken for the simulations and estimated wall distance for the inflation first layer thickness is calculated using this Y+ value. Less than 0.01% of elements are below the orthogonal quality of 0.1 and maximum skewness is 0.99. For meshing inflation, body sizing, face meshing is adopted.

Turbulence model

A series of turbulence models offered by Fluent, including the standard k-e model, Realizable k-e, standard k-x model, SST k-omega model, Transition SST, and Reynolds stress model (RSM), is investigated to model the Reynolds stresses in the Reynolds averaged Navier-Stokes equations in the Development of flow sweeping mixing model for helical fuel rod bundles[6]. As the SST k-ω the model gives the best prediction [6], the simulations are done with the SST k-ω model. The calculation is in steady state, and the numerical scheme is COUPLED. For the spatial discretization, the pressure is second order, the momentum, Turbulent Kinetic Energy, and turbulent dissipation rate are second-order upwind. Energy residual levels of 10^{-6} and other residual levels of 0.001 are taken as the convergence criteria.

TABLE 2. Configurations for simulation

No of configuration	Fluid	Helical Fuel Rod Twist angle (°)
1.	Water	180
2.	Water	360
3.	Water + 1% Al_2O_3	180
4.	Water + 1% Al_2O_3	360
5.	Water + 4% Al_2O_3	180
6.	Water + 4% Al_2O_3	360

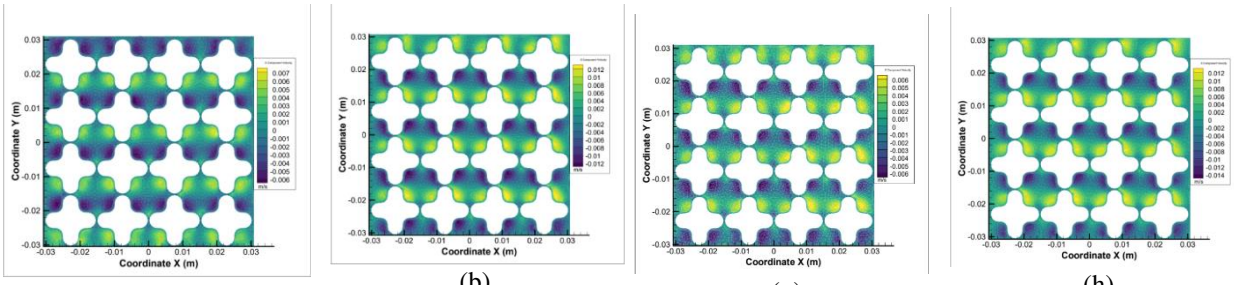
RESULTS AND DISCUSSIONS

3D Computational Fluid Dynamics (CFD) simulations have been carried out for the configuration presented in table-4 in order to compare various configurations and determine the optimal condition. The simulations were performed with twist pitches of 180 °s and 360 °s, using both water and Al_2O_3 nanofluid, while considering void intensities of 1% and 4%.

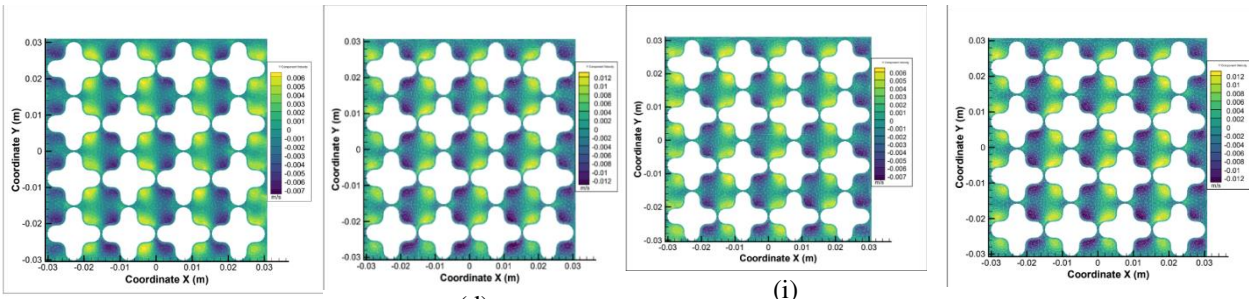
VELOCITY CONTOUR

Velocity components in x, y, z direction at the outlet is compared in the figures. The contour plots in figures 3 and 4 depict the velocity distribution along x, y, z axis (U, V, W) of the simulated model at the outlet of helical fuel rod bundles for 180° and 360° twist angles. The U and W velocity components show alternating high and low-velocity regions, with the 360° twist exhibiting more intense variations, indicating enhanced mixing. The V velocity displays more uniform distribution in the 180° twist and more pronounced variations in the 360° twist, suggesting better flow distribution. Overall, the 360° twist enhances turbulence and mixing efficiency compared to the 180° twist, improving heat transfer and flow distribution. The contour plots illustrate in figures 4 shows the velocity profiles at the outlet of a helical fuel rod with 4% concentration of Al_2O_3 nanoparticles, comparing 180° and 360° twist angles. For both twist angles, the v_x (U) and v_y (V) plots display velocity distributions ranging from negative to positive values, indicating lateral and vertical fluid movement, respectively. The v_z (W) component, with a range from 0.05 to 0.45 m/s, represents the primary axial flow direction. The 360° twist angle generates more complex flow patterns, potentially enhancing mixing and heat transfer compared to the 180° twist angle.

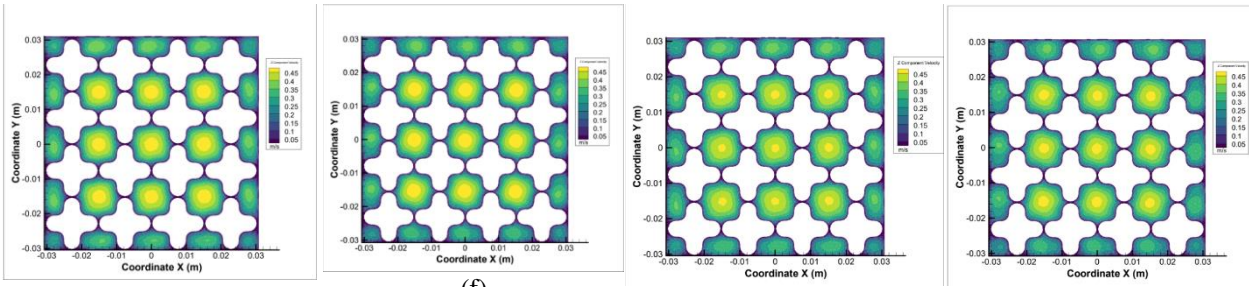
FOR WATER *For Al_2O_3 (4%)*



(a) (b) (g) (h)



(c) (d) (i) (j)

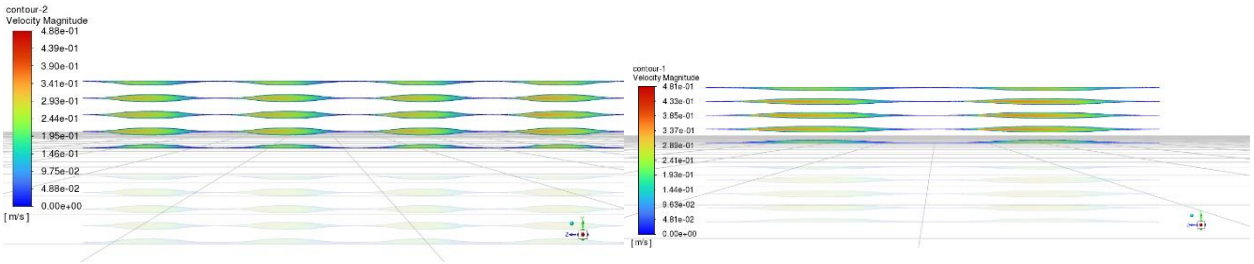


(e) (f) (k) (l)

FIGURE 3. velocity u, v, w respectively for water at (a) (c) (e) 180 ° & (b) (d) (f) 360º twist

FIGURE 4. velocity u, v, w respectively for Al_2O_3 (4%) at (g) (i) (k) 180 ° & (h) (j) (l) 360º twist

FLOW FIELD ANALYSIS



(a) (b)

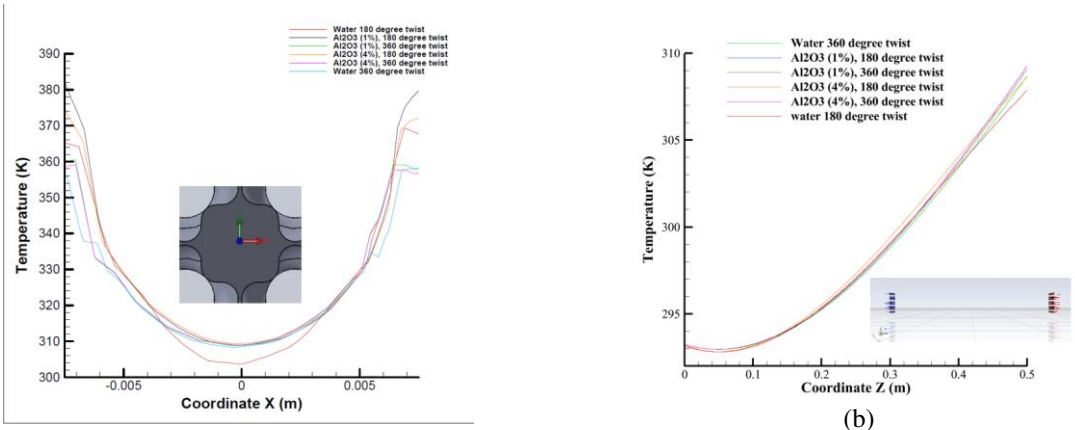
FIGURE 5. (a) velocity distribution at interior gap along length for water for 360 ° twist pitch and (b) velocity distribution at interior gap along length for water for 180 ° twist pitch

Figure 5 depict contour plots of velocity distribution at the interior gap for water with 360° and 180° twist pitches, respectively. The color contours represent velocity magnitudes ranging from 0 to 0.488 m/s. In Fig. 5, for the 360° twist pitch, the velocity distribution shows alternating high and low-velocity regions, indicating enhanced mixing and turbulence along the channel length. In Fig. 6, for the 180° twist pitch, the velocity distribution is more uniform with less pronounced high-velocity regions, suggesting a different flow pattern with reduced mixing intensity compared to the 360° twist. These plots highlight the significant impact of twist pitch on the flow characteristics within the channel.

A higher twist angle (360° compared to 180°) results in more pronounced secondary flows and turbulence. This turbulence increases the fluid velocity near the rod surfaces, improving the convective heat transfer. The improved mixing ensures that the coolant is evenly distributed, reducing temperature gradients and enhancing thermal efficiency.

THERMAL VARIATIONS

Fuel rod with 180 & 360° twist is used and subchannel flow is analyzed for water and Al_2O_3 nanofluid with 4% void intensity.



(a) (b)

FIGURE 7. (a)Temperature variation at outlet along midline at the middle channel and (b) Temperature rise along the length

The temperature plot along the x-axis of helical fuel rod bundles shows better heat transfer for 360° twists compared to 180°, with 4% Al_2O_3 nanofluids achieving the highest outlet temperatures (300 K to 390 K). Along the longitudinal axis, 360° twists and 4% Al_2O_3 raise outlet temperatures more than lower concentrations and pure water, indicating superior thermal performance.

Helical rods create secondary flows that break the thermal boundary layer, enhancing heat transfer and fluid mixing. Reynolds number fluctuations arise from twist angles, nanofluid concentrations, and flow instabilities, with higher nanoparticle concentrations (4%) and 360° twists significantly affecting flow characteristics.

MATHEMATICAL MODEL AND NECESSARY GOVERNING EQUATION

The validity of the continuum approach is ensured. The utilization of classical momentum, continuity, and energy equations for turbulent flow is permissible. The underlying necessary assumptions consist of the following: 1) The flow is three-dimensional, steady-state, incompressible, and turbulent, involving a Newtonian fluid. 2) The impact of body forces, such as gravity and others, is deemed insignificant. 3) Viscous dissipation is taken into consideration. The Governing equation for the flow regime and heat transfer are the Navier equations for turbulent flow which are-

Continuity equation:

$$\frac{\{\bar{\partial}\{u\}\}}{\{\partial x\}} + \frac{\{\bar{\partial}\{v\}\}}{\{\partial y\}} + \frac{\{\bar{\partial}\{w\}\}}{\{\partial z\}} = 0 \tag{1}$$

Energy Equation:

$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \left(\frac{1}{Re_{t*}\,Pr_t}\right) * \left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right)$$
$$+ \left(\frac{1}{Re_t}\right) * \left[\frac{\partial}{\partial x}\left(u\tau_{xx} + v\tau_{xy} + w\tau_{xz}\right) + \frac{\partial}{\partial y}\left(u\tau_{xy} + v\tau_{yy} + w\tau_{yz}\right) + \frac{\partial}{\partial z}\left(u\tau_{xz} + v\tau_{yz} + w\tau_{zz}\right)\right] \tag{2}$$

The determination of pressure drop relies on the utilization of the friction factor. The formula for the friction factor[6] is expressed as,

$$f_e = 1.055 * 0.11 * \left(\frac{\Delta(absolute\ roughness)}{De} + \frac{68}{Re_e}\right)^{0.25} \tag{3}$$

Equivalent Diameter, denoted as,

$$D_e = 1.1D_h = 1.11\left(\frac{4A_f}{P_w}\right) \quad (4)$$

The outlay on pumping constitutes a substantial portion of the overall operating expenditure. The intricacies of subchannel pressure drop are closely intertwined with coolant flow dynamics and enthalpy distribution. The pressure drop is defined as

$$\Delta P_{fric} = f_e * \left(\frac{L}{2D_e}\right) * \rho * v^2 \quad (5)$$

In this context, ΔP_{fric} is the frictional pressure drop, f e is the friction coefficient, Re is the Reynolds Number, Q is heat transfer to coolant, Pr is the Prandtl Number, D is equivalent diameter, Dh is hydraulic diameter, h is the heat transfer coefficient, and Nu is the Nusselt Number, which measures heat transfer relative to conduction.

CONCLUSION

The study shows that helical fuel rod assemblies significantly enhance heat transfer compared to traditional designs due to improved fluid mixing and disruption of the thermal boundary layer. A 360° twist angle is identified as optimal for maximum heat transfer, outperforming the 180° configuration. Incorporating Al_2O_3 nanofluids further boosts thermal performance, with a 4% concentration offering the best balance between heat conductivity and viscosity. While these enhancements improve efficiency, they also increase pressure drop, requiring careful system design. Overall, the research highlights the potential for helical rods and nanofluids to improve reactor performance and safety in nuclear energy systems.

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