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Preliminary Analysis of Spacer Grids for Enhanced Thermal Hydraulic Performance inside Nuclear Fuel Assembly

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1. Introduction

The thermal-hydraulic design of nuclear reactors plays a critical role in ensuring both the safe operation and economic benefits of nuclear power plants and achieving sufficient thermal margin is of paramount importance.

In the arrangement of nuclear fuel rods within an assembly, a spacer grid is employed to maintain their positioning. Notably, certain reactor models like the OPR 1000 and APR 1400 incorporate intermediate spacer grids equipped with mixing vanes. These vanes serve to enhance heat transfer through the creation of vortexes. By inducing swirl flow and cross flow, these mixing vanes facilitate convective heat transfer. However, this design choice can also lead to a consequential pressure drop [1].

In a contrasting approach, the NuScale, a small modular reactor that has successfully undergone a U.S. NRC design certification review, adopts a distinctive channel-type grid as its intermediate spacer grid. This grid design ingeniously integrates fuel rod support and coolant flow mixing within a single component. The structural configuration of the flow channels in this grid is angled at the outlets, resulting in a beneficial crossflow pattern. Moreover, the hole arrangement in the channel-type grid contributes to maintaining a low-pressure drop [2].

Computational fluid dynamics (CFD) simulations are being extensively employed to identify intricate flow distribution phenomena such as swirling flows and flow separation around spacer grids [3-5].

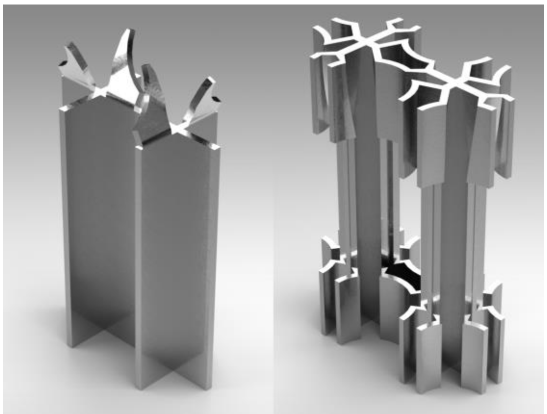

Fig. 1. Isometric view of the mixing vane type spacer grid(left) and the channel type spacer grid(right).

The present study aims to conduct a comparative CFD analysis to explore the internal flow distribution within subchannels. Specifically, the investigation encompasses spacer grids of two distinct types: mixing vane-type spacer grids and channel-type spacer grids, as illustrated in Fig. 1. This analysis also includes an assessment of outlet temperature and the associated pressure drop for each respective design.

2. Methods of CFD Analysis

The design of the mixing vane followed a conventional approach, while the support structure, apart from the vane, was simplified. The design of the channel-type grid was based on the dimensions outlined in the work of Camila et al [6]. Both spacer grids shared a height of 40 mm, except for the vane section. The entrance length measured 45 mm, and the overall height of the computational grid spanned 580 mm. This extended height was chosen to identify the flow distribution immediately prior to entering the subsequent spacer grid.

The mesh generation process was executed using the commercial CFD software, ANSYS-Fluent. About 7 million elements of mesh were used for both cases. For wall boundaries, prism layers were employed with the initial cell height set at $y^+=100$ for both cases. Since similar levels of mesh number and quality were applied in both cases, the mesh sensitivity test was omitted.

A reduction in the computational domain was achieved by narrowing the computational domain to 1×2 subchannels. This was enabled through the implementation of periodic boundary conditions, a strategy corresponding to the spatial arrangement of spacer grids (as depicted in Fig. 2). All other boundary conditions are enumerated in Table I. The k-epsilon turbulent model with a standard wall function, was selected, in that it was validated in many studies [3,7].

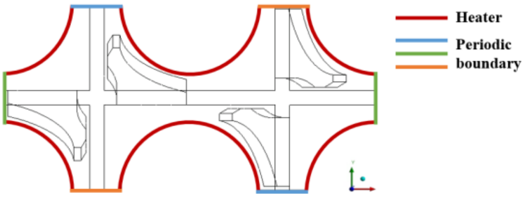

Fig. 2. Computational domain of 1x2 subchannels with mixing vane type spacer and boundary conditions.

Table I: Boundary Conditions

Location	Boundary Type	Boundary Condition	Value
Inlet	Velocity Inlet	Velocity	4.7 m/s
		Temperature	563.75 K
Outlet	Pressure Outlet	Gauge Pressure	15.5 MPa
Heater	Wall	Heat flux	600.43 kW/m^2

3. Results and Discussion

To scrutinize the varying flow characteristics influenced by the type of spacer grid employed, the axial streamlines of the coolant within the subchannels containing two types of spacer grids were shown in Fig. 3.

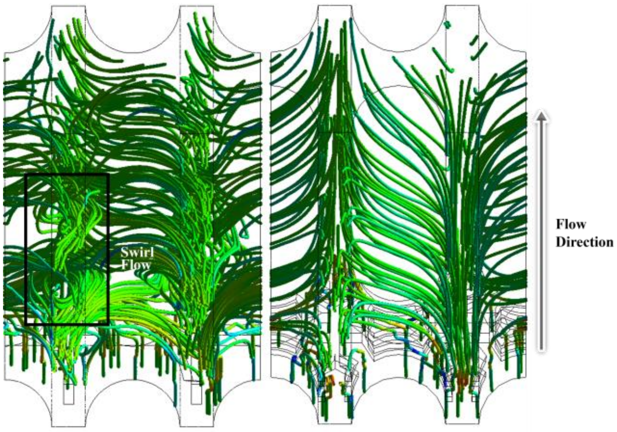

Fig. 3. The axial streamlines of the coolant in the subchannels with vane-type spacer grid (left) and channel-type spacer grid (right).

Both grid configurations cause mixing effects, attributed to the angle of the vanes and the distribution of the channels. In the case of the vane-type grid, apparent swirl flow pattern becomes apparent immediately after the coolant traverses the spacer grid. This modified flow distribution for both grid types endures until it reaches the subsequent spacer grid, in that the height of the computational domain was selected more conservatively than the interval of the actual spacer grid. At the streamline and velocity vector field (at the plane located 1 mm after each spacer grid) of Fig. 4, the coolant for both grid types engages in effective heat and mass exchange via crossflow between adjacent subchannels. This phenomenon mitigates the likelihood of localized hot channel occurrences.

In both types of spacer grids, the coolant interacts with adjacent subchannels via effective turbulent mixing, but in different ways. The top view of the type streamline in Fig. 4 reveals the counterflow within the subchannels, whereas the channel type demonstrates parallel flow behavior, showing part of the axial streamline (in Fig. 3) winds around one rod, while others turned toward the adjacent subchannels. In the vector field in Fig. 4, the crossflow to adjacent subchannels appears to be more vigorous in the vane type, also in Fig. 5, the area average turbulent kinetic energy of the vane type was larger. In contrast, it seemed that a local hot spot could occur in the temperature field.

The pressure drop and the volume-averaged turbulent kinetic energy of the whole computational domain, and outlet coolant temperatures were presented in Table II for two distinct grids. The mixing vane-type spacer grid demonstrates favorable performance with its combination of low-pressure drop and heightened heat transfer rate. However, it is essential to acknowledge that the design of the two grids under analysis entailed certain omissions of components, limiting the quantitative comparability of the results obtained. Notably, due to the rapid reduction of the flow passage area, a notable increase in flow resistance arises, resulting in elevated pressure drops and significantly augmented velocities.

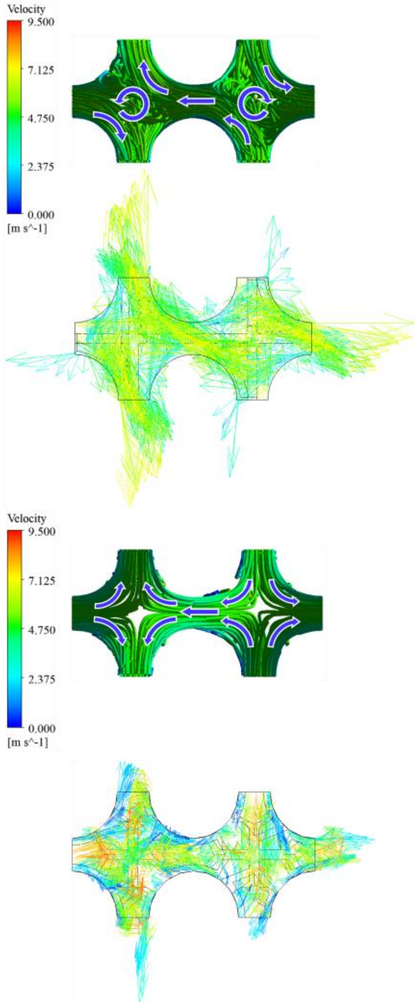

Fig. 4. Top view of streamlines and velocity vector of the coolant in the subchannels with vane-type spacer grid (top) and channel-type spacer grid (bottom).

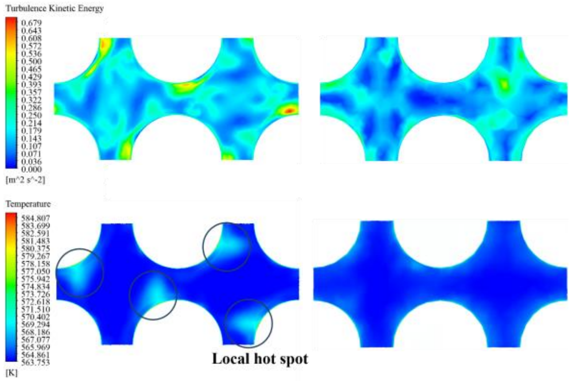

Fig. 5. The turbulence kinetic energy and temperature of the coolant in the subchannels with vane-type spacer grid (left) and channel-type spacer grid (right) at the plane 1mm after each spacer grid.

Table II: Summary of the CFD Analysis Results

Type of Spacer Grid	Pressure Drop	Average Turbulent Kinetic Energy	Average Outlet Temperature
Mixing Vane	24.626 kPa	0.052 J/kg	569.673 K
Channel	27.636 kPa	0.024 J/kg	569.732 K

Specifically, for the channel-type grid, opting for a larger thickness leads to a substantial reduction in the subchannel area imposed by the grid structure. Consequently, a significant challenge arises in achieving the low-pressure drop characteristic of the channel-type grid design. Furthermore, the thermal performance exhibited by the channel-type grid lags that of the vane-type grid. The obtained results underscore the importance of striking a delicate balance between the dimensions of the grid, flow dynamics, and thermal performance. This analysis, while shedding light on certain limitations, serves as a stepping stone for refining future grid designs to achieve optimal outcomes in both pressure drop and thermal efficiency.

To quantitatively compare and analyze the thermal-hydraulic performance of the two types of grids, a study for optimization of each design in the identical method is planned to be performed. After optimizing each design, the thermal performance of each spacer grid will be comparatively analyzed in various boundary conditions.

4. Conclusion

In conclusion, this comparative computational fluid dynamics (CFD) analysis investigated the flow distribution and thermal-hydraulic characteristics of two distinct nuclear reactor spacer grids: mixing vane-type and channel-type grids. The study revealed that the mixing vane-type grid promotes efficient heat transfer through active swirl flow and crossflow, effectively reducing the likelihood of local hot channels. The channel-type grid exhibited higher pressure drops, and its thermal performance was comparatively less favorable. These findings underscore the need for a nuanced balance between grid dimensions, flow dynamics, and thermal efficiency. Further optimization of each design will be conducted to enhance both pressure-drop management and thermal performance.

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