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CFD analysis of the impact of a novel spacer grid with longitudinal vortex generators on the sub-channel flow and heat transfer of a rod bundle

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A B S T R A C T

In this study, a novel spacer grid with rectangular wing longitudinal vortex generators (RLVGs) is designed to improve the thermal–hydraulic characteristics of fuel assembly and simplify the spacer grid structures. The impacts of the attack angle (30°, 45°and 60°) and the distribution (two patterns) of RLVGs on the thermal–hydraulic characteristics in the sub-channels of a rod bundle are numerically investigated. Numerical results show that the secondary flow generated by the RLVGs can spread to the downstream region of spacer grid, disturb the boundary layer of the rods and improve the heat transfer of coolant. For the novel design of pattern 1, the spacer grid with RLVGs in attack angle of 45° generates secondary flow around the fuel rods just like a circulating flow in higher velocity, resulting better heat transfer performance and uniform cooling of fuel rods. Based on these results, a novel design of pattern 2 with doubled RLVGs number of pattern 1 is introduced and numerically investigated too. With the same attack angle of 45°, pattern 2 increases the average transverse velocity of the secondary flow and decreases the rod wall temperature in comparison with those of pattern 1 at the same Reynolds number conditions. Maximum increase in Nusselt number in the sub-channels is up to 30% while the increase in the total pressure drop is about 7.6% comparing with those of pattern 1. The present results indicate that the novel design of pattern 2 is an efficient way on improving the heat transfer of the fuel rod bundle, deserving more work to optimize its geometry structure and distribution before practical application.

1. Introduction

The safety and economy characteristics of a nuclear power plant are greatly influenced by the thermal-hydraulic characteristics of fuel assemblies. As one of the essential components in fuel assemblies, the spacer grid is designed to support the fuel rods mechanically, reduce the flow-induced vibration, as well as generate secondary-flow in sub-channels and improve the thermal-hydraulic performance of the rods fuel assembly.

Spacer grid with different mixing vanes is often used in fuel rod assemblies to create a specific coolant mixing behavior by increasing the turbulence level and guiding the transverse flow to further downstream of the grid in the fuel rod sub-channels. Specifically designed vanes on the spacer grid have great effects on the turbulence level and the secondary flow pattern in the sub-channels of fuel rod bundle. Fig. 1 shows a typical spacer grid used in the fuel rod assembly of pressurized water reactors (PWR) (Su et al., 2013). So far, considerable work has focused on the performance of fuel assemblies with mixing grids. Holloway et al. (2008) experimentally investigated the performance of the convective heat transfer in rod bundles with three different type of spacer grids (split-vane pair support grids, disc support grids, and standard support grids). It was found that the local heat transfer was enhanced by the support grids. For the support grids with split-vane pair, heat transfer enhancement was also found further downstream of the spacer grid at a distance of as much as 10 times the hydraulic diameter of sub-channel. To understand the turbulent flow characteristics in the sub-channel of fuel rod bundle with split type and swirl type mixing vanes, respectively, Chang et al. (2008) observed the velocity distribution in the sub-channel using a two-component Laser Doppler Anemometry (LDA). The results showed that the mixing vanes (split type and swirl type) increased the turbulent intensities of the flow at the center of sub-channels. The turbulent intensities decayed quickly in the downstream of spacer grid for both types of mixing vane. The flow mixing between the neighboring sub-channels was stronger than the mixing within a sub-channel for the case with a split type spacer grid. While for the case with swirl type spacer grid, the opposite had occurred. At just behind the spacer grid, split type vanes generated stronger turbulent intensity than swirl type vanes did. Han et al. (2009)

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Nomenclature

C_d	Resistance factor
D_e	Hydraulic diameter of sub-channel, m
Nu	Nusselt number
p	Static pressure, Pa
v	Transverse velocity, ms^{-1}
T	Bulk temperature of coolant, K
T_w	Wall temperature of rods, K

Greek symbols

α	Attack angle of RLVG, °

Abbreviations

LVG	Longitudinal vortex generator
RLVG	Rectangular wing longitudinal vortex generator

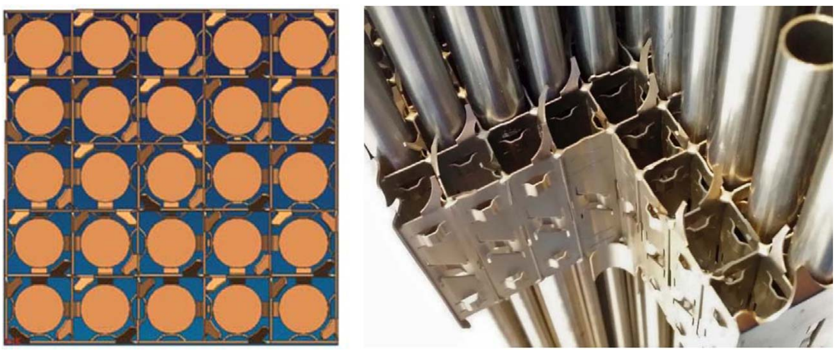

Fig. 1. Typical structures of the spacer grid used in the rods fuel assembly.

designed a new type of vane (Tandem Arrangement Vane, TAV) and experimentally studied the flow features in the cross sections of a 6 × 6 rod bundle with that design. The results showed that the swirling flow generated by the designed vane could be maintained in the downstream of spacer grid up to 20 times the hydraulic diameter of sub-channel.

As we know, the geometric structure of the spacer grid with different mixing vanes is relatively complicated, twisted and with many narrow gaps. The detailed flow characteristics in these narrow gaps is hard to be detected by experiment. However, Computational Fluid Dynamics (CFD) method is greatly helpful to get the flow details in this kind of complex structure. The effect of the spacer grid with different mixing vanes on the sub-channel flow and heat transfer of a fuel rod bundle is being increasingly investigated with the rapid development of CFD technologies. Nematollahi and Nazifi (2008) carried out a CFD analysis to examine the flow characteristics in the sub-channels, the overall heat transfers and pressure drops of a fuel assembly with different mixing vanes on the spacer grid. In the simulation, a standard k-ε model was used. An increase of 9.82% in the total heat transfer of the case with split vanes on the spacer grid was found and deemed reasonable, however, the pumping cost increases with considering the manufacturing possibility. The critical heat flux (CHF) phenomenon in a 2 × 3 rod bundle with different mixing vanes (split, swirl and hybrid types) was tested at KAIST R-134a Loop and numerically analyzed by CFX in Shin and Chang's work (Shin and Chang, 2009). It was found that mixing vanes could bring about an increase in CHF, especially under the conditions with higher mass flux and lower pressure. This is because the secondary flow generated by the mixing vane on the spacer grid flattened the void fraction distribution and decreased the maximum value of void fraction. Under the conditions with lower pressure and smaller mass flux, the swirl vane had the highest performance. Under PWR operating conditions, the hybrid vane had the best performance. Tóth and Aszódi (2010) investigated the flow field numerically in the sub-channels of fuel assemblies used in VVER-440, a pressurized water reactor designed by Russian, to examine the applicability of turbulence models (k-ε, SST k-ω, BSL and SSG Reynolds stress models) in modeling the sub-channels. A triangular configuration was adopted to arrange the fuel rods in VVER-440. It should be noted that no spacer grid was enclosed in the selected geometrical model. Obviously this is not the situation of the rod bundle's sub-channels in practical reactors. It was concluded that the BSL model could capture the turbulence flow characteristics rather well in the sub-channels by comparing the numerical results with experimental data. Conner et al. (2010) developed a CFD methodology using the STAR-CD code to predict the flow characteristics and heat transfer in PWR fuel assemblies behind the spacer grids with mixing vanes. The computational domain included one span length of a 5 × 5 fuel rod bundle, spacer grid with springs and mixing vanes. The renormalization group (RNG) k-ω model was used with y^+ value of 40–100. The numerical results and the methodology were validated by small-scale experiment data obtained under low Reynolds number and low temperature conditions. Gandhir and Hassan (2011) numerically investigated the effect of the structural spacer grid with concept mixing vanes on the flow characteristics of the downstream of the spacer grid in a 5 × 5 fuel rod bundle. In this steady and isothermal simulation, turbulence models of realizable k-ε and SST k-ω, and an open source code were used. The results showed that SST k-ω predicted pressure drop more accurate than realizable k-ε did. Liu et al. (2012) utilized CFD to examine the turbulence models and wall treatment, mesh refinement and boundary conditions in modeling the fluid dynamics and heat transfer in sub-channels of a rod bundle with split vanes on the supporting grid. It was suggested that the near-wall treatment method and mesh were of great importance in determining the turbulent models best suited to simulate the flow feature in rod bundle sub-channels. In their flow conditions, the SST k-ω turbulence model with standard wall function could predict the Nusselt number near the walls with higher accuracy. However, the realizable k-ε turbulence model was considered to be able to predict the surface heat transfer very well by integrating the enhanced wall treatment method. Jayanti and Rajesh (2013) numerically investigated the characteristics of vapor single phase flow and heat transfer through the rods bundle channels (with spacer grid but without mixing vane) by CFX code. Eulerian–Lagrangian approach was used to solve the gas-droplet two-phase flow. The droplets deposition and film formation on the spacer