This paper evaluates three-dimensional turbulent flow and convective heat transfer through mixing split vane in a single-phase and steady-state sub-channel of AP1000 nuclear reactor core by using general computational fluid dynamics code, Fluent6.3.26. Realizable K-ε model is used as a turbulent closure model, and the sub-channel is analyzed by numerical simulation. The results show that the mixing split vanes, which affect strongly the heat transfer in the sub-channel, are lateral flow, swirl and turbulent intensity between the sub-channels, and give reasonable agreements with experimental equations and AP1000 thermal hydraulic design.
mixing split vane in a single-phase and steady-state sub-channel of AP1000 nuclear reactor core by using general computational fluid dynamics code, Fluent6.3.26. The results show that the mixing split vanes, which affect strongly the heat transfer in the sub-channel, are lateral flow, swirl and turbulent intensity between the sub-channels. The performances of two different turbulent configurations are evaluated by comparing the results with experimental relations and AP1000 thermal hydraulic design.

2. An AP1000 Fuel Assembly Description

An AP1000 fuel assembly consists of 264 fuel rods in a 17x17 square array. The center position in the fuel assembly has a guide thimble that is reserved for in-core instrumentation. The remaining 24 positions in the fuel assembly have guide thimbles. The guide thimbles are joined to the top and bottom nozzles of the fuel assembly and provide the supporting structure for the fuel grids. The fuel grids consist of an egg-crate arrangement of inter-locked straps that maintain lateral spacing between the rods. The grid straps have spring fingers and dimples that grip and support the fuel rods. The intermediate mixing vane grids also have coolant mixing vanes. In addition, there are four intermediate flow mixing (IFM) grids. The IFM grid straps contain support dimples and coolant mixing vanes only. The top and bottom grids do not contain mixing vanes. The AP1000 fuel assembly design includes: low pressure drop intermediate grids, four intermediate flow mixing (IFM) grids, a reconstitutable integral clamp top nozzle (ICTN), and extended burnup capability. The bottom nozzle is a debris filter bottom nozzle (DFBN) that minimizes the potential for fuel damage due to debris in the reactor coolant. The AP1000 fuel assembly design also includes a protective grid for enhanced debris resistance. The 17x17 XL Robust fuel assemblies are the same as the 17x17 XL Robust fuel assemblies except that they have four intermediate flow mixing grids in the top mixing vane grid spans[3]. Figure 1 shows the AP1000 fuel assembly outline. Figure 2 shows a reduced sketch of the AP1000 mixing split vane. The representative area of the AP1000 sub-channel is shown in Figure 3. Figure 4 shows a reduced outline of the AP1000 IFM geometrical model. The AP1000 representative thermal and hydraulic design parameters are listed in Table 1.
THERMAL AND HYDRAULIC DESIGN PARAMETERS

<table>
<thead>
<tr>
<th>parameters</th>
<th>units</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor core heat output</td>
<td>MWt</td>
<td>3400</td>
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<tr>
<td>System pressure, nominal</td>
<td>MPa</td>
<td>15.5133</td>
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<tr>
<td>Effective flow area for heat transfer</td>
<td>m²</td>
<td>3.8555</td>
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<td>Average velocity along fuel rods</td>
<td>m/s</td>
<td>4.846</td>
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<td>Coolant temperature, nominal inlet</td>
<td>°C</td>
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<tr>
<td>Coolant temperature, average rise in core</td>
<td>°C</td>
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<tr>
<td>Heat flux hot channel factor (F_Q)</td>
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<tr>
<td>Active heat transfer surface area</td>
<td>m²</td>
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<tr>
<td>Average area power</td>
<td>Kw/m²</td>
<td>644.5</td>
</tr>
</tbody>
</table>

3.CFD Analysis

3.1. Numerical simulation in the AP1000 sub-channel

The model of part length of the AP1000 sub-channel, including the very complex grid spacers and mixing split vane area, has been created using the preprocessing capabilities of the code Gambit 2.2.30. The software allows generating a high quality, predominantly hexahedral, unstructured grid, and Figure 5 shows a representative detail of the mesh in region of the spacer surrounding the AP1000 sub-channel. Mesh dependency of the solution is tested first. From the results, 2,166,793 is selected as optimum number of mesh volumes, and cell size is 0.5mm.

Heat transfer and flow domain including a spacer grid and IFM in a single sub-channel is selected as target analysis. Height of spacer grid is 38.1mm, height of IFM12.06mm, and upstream distance of IFM is 440mm, downstream distance of IFM 260mm. With fuel rod diameter of 9.5 mm and pitch of 12.6 mm, hydraulic diameter (D_h) of the sub-channel is 11.79mm.

Uniform flow at inlet and constant pressure at exit are specified. Adiabatic condition is used at the surfaces of mixing split vane and spacer grid. Heat flux boundary condition is applied the surface of four fuel rods, and the thermal power density is described by a formula[4]:

$$ q_{Fuel}(r,z) = q_{Fuel,max} J_0 (2.4048 \frac{r}{R}) \cos \left( \frac{\pi z}{H} \right) $$  \hspace{1cm} (1)

Where $ q_{Fuel}(r,z) $ indicates the local thermal power production per unit volume in the reactor core, and $ q_{Fuel,max} $ is the maximum thermal power production per unit volume in the reactor core; $ R $ shows the outer radius and $ H $ is the height of the core; $ J_0 $ indicates the Zero-Order Bessel Function of the First Kind. Periodic condition is used at inter-channel boundaries, and the periodic boundary conditions are defined as...
a translationally periodic zone and a periodic shadow. For flow in the sub-channel, Reynolds number is 519,314, and Prandtl number is 0.973.

Selections of turbulent models in CFD have great importance in accurate predictions and capturing the details of the flow parameters. With general CFD code Fluent6.3.26, three-dimensional heat transfer computational domain is analyzed by using Reynolds-averaged Navier-Stokes equations (RANS). Realizable standard k-ε model is employed as a turbulent closure by comparable analysis.

Figure 6 shows the velocity vectors on axial cross section, x=0, for mixing split vane. Figure 7 describes the velocity vectors on six different cross sections, $z/D_h=-20,-10,-5,5,10$ and 20, through mixing split vane in the sub-channel: lower $z/D_h=-20,-10$ and -5(from left); upper $z/D_h=5,10$ and 20(from left) . Through mixing split vane, swirling zones of elliptic shape are well observed, but cross flow between sub-channels almost disappears downstream. Figure 8 reflects y velocity on the interface of the sub-channel with mixing split vanes (upper) and no mixing split vanes (lower), respectively. The cross flow decays rapidly downstream as well as the swirl. The results show that the mixing split vanes, which affect strongly the heat transfer in the sub-channel, are lateral flow, swirl and turbulent intensity between the sub-channels, and give reasonable agreements with experimental equations and AP1000 thermal hydraulic design.

3.2. Friction factor and temperature analysis

Most correlations for the friction and heat transfer coefficients in turbulent flow are based on
experimental studies because of the difficulty in dealing with turbulent flow theoretically. For smooth tubes, the friction factor in turbulent flow can be determined from the explicit first Petukhov equation\(^5\) given as

\[
f = (0.790 \ln \text{Re} - 1.64)^{-2} \quad 10^4 \text{Re} < 10^6 \quad (2)
\]

Haaland combined the smooth wall and fully rough relations into an explicit formula\(^6\):

\[
\frac{1}{f^{1/2}} \approx -1.8 \log \left[ \frac{6.9}{\text{Re}_d} + \left( \frac{\varepsilon}{d} \right)^{1.11} \right]
\]

Where \(\varepsilon/d\) indicates relative roughness. The error can be reduced considerably to less than 10 percent by using more complex but accurate relations such as the second Petukhov equation\(^5\) (the Nusselt number relation in turbulent flow) expressed as

\[
\text{Nu} = \frac{(f/8) \text{RePr}}{1.07 + 12.7(f/8)^{0.5}\left(\text{Pr}^{2/3} - 1\right)}\quad 0.5 \leq \text{Pr} \leq 2000, \quad 10^4 \text{Re} < 5 \times 10^6 \quad (4)
\]

For smooth tubes, the friction factor is 0.013, and Nusselt number is 776.553. Averaged area-weighted wall temperature is determined as 636.07k by the Nusselt number. For rough tubes, the friction factor is given as 0.028, and Nusselt number is given as 1607.212. Area-weighted average wall temperature is defined as 610.49k as 636.07k by numerical simulation, respectively. Mass-weighted average static pressure head losses are given as 40214 Pa and 35010 Pa in the sub-channel with mixing split vanes and no mixing split vanes, respectively. This error gives reasonable agreement with engineering application.

4. Conclusion

According to numerical simulation results, temperature, velocity and pressure magnitude show that on single-phase and steady-state condition, there is a good relation between realizable standard k-\(\varepsilon\) model, analytical data and AP1000 design data. Predicting axial distribution of local heat transfer becomes important as the thermal-hydraulic design method becomes sophisticated: the current DNB-based design will be technique enlarges applicability of computational fluid dynamics not only for predicting parameters to control the flow but also for explaining mechanisms to model the flow.

Reference