Development of Mitsubishi High Thermal Performance Grid*

(CFD Applicability for Thermal Hydraulic Design)

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Mitsubishi has developed a new zircalloy grid spacer for PWR fuel with higher thermal performance. Computational Fluid Dynamics (CFD) evaluation method has been applied for designing of the new lower pressure loss and higher Departure from Nucleate Boiling (DNB) benefit grid spacer. Reduction of pressure loss of grid structures has been examined by CFD. Also, CFD has been developed as a design tool to predict the coolant mixing ability of vane structures, which is to compare the relative peak spot temperatures around fuel rods at the same heat flux condition. Prototype grids were manufactured and several tests, which were pressure loss measurements, cross-flow measurements and freon DNB tests, were conducted to verify CFD predictions. It is concluded that the applicability of the CFD evaluation method for the thermal hydraulic design of the grid is confirmed.

Key Words: Computational Fluid Dynamics, Nuclear Reactor, Fuel, Critical Heat Flux, Laser Doppler Velocimeter

1. Introduction

PWR grid spacer has mixing structures (vanes) to promote the coolant mixing around fuel rods. It is supposed that the larger mixing vane creates the higher coolant mixing, which is expected to increase the DNB benefit of fuel. On the other hand, higher pressure loss with the larger mixing vane would be injurious to the DNB margin due to decreasing of coolant flow, especially at the mixed fuel core. So, it is necessary to develop the new grid spacer, which has equal or less pressure loss and higher DNB performance. It is important that the compatibility of pressure loss and DNB in designing the high thermal hydraulic performance grid. In this aspect, a design tool, which is able to predict pressure loss and DNB performance of the grid, is necessary.

Mitsubishi has developed the CFD analytical

method around fuel rods, mainly cross-flow evaluation at downstream of a grid⁽¹⁾⁻⁽⁴⁾. Mitsubishi applied the CFD evaluation method for designing of the new high thermal performance grid. Pressure loss coefficient of a grid is evaluated by the optimum modeling of fluid around rods and a grid. Also, DNB benefit is judged by comparing the peak spot temperatures around fuel rods in each grid structure at the same heat flux condition. That is to estimate the coolant mixing ability due to the difference of mixing vane structure. The prototype grids were manufactured and the pressure loss, cross-flow measurements and freon DNB tests were conducted to verify the CFD predictions.

The parametric studies of new designs have been performed by CFD evaluation method. The grid, which was optimized in the aspect both of low-pressure loss and high-DNB performance, was selected for the final design. The DNB test is the test to measure the critical heat flux of a grid spacer in pressurized water condition. The DNB test was conducted at the Columbia University Heat Transfer Research Facility to confirm the DNB benefit of the final design grid^{(5),(6)}. The pressure loss measurement

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Fig. 1 Transversal modeling region

was also conducted in the test loop of Nuclear Development Corporation⁽⁶⁾.

2. CFD Modeling

5×5 partial grid of 17×17-type fuel is normally manufactured to develop a new grid spacer and pressure loss and DNB tests are conducted to confirm the fundamental properties of it. So, 5×5 partial grid spacer with a rod bundle of the DNB test is modeled for CFD analysis. As Reynolds number of the analyses is above $5E+4$, CFD calculations carried out by Star-CD employed K-epsilon turbulence model for the good correspondence to the hydraulic flow tests. Pressure loss of a grid and fluid temperature distribution of fuel rods are evaluated at the same calculation. In analyses, only single-phase flow, not two-phase flow, is considered.

The lateral distribution of heater rod power of a rod bundle is simulated as the DNB test configuration, that is peripheral rods are 15% lower than interior rods. The relative power ratio of each rod and mixing vane arrangement of a grid is shown in Fig. 1. The axial modeling region, which includes a rod bundle consists of 25 rods and one grid spacer, is shown in Fig. 2. The axial length of model is only one span with a grid spacer for the limit of available calculation time and machine memory. For this aspect, a cyclic boundary of inlet and outlet at which the flow repeats is employed. It is possible to solve the flow field simulated multi-span configuration. The axial CFD model near a grid and a transversal grid model from the top view are shown in Fig. 3. Grid structures, which are strap, spring, dimple, mixing vane and welding nugget, are modeled in detail. The total number of fluid elements is around 2,000,000. The relative DNB benefit is evaluated by comparing the peak spot temperature of fluid around rods at 400 mm downstream of each grid, where is likely to occur

Fig. 2 Axial modeling region

Fig. 3 CFD modeling

DNB phenomena.

3. Verification of CFD predictions

The prototype grid p1-3 was manufactured to confirm the CFD prediction and the pressure loss measurement was conducted. The pressure loss

Fig. 4 Pressure loss coefficient of P1-3 grid

Fig. 5 Schematic of the rod LDV

coefficient of the measurement and the CFD calculation of P1-3 are shown in Fig. 4. The CFD prediction is about 5% higher than the measurement, but the test grid has a little shallow angle of mixing vanes than the design angle, so that the difference of CFD and measurement is diminished. Also, several comparison of pressure loss measurements and CFD for various grids were performed. The measured data and CFD predictions are in good agreement within 5%.

Cross-flows due to mixing vanes, were measured by a rod type Laser Doppler Velocimetry (the rod LDV). The schematic of the rod LDV is shown in Fig. 5. The rod LDV has a LDV mechanism inside a cladding, and the laser beams from the window on the cladding are focused at flow field and the flow velocity is measured to receive the burst signal when a seed particle passes through the focused volume. The focused volume size is $0.06 \text{ mm} \times 0.06 \text{ mm} \times 0.44 \text{ mm}$.

Fig. 6 Cross-flow measured position at rod gaps

Fig. 7 Measure cross-flow at A1 by the rod LDV

So, It is possible to measure several points between the narrow rod-rod gaps. Also, cross-flow and axial-flow can be measurable by 90 degrees rotating the beam direction. As the rod LDV has the same diameter of a fuel rod, it could be inserted into any grid cell instead of a fuel rod. The rod LDV has a merit to measure any rod gap position, where is impossible by using a conventional LDV from outside of the test section. The cross-flows of 4 rod-rod gaps around the center rod at downstream from 30 mm to 410 mm of the current zircalloy grid (Z2) were measured. In Fig. 6, the transversal measured 3 points of each gap are shown. The distributions of measured cross-flow velocity at position A1 are shown in Fig. 7. The average and standard deviation of cross-flow at 30 mm are relatively larger than that at 100 mm, which can be explained by the distance from the mixing

Fig. 8 Cross-flow vector at 30 mm downstream of Z2

Fig. 9 Rod gap cross-flow of Z2

vanes. It is considered that the cross-flow is stronger and flow field is unsettled near the mixing vanes. More than 2 000 points of data are obtained in each measurement and the distribution shape of data is close to the normal distribution.

The CFD analysis has been carried out at the same condition of the cross-flow measurement. The calculated cross-flow vector at 30 mm downstream from the Z2 grid is shown in Fig. 8. Unsymmetrical flows are observed at the symmetrical gap positions concerning mixing vane arrangement as shown in Fig. 3. It is interpreted that flow distribution occurs at upstream of mixing vanes due to the unsymmetrical spring and dimple arrangement in the 5×5 partial grid. As measured cross-flow velocities are different at symmetrical gap A and C, B and D, the CFD can predict the structural effect for the flow field. The comparison of the measured and calculated cross-flow at A2 position is shown in Fig. 9. It is observed that the cross-flow decreases as going to downstream from the grid. The averaged cross-flows of measured three points are a little more or less than the CFD predictions at each axial position. The CFD results are enough within 1 sigma of standard deviation of the measurement, so that the CFD predictions are considerably in good agreement with the measured data.

Vane arrangement type-1

Vane arrangement type-2

Fig. 10 3×3 rod bundle Freon DNB test analysis

Though the DNB phenomenon is two-phase flow behavior, the CFD analysis can treat only single-phase flow. But it is possible to judge the coolant mixing ability of the grid to compare the peak fluid temperature at the rod surface, because the enthalpy from fuel rods mainly distributes by cross-flow due to mixing vanes and grid structures. To select for the DNB test grid in Columbia University, it was assumed that the coolant mixing ability is directly corresponding to the DNB performance of the grid. It means that the grid that has the lower peak fluid temperature is expected better DNB performance.

There are some proofs that the CFD predictions of the relative DNB power and position are in good agreement for the freon DNB tests, which are in the condition of two-phase flow of freon⁽⁶⁾. Calculated fluid temperature distributions of 3×3 rods bundle freon DNB tests, which are for Z2 grids with different mixing vane arrangement, are shown in Fig. 10. Both of them have 8 fuel rods and 1 thimble tube, and the type-1 grid has 12 mixing vanes and the type-2 grid has 18 mixing vanes. The power ratio of freon DNB test for type-1 and type-2 is shown in Fig. 11. The averaged ratio of (type-2/type-1) is 1.09, which means type-2 has better DNB property than type-1. The peak spot temperature predicted by CFD is also lower in type-2 than type-1. This result corresponds to the assumption that the lower peak fluid temperature grid has better DNB property. It is hard to

Fig. 11 DNB power ratio of type-2/type-1

Fig. 12 Comparison of hot spots in CFD and first DNB position/frequency in Freon DNB test (type-2)

predict the quantitative DNB power improvement from the difference of peak spot temperature, but it is considerably possible to judge the qualitative DNB performance from the comparison of the peak spot temperatures of grids. The comparison of the CFD hot spots and the first DNB position and frequency of the type-2 test is shown in Fig. 12. It is observed a good correlation between the CFD prediction and the test. It may be possible to predict the first DNB position in the DNB test in Columbia University. Further investigations will be performed.

It is confirmed that the CFD analytical method is available as a design tool for the thermal hydraulic design of a grid spacer.

4. Parametric Surveys of New Designs

Parametric studies of thermal hydraulic performance of grid structures have been performed. Analytical parameters were structures of mixing vane, spring and dimple, strap thickness and welding nugget size. Especially, mixing vane is important for thermal hydraulic design. It is supposed that the larger mixing vane creates the higher coolant mixing, which is expected to increase the DNB benefit of fuel. On the other hand, higher pressure loss with the larger mixing vane would be injurious to the DNB margin due to decreasing of coolant flow, especially at the mixed fuel core. So, it is necessary to develop the new grid spacer, which has equal or less pressure loss and higher DNB performance. In this concept, crossover

Fig. 13 Schematic of crossover vane

Fig. 14 Fluid temperature distribution at 400 mm of P6M by CFD

vane was designed. Conventional design of mixing vane is leaned toward a fuel rod paralleling to grid strap. Cross-flow hits directly the rod surface, then it would lose its momentum. The crossover vane is designed to create cross-flow to the direction, which is closer to tangent line of rod surface. The cross-flow created by the crossover vane would not hit directly a rod surface, then it would not lose its momentum compared with conventional vane. As a result, the crossover vane is expected to have higher DNB performance with keeping relatively lower pressure loss. The schematic of the crossover vane is shown in Fig. 13.

The calculated fluid temperature distribution at 400 mm downstream of P6M Grid is shown in Fig. 14. There are several designs of crossover vane, P6M grid has crossover vane type M. It is observed that high temperature fluid exist around rod surface. Though fluid temperatures around the interior nine rods are relatively higher, they are distributed around rods because of the influence of coolant mixing by vanes. In this case, the peak fluid temperature exists at indicated position in Fig. 14. The peak spot temperatures and the pressure losses were obtained by the analyses in each design. The calculated relative

Fig. 15 Relative pressure loss and peak spot temperature by CFD

pressure losses and peak spot temperatures of five designs included the current zircalloy grid (Z2) are shown in Fig. 15. Each value is normalized by Z2. Every new design has lower pressure loss and lower peak spot temperature than Z2. P5K is expected to have the lowest pressure loss, but the peak temperature is highest among new designs. On the other hand, P6M is estimated to have the best coolant mixing ability, that is the lowest peak spot temperature, but the reduction of pressure loss is judged not to be sufficient. In the aspect of the compatibility of pressure loss and DNB performance, P8R grid, which has type N crossover vane, is selected as a final design for the pressure loss test and the DNB test. The pressure loss measurement and the critical heat flux measurement of P8R grid were conducted. The measured pressure loss of P8R grid is about 4% lower than Z2 grid⁽⁶⁾. The measured DNB performance of P8R in the DNB test is 12% higher than Z2⁽⁶⁾. The CFD evaluation method is confirmed to adopt for a thermal hydraulic design of a grid spacer.

5. Conclusions

Mitsubishi applied the CFD evaluation method for

designing of the high thermal performance grid. The pressure losses of several grids are predicted by the CFD. Also, the relative coolant mixing abilities are compared by the peak spot temperature, which is assumed to represent the DNB performance. CFD predictions were verified by several tests, which were pressure loss measurements, cross-flow measurements and freon DNB tests. The parametric surveys of pressure loss and coolant mixing ability of new designs have been performed. As a result, P8R grid, which has crossover vane, is selected for the final design in the aspect of the compatibility of pressure loss and DNB performance. The newly designed P8R test grid was manufactured, and the pressure loss measurement and the DNB test have been conducted. The results of improvement of pressure loss and DNB performance compared to the current zircalloy grid were obtained. Therefore, the applicability of the CFD evaluation method for the thermal hydraulic design of a grid spacer is confirmed.

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