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Investigation of PWR Fuel Rod Vibration Induced by Cross-Flow

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ABSTRACT

A number of studies have been made on the influence of cross-flow on rod vibration of PWR (Pressurized water reactor) fuel rods, but it has not been clarified. In this study, rod vibration and cross-flow are measured to investigate this influence. The results of vibration measurements indicate that the cross-flow induced by the mixing structures of a grid spacer (grid) makes rod vibration greater. Moreover, the combination of mixing structures influences the rod vibration. The results of cross-flow measurements are consistent with the results of rod vibration. An analytical approach is conducted which confirms the measurement results. It is concluded that the mixing structures induce cross-flow and the cross-flow makes PWR rod vibration greater.

1. Objective

In the design of PWR (pressurized water reactor) fuel grids, flow mixing performance is very important from thermal and hydraulic points of view. MHI(Mitsubishi Heavy Industries,Ltd) has developed a number of methods that utilize CFD (Computational Fluid Dynamics) and hydraulic experiments for evaluating this performance(1),(2),(3). Rod vibration, however, is also a significant factor in the design of a grid and can be influenced by cross-flow generated by the grid. Therefore, both mixing performance and rod vibration must be evaluated to optimize the grid design. In this study, the effect of cross-flow on rod vibration is investigated through an experimental and analytical approach.

2. Rod Vibration and Cross-Flow Measurement

A PWR grid has several mixing structures such as mixing vanes, guide vanes and guide tabs. The mixing structures induce cross-flow which is thought to influence fuel rod vibration. In this study, a series of hydraulic tests were conducted to analyze the influence of cross-flow on rod vibration.

Two cases of hydraulic tests were conducted in a hydraulic loop. Different test assemblies were prepared for the each cases to clarify the influence of the cross-flow. The test assemblies for a case had normal grids with the mixing structures and those for the other case had special grids without any mixing structures. All the test assemblies were about 2 meters long and had a 5x5 rod array bundle and six grids. The hydraulic test loop was able to hold two assemblies at the same time. A schematic figure of the hydraulic tests is shown in Fig 1. The test section in the loop had a clear window which allowed flow velocity to be measured by Laser Doppler Velocimetry (LDV). Accelerometers were installed in some of the rods to measure rod vibration.

The test cases and the specifications of the test assemblies are summarized in Table 1. Case 1 focuses on the rod vibration with the normal grids. .Case 2 focuses on the rod vibration with the special grids without any mixing structures.

Table 1. Summary of Specification of the test Assemblies

	No. of Assemblies	No. of Grids	Kind of Grids
Case 1	2	6	Normal Grid
Case 2	2	6	Non-Mixing Structures

2.1. Experimental Technique and Experimental Condition

2.1.1. Rod Vibration Measurement

Specially prepared accelerometers were installed in the rods to measure the rod vibration. The accelerometer-installed rods (Acc-rods) were placed in the certain positions in the test assemblies as shown in Fig 2. All the accelerometers were set in the Span 3 as illustrated in Fig. 1. The length of this span is the same as the length of an actual PWR fuel assembly.

The rod vibration was measured by varying the average velocity at the rod bundle from 5.0 to 8.0 m/sec. The temperature of the water in the loop was kept constant at around 30 °C. These conditions are listed in Table 2. All the data from the Acc-rods were converted to rod vibration amplitude data.

2.1.2. Cross-Flow Velocity Measurement

Measuring cross-flow velocity provides information on the cross-flow field. This information helps us understand the relationship between rod vibration amplitude and cross-flow around the rod.

The LDV system was adopted to measure the cross-flow velocity. Two different LDV systems were used. One was a normal LDV system for measuring the velocity through the window of the test section. The data obtained is useful for understanding velocity distribution. The measuring points are shown in Fig. 3. The other LDV system is a LDV probe in the rod (rod LDV). The rod LDV was developed by the NDC (Nuclear Development Corporation) and enables measurements to be taken of the velocity behind and beside the rod where the normal LDV system is ineffective. The rod LDV set up in the position shown in Fig. 3 was used to measure the velocity of the cross-flow surrounding it.

These velocity measurement were conducted at a rod bundle velocity of 5.0 m/sec. The water temperature in the loop had been kept around 30 °C.

Table 2. Test Condition

Measurement	Tools	Average Flow Velocity	Temperature
Rod Vibration	Acc Rod	5.0-8.5 (m/s) by every 0.5 (m/s)	30 (°C)
Cross-Flow	LDV	5.0 (m/s)	
	rod LDV	5.0 (m/s)	

2.2.Results of Measurements

2.2.1. Rod Vibration Measurement

The rod vibration amplitude of Acc-rod No.3 is shown in Fig. 4 as an example. The amplitude was normalized by that of Case 1 at the velocity of 5.0 m/sec. In this figure, the amplitude of both cases increases as the velocity increases. The amplitude is almost proportional to the square of the velocity. The normalized amplitude of Case 1 is remarkably greater than that of Case 2. This result indicates that the mixing structures of the grid causes the greater rod vibration.

The difference in amplitude between both cases indicates the influence of mixing structures, while the difference in amplitude between each rod shows the influence of the local cross-flow induced by the neighboring mixing structures of each rod. The difference in amplitude of both cases are compared for each rod and shown in Fig. 5 to analyze the effect of cross-flow difference. All these difference in amplitude are normalized by the difference in amplitude at Acc-rod No.3, where the vibration was greatest. Fig.5 shows that the difference in amplitude is largest at Acc-rod No.3. At this rod position the bending direction of the closest guide vane in the other grid in the other assembly is consistent with the that of mixing vanes as illustrated in Fig. 6. It is inferred that the greatest cross-flow would be generated by these mixing structures at this rod position. On the other hand, the difference in amplitude of Acc-rod No.1 is smaller than that of No.3. In the case of No.1, the bending direction of the closest guide are perpendicular to that of the mixing vanes and it is inferred that the cross-flow around Acc-rod No.1 would be lower than that around No.3. It is thought that the rod vibration is highly influenced by a combination of cross-flow and mixing structures. The cross-flow measurements shown below confirm this conclusion.

2.2.2. Cross-Flow Velocity Measurement

2.2.2-1. Velocity Measured by the normal LDV system

Cross-flow was measured at a lot of points as shown in Fig. 3. The measured velocity of Case 1 is illustrated in Fig. 7. Relatively higher velocity was measured where the guide vanes were located. It was thought that guide vanes would induce a straight and strong cross-flow to the bending direction of the vanes. However, the direction of the flow in the assembly doesn't seem to be consistent with the direction of the mixing vanes. It is thought that the mixing vanes create a swirl in the downstream region of the vanes, complicating the cross-flow distribution.

The velocity was also measured in Case 2 (without any mixing structures). The velocity level of Case 2 was very low and is considered to be negligible when compared with the velocity of Case 1. This result is consistent with the result of the rod vibration measurement and it is thought that the difference in the rod vibration between Case 1 and Case 2 is due to the cross-flow. It is concluded that the mixing structures induce a higher cross-flow and this cross-flow makes rod vibration greater.

2.2.2-2 Velocity Measured by the rod LDV system

The rod LDV system was used to measure the tangential velocity of Acc-rod No.3. An axial profile of the velocity is shown in Fig. 8. The velocity in region C is higher and lasts longer than the velocity in the other regions, which can be explained by the combination of the mixing vane in the grid and the guide vane in the other grid. The above comparison of the rod vibration also shows that the vibration amplitude of Acc-rod No.3 is greater than the others. It is thought that the combination of the mixing vane and the guide vane induces a strong local cross-flow and this makes rod vibration greater.

3. Discussion

The above velocity measurement does not complete all the information about the cross-flow, so an analytical approach was taken to provide further information.

CFD was used in this analysis, a k-ε model was adopted as a turbulence model, and a control volume method is used as a solution method.

3.1. Analysis Model

An analysis model was constructed by focusing on a part of Case 1 test where the above measurement was conducted. The schematic view of this model are shown in Fig. 9. The model covers the mixing structures precisely, and has about 310,000 fluid elements. The inlet velocity of this analysis was 5.0 m/sec and water temperature was set at 30 °C. The conditions are almost the same as those in Case 1.

3.2. Analysis Result and Consideration

Calculated cross-flow velocity is shown in Fig. 10. This velocity was obtained 40 mm downstream from the top of the grid. The mixing vanes induced a flow across the rod gap (or channel) and the swirl motion in the downstream area from the mixing vanes. The guide vanes generated a strong flow passing through the rod gap. The cross-flow velocity was the highest where the bending direction of the mixing vane was consistent with that of the guide vane such as illustrated in Fig.6. This position is corresponding to region C (rod LDV measuring point). The calculated velocity of region C is compared with that of region A as shown in Fig. 11. The velocity in the analysis was higher in region C than in region A. This result is qualitatively consistent with the measured result. It was concluded that the pattern of mixing structures significantly influences the cross-flow intensity.

The CFD result is verified qualitatively by the measured result. This mean that the CFD can provide information on the local cross-flow distribution qualitatively and this information might make it possible to predict the rod position where the vibration would be highest. For this purpose, the CFD should be developed further and verified by experimental results. Rod-LDV results would be very valuable for verifying the CFD. This kind of experimental and analytical approach seems to be valuable for developing a method to estimate the effect of mixing structures on rod vibration qualitatively and for utilizing the method in designing grids.

4. Conclusion

Rod vibration and cross-flow were measured for two kinds of test assemblies, one with and one without mixing structures. The results of these measurements and CFD calculation led to the following conclusions.

- Mixing structures induce cross-flow and the cross-flow makes the rod vibration greater.
- The combination of a mixing vane and a guide vane induces greater cross-flow and this cross-flow makes the rod vibration greater.
- The experimental and the analytical approach as described in this paper is useful to develop an estimation method of rod vibration and it would be possible to utilize the method for a grid designing.

5. Future Work

It is thought that turbulent intensity influences rod vibration. The analysis method is planed to develop further and the analysis will provide information on the relationship between the turbulent intensity and rod vibration. The relationship will be the next subject of this study. The developed analytical method and the obtained relation will be utilized for a PWR grid designing.

Reference

(1) M.Imaizumi et al. "Development of CFD Method to Evaluate 3-D Flow Characteristics for PWR Fuel Assembly", SMIRT-13 in 1995

(2) K.Ikeda et al. "Cross Flow Study of PWR Mixed Core I –Measurement and CFD Prediction-", ICON-6 in 1998

(3) M.Hoshi et al. "Cross Flow Study of PWR Mixed Core II – Evaluation for Staggerd Mixing VaneGrid", ICON-6 in 1998

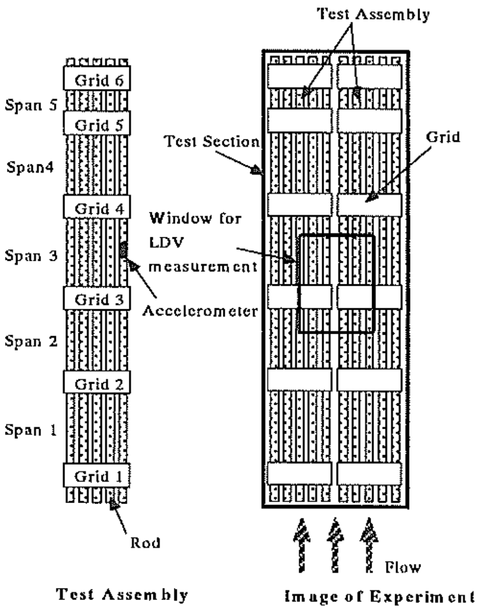

Figure 1. Schematic of the test assembly and the experiment

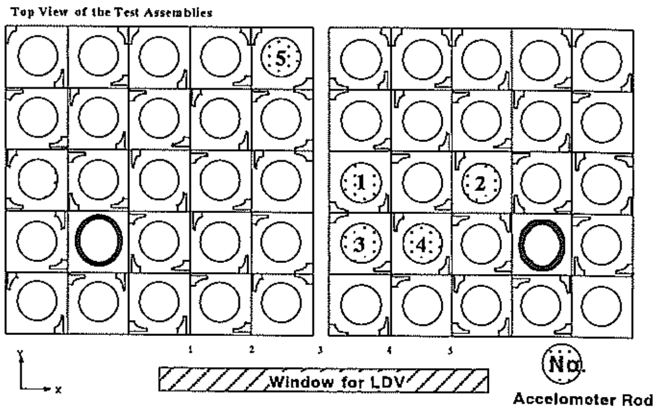

Figure 2. Cross-Section of Assembly and Accelerometer Rod Position

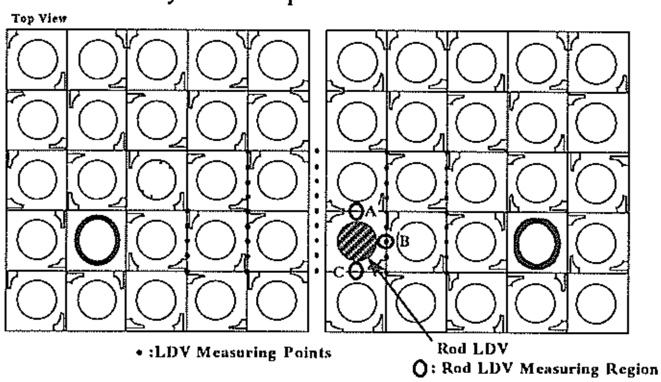

Figure 3. Cross-flow Measured Points and Rod LDV Position

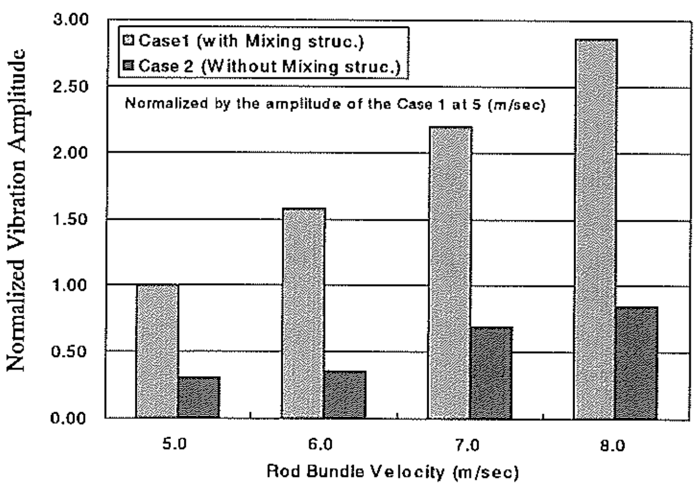

Figure 4. Normalized Rod Vibration Amplitude of Acc-rod No. 3

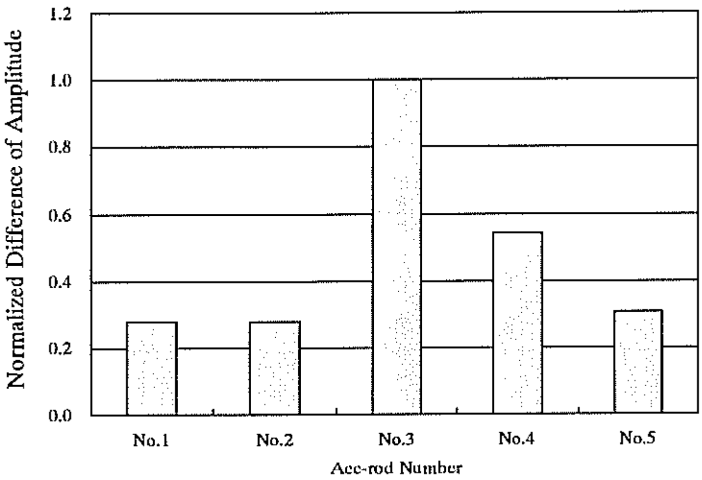

Figure 5. Comparison of Normalized Difference of Amplitude

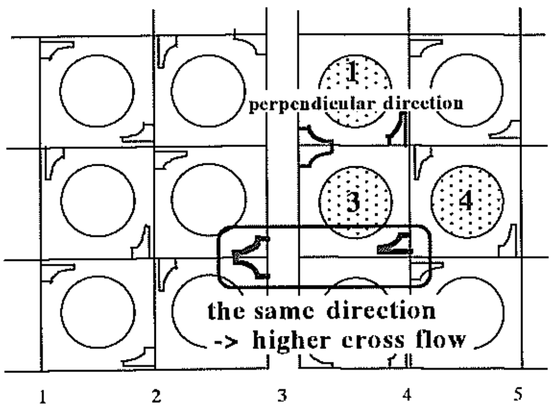

Figure 6. Direction of mixing vanes and guide vanes

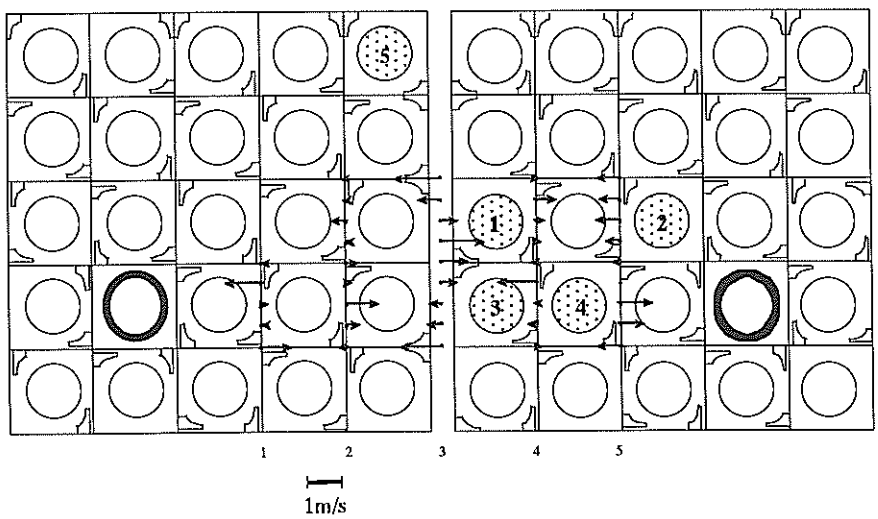

Figure 7. An Representative Result of Cross-flow Measurement

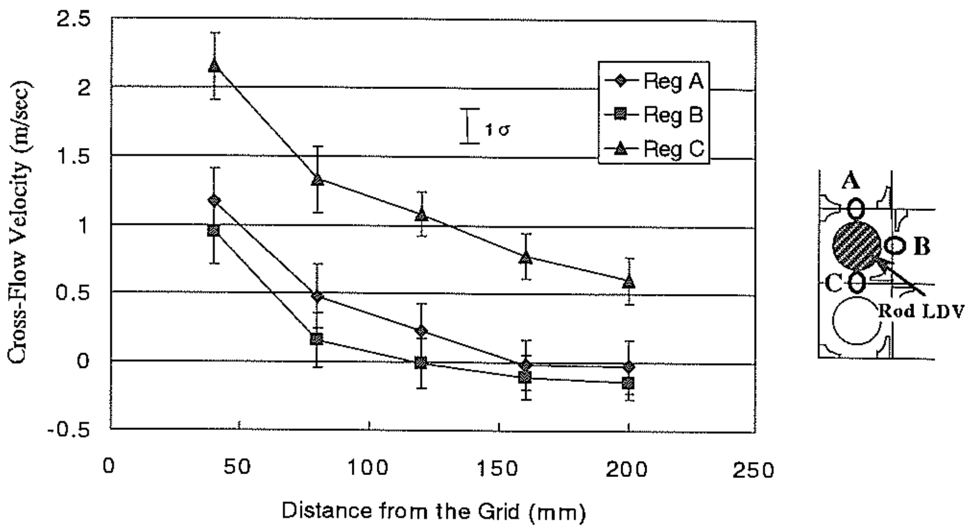

Figure 8. Cross-flow Profile measured by rod-LDV

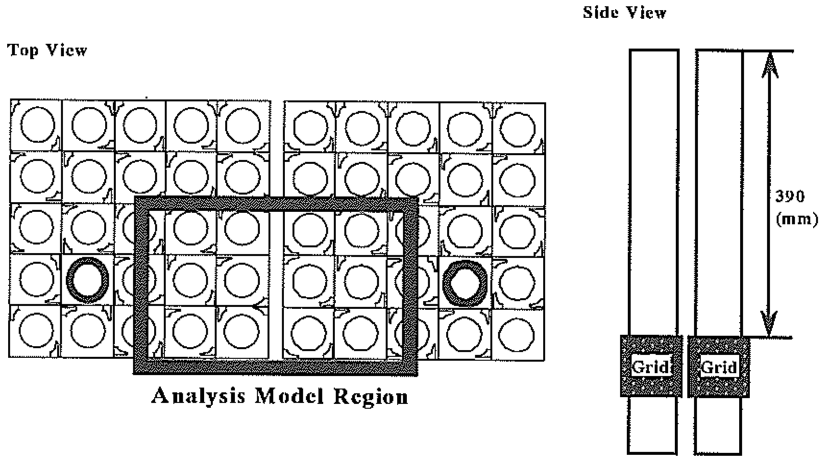

Figure 9. Schematic of the Analytical Model

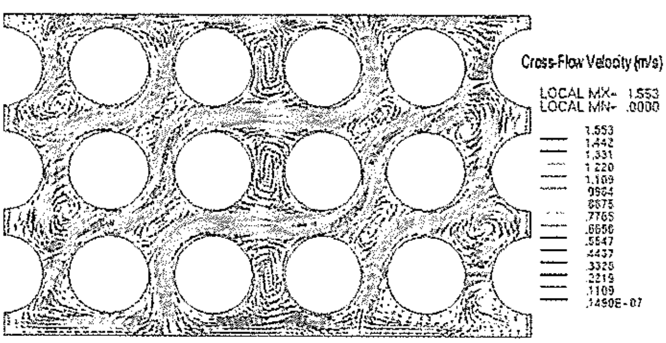

Figure 10. Cross-Flow Distribution Calculated by CFD

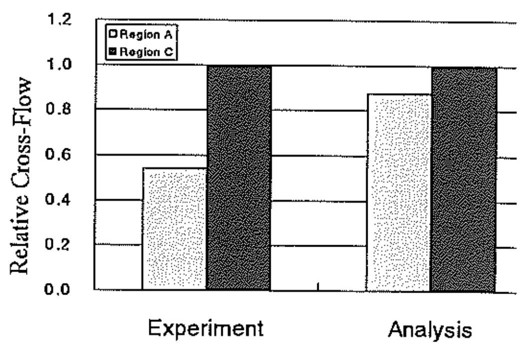

Figure 11. Comparison of Relative Cross-flow between Region A and C