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Experimental investigation on the flow-induced vibration in the control rod guide cylinder of pressurized-water reactor

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Abstract: An experiment was conducted to investigate flow-induced vibration (FIV) in the control rods of a pressurized water reactor. Control rods and a guide cylinder (full scale compared with the real structure) were installed on an FIV experiment platform, with which flow distributions were simulated according to actual situations. The vibration displacements of the control rods were observed in different flow rate ranges of transverse and vertical flows. Several FIV characteristics of the control rods under different transverse and vertical flows were determined by analyzing the experimental results. A formula was also proposed to predict vibration.

Key words: flow induced vibration; control rod; PWR; prediction; vertical flow; transverse flow

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1 Introduction

Various flow-induced vibration (FIV) accidents have occurred since the operation of the first pressurized-water reactor (PWR) in the 1960s. Serious accidents caused by the FIV problem have elicited much concern. Almost all reactors encounter the problem of FIV, which frequently arises from the control rods and control rod guide tubes inside a reactor pressure vessel. In PWR, control rod assemblies are used to control the neutronic activity of the core. Control rods must be dropped for 2 or 3 seconds in guide tubes, which are slightly larger than the rods in diameter. The coolant FIV and the wear deformation of the rod seriously affect the rod's drop time and the safety of the plant [1-4].

Extensive research has been conducted on FIV. Most researchers have studied the control rod FIV problem by performing either small-scale experiments or numerical analyses. The main contributors to this area are Pázsit (1988) [3], Pfizsit and Gaffs (1995), Kim and Shin. (2001), Lina, Moinereau et al. (2001), Wu et al. (2012) [4]. Many measurement limitations exist because the structure of control rod components is relatively complex [5, 6]. The mechanism of the FIV of control rods remains a problem.

In this work, an improved experiment was performed on an FIV experiment platform (Fig. 1) that employed full-scale control rods, guide cylinders, continuous guide tube sections, and guide plates. The full-scale structure is essentially similar to a real control rod assembly. The experiment was conducted to determine the influence of FIV on the control rod vibration characteristics under different transverse and

vertical flows. The experiment also aimed to generalize the formula between vibration displacement and flow rate [7-12]. The simplified upper plenum structure was used. This first-stage experiment provides a reference for further research on the FIV mechanism of control rods.

2 Experimental system

2.1 Test loop

The test loop consisted of an upper plenum test section, three centrifugal pumps, two inverters for the pumps, a large water tank, four orifice plate flowmeters, a water purification system, a drainage system, stainless steel pipes, and valves (Fig. 1).

The control rod components and the guide cylinder were installed inside the test section. The experiment was conducted at room temperature and atmospheric pressure. The water from the deionized processor was used as the coolant in the core. The flowmeters were installed before the inlets of the test section. The valves were used to control the flow in the pipes. Variable frequency pumps provided power for the coolant and regulated the flow rate range of different inlets. The maximum flow provided by each pump was 550 t h^{-1} . Therefore, the maximum flow condition was as follows: transverse flow could reach $1,100 \text{ t h}^{-1}$ and vertical flow could reach 550 t h^{-1} . The coolant flowed back into the water tank through the test section. Two flexible connections were installed at both sides of each pump to release the vibration from the pump to the fluid flow.

Place Fig.1 here

2.2 Test section

The test section of a rectangular flow channel was made of a stainless steel plate, on which eight transparent glass windows were installed. The experiment on the internal flow field could be observed through the glass windows, and the vibration characteristics could be measured with a laser displacement sensor. The test section consisted of three parts, namely, upper, lower, and buffer sections at the bottom (Fig. 2(a)). The entire test section was 4,790 mm high. The guide cylinder and rod components were installed inside the outer section. The entire test section was designed to be removed and installed conveniently when replacing the internal components. The guide cylinder section was 4,050 mm high and was divided into upper and lower guide cylinders.

Place Fig.2 here

Three inlets, one outlet, and one drain were set on the external test section. The upper and lower guide cylinders were installed together in a square cross section with a side length of 200 mm (Fig. 3(a)). The inside model of the test section was shown in Figure 2 (b). In the experiment, the inlet at the top was not used because the leakage flow from the top could be ignored. The other two inlets and the outlet were used. The internal flow field was composed of vertical flow and transverse flow which produced energy to induce vibrations in the control rod. The lower guide cylinder had eight rectangular holes, through which the vibration of the rod could be observed and

measured (Fig. 3(b)).

Place Fig.3 here

The cross sections of the external section and guide cylinder were square shaped and 400 and 200 mm wide, respectively. Inside the guide cylinder, three pieces of guide plates were installed top to bottom in the slender structure. A continuous guidance section with a vertical arrangement was fixed on the bottom guide tube. The control rod was composed of a star frame and four root control rods, and it was hung in the interior of the experimental section. The control rods were installed by bolt connection on the star shelf which was the same as the practical design of control rods. The diameter and length of each rod were 0.95 and 3,850 mm, respectively. The shape of the model was exactly the same with the practical design. One rod was inserted into the continuous guide tube, in which a small hole was created to be measured by the laser sensor. The control rods in the guide cylinder were impacted by the coolant from the eight lower holes and the vertical flow inlet at the bottom. In the experiment, the structure and the support of the model could meet the requirements of similarity. And after calculation, the Strouhal Number was approximately equal to 0.2. Therefore, the experimental model was reasonable in the flow induced vibration experiments.

2.3 Measuring system

In the experiment, measuring system consisted of orifice flowmeters, laser displacement sensor, data transmission system, signal acquisition, data

post-processing equipment and all kinds of cables. Laser displacement sensor was used to measure the FIV characteristics at the bottom of the control rod. Orifice flowmeters were used for real-time monitoring of fluid flow. The vibration signal measured was sent back to the post-processing equipment, then the data was processed. The bad data was eliminated and the good data was analyzed. In the experiments, the particle velocity measurement instrument was also used to observe the velocity of fluid. The software was used to analyze the signals, in which the time histories of the displacements were transformed into frequency spectrum by a FFT (fast fourier trans-form) [8, 9].

3 Experimental process and data

3.1 Numerical simulation

Before the experiment, we carried on the numerical simulation about various working conditions by CFD software. The simulation results showed that this model was sufficiently valid to support optional simulation. And when the values of vertical and transverse flows were 200 t h^{-1} , the flow field of the model were similar with the real situation in PWR. The calculation results of the inlet section and the export section were shown in Fig. 4 and Fig. 5, which were consistent with the real flow parameters in PWR [13-17].

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Place Fig.4 here

Place Fig.5 here

Under the same conditions with the real structure, the velocity distribution and static pressure distribution of the test section were shown in Fig. 6 and Fig. 7. We found that the fluid disturbance increased obviously near the eight rectangular holes, which would cause the severe vibration of the control rods.

Place Fig.6 here

Place Fig.7 here

Place Fig.8 here

The velocity field measured by PIV instrument was as shown in Fig. 8. The result was consistent with the numerical calculation and the error was within the acceptable range [18-22].

3. 2 Experimental process and data

In the experiment, we opened the pumps and frequency converter and increased the vertical flow rate from 0 t h^{-1} to 200 t h^{-1} . By adjusting the converter, we slowly changed the transverse flow rate from 200 t h^{-1} to 650 t h^{-1} by adjusting the converter while maintaining the value of the vertical flow. The transverse flow rate was added with 50 t h^{-1} each time. We measured the vibration displacement of the control rod and recorded the data after each flow rate value achieved stability. Small vibration displacements were measured with the laser displacement sensor. However, the vibration of the control rod could not be detected with the naked eye when the values of vertical and transverse flows were 200 t h^{-1} .

After measuring this set of data measurements, we continued to adjust the frequency converter and increased the vertical flow rate to 250 t h^{-1} . Then, we changed the transverse flow rate in the same range of 200 t h^{-1} to 650 t h^{-1} by adding 50 t h^{-1} each time. After each flow rate value achieved stability, we measured the displacements of the control rod and recorded the data. Using the same method, we increased the flow rate of the vertical flow to 500 t h^{-1} and recorded the displacement data. When the transverse flow value was increased to 300 t h^{-1} , even in the case without any vertical flow, we could observe the vibrations of the rod using our eyes only. The vibration displacements increased with the increase in the value of transverse flow, and the vibration phenomenon became serious. Fig. 9 shows the displacements at different vertical flow rates in the experiment. The maximum vibration displacement was 0.4971 mm . The displacement increased by 0.3649 mm compared with the first displacement value, which was 0.1322 mm . A significant

increase was observed when the transverse flow rate was in the range of 300 t h^{-1} to 500 t h^{-1} and the maximum displacement was 0.4802 mm , as shown in Fig. 9. The transverse flow in this range exerted an important influence on the FIV of the rod.

Place Fig.9 here

In the next phase, we operated the experiment about changing of vertical flow on the basis of specific transverse flow value. We wondered to observe the effect on flow induced vibration of control rod by the two flow directions.

We increased the transverse flow rate from 0 t h^{-1} to 200 t h^{-1} firstly. By adjusting the converter, we slowly changed the vertical flow rate from 200 t h^{-1} to 500 t h^{-1} by adjusting the converter while maintaining the value of the transverse flow. The vertical flow rate was added with 25 t h^{-1} each time. Using the same method with the former experiment, we measured the vibration displacement of the control rod and recorded the data. Small vibration displacements were measured with the laser displacement sensor. However, the vibration of the control rod could not be detected with the naked eye when the values of vertical and transverse flows were from 200 t h^{-1} to 275 t h^{-1} .

Then we continued to adjust the frequency converter and increased the transverse flow rate to 250 t h^{-1} . Then we changed the vertical flow rate in the same range of 200 t h^{-1} to 500 t h^{-1} , by adding with 25 t h^{-1} each time. After each flow rate value achieved stability, we measured the vibration displacement of the control rod and recorded the data. Using the same method, we increased the flow rate of the transverse flow to 650

t h^{-1} . Fig. 10 shows the displacements at different transverse flow rate in the experiment.

We observed that when the vertical flow rate was kept in a constant value, the change of vertical flow rate caused obvious vibrations. When the vertical flow value was increased to 300 t h^{-1} , the maximum difference of the displacement appeared. A significant increase was observed when the vertical flow rate was in the range of 200 t h^{-1} to 650 t h^{-1} and the maximum displacement was from 0.1522mm to 0.4538mm , as shown in Fig. 10. And the vibration phenomenon was more and more obvious. There was an obvious increase when the transverse flow rate changed. In the experiment, we observed that the change of transverse flow caused more obvious vibrations comparing with the change of vertical flow.

Place Fig.10 here

3. 3 Frequency spectrum

In the experiments, we found that the random vibration of the control rods was not regular. In the experiments, we chose eleven different conditions as follows: We changed the transverse flow rate from 200 t h^{-1} to 600 t h^{-1} by adjusting the converter while maintaining the value of the vertical flow was 300 t h^{-1} . The transverse flow rate was added with 100 t h^{-1} each time. The above conditions were marked as 6#1, 7#1, 8#1, 9# and 10#1. In the same way, we changed the transverse flow rate from 300 t h^{-1} to 500 t h^{-1} by adjusting the converter while maintaining the value of the vertical flow was 400 t h^{-1} . The conditions were marked as 11#1, 12#1 and 13#1.

Then we changed the vertical flow rate from 300 t h^{-1} to 500 t h^{-1} while maintaining the value of the transverse flow was 300 t h^{-1} . The vertical flow rate was added with 100 t h^{-1} each time. The new conditions were marked as 14#1, 15#1 and 16#1. The time histories of the displacements were transformed into frequency spectrum by the software. We obtained the following relationship between vibration force and frequency (Fig.11). Fig.11 showed that the vibration force in the low frequency was obvious. The influence of the vibration force in high frequency even could be ignored [18-20].

Place Fig.11 here

4 Relationship between the maximal displacement and flow rate

In the two experiments, we observed the main range of the vertical flow rate that caused excessive vibration of the control rod (Fig.9, Fig.10). We noticed that a change in transverse flow exerted an influence on the FIV of the control rod. Then, we sorted these data in the experiments and conducted nonlinear fitting to determine the relationship between the control rod's maximum vibration displacement and the flow rate in the experiments.

Fig. 12 showed the curved surface of maximum vibration displacements at different flow rates. We used the Levenberg–Marquardt algorithm and the general optimization algorithm [14~16] provided by the software 1stOp v1.5. The calculation parameters were selected as follows: the convergence indicator was $1.00\text{E-}10$, the maximum number of iterations was 1,000, and the instant-output-control value was

20[17-21]. After iterative calculations, we obtained the relation equation as Equation.1.

Place Fig.12 here

Equation 1 showed the relationship between the control rod's maximum vibration displacement and the flow rate in the experiments. This equation would be modified further in our subsequent study about control rod FIV.

$$D_m = p_1 + p_2 Q_h + p_3 Q_h^2 + p_4 Q_h^3 + p_5 Q_v + p_6 Q_v^2 + p_7 Q_v^3 \quad (\text{Equation.1.})$$

Nomenclature

D_m maximum displacement of control rod (mm)

Q_h transverse flow rate (t h^{-1})

Q_v vertical flow rate (t h^{-1})

p_1 0.520815705023767

p_2 -0.00311487428050761

p_3 1.0280105358645E-5

p_4 -8.40474519088963E-9

p_5 -0.00163911603035928

p_6 6.49971574175738E-6

p_7 -6.42212845815544E-9

5 Conclusions

An experiment was conducted to investigate the FIV phenomenon in the control rod of PWR. Three conclusions were obtained from the experimental data and

analytical results.

(1) Analysis of the experimental results showed that within the scope of this test, the influence of vertical flow on control rod vibration was small, and transverse flow was the main factor that influenced FIV.

(2) An obvious increase was observed when the transverse flow rate was in the range of 300 t h^{-1} to 500 t h^{-1} . In the experiment, the transverse flow in this range could cause strong FIV to the control rod.

(3) A related equation for the maximum FIV displacement of the control rod and the flow rate equation were proposed. This is a first-stage work but can still provide a reference for further research on the FIV mechanism.

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Figure Captions

Fig. 1. Scheme of the experiment test loop.

Fig. 2. Experiment test section: (a) external view of the test section; (b) the inside model of the test section

Fig. 3. Model structure of the test section: (a) the cross section of the model; (b) external view of the rectangular holes

Fig. 4. Velocity field nephogram of the inlet section: (a) velocity vector; (b) velocity distribution

Fig. 5. Velocity field nephogram of the outlet section: (a) velocity vector; (b) velocity distribution

Fig. 6. Velocity distribution of the test section: (a) velocity vector; (b) velocity distribution

Fig. 7. Static pressure distribution of the test section

Fig. 8. Velocity distribution of the 1# rectangular hole

Fig. 9. Displacements at different vertical flow rates

Fig. 10. Displacements at different transverse flow rates

Fig.11. Relationship between vibration force and frequency

Fig.12. Curved surface of maximum vibration displacements at different flow rates

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