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High-level Vibration and Noise Analysis of Nuclear Pipes with Orifice

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ABSTRACT

Vibration caused structure failure is a common occurrence in industry piping. In the design process of nuclear piping, fluid-induced vibration effect is normally not taken into account because of the lack of practical guidance and regulatory requirements. Nuclear pipes suffering from high-level vibration and noise problems have been studied in this paper. Field investigation and vibration measurement provide basic information to exclude resonance and pump excitation from the fundamental cause of this issue. Since the vibration and noise is extremely high at the position near a single throttle orifice, cavitation after the orifice is believed to be the fundamental reason to cause the problem. Numerical analysis and laboratory simulating test have been implemented to validate this engineering judgment. In order to eliminate cavitation phenomenon, multi-step orifice design as well as the relevant validation test have been made. After field modification, the vibration and noise are both significantly reduced.

KEY WORDS: nuclear piping, vibration and noise, orifice, cavitation.

PREFACE

Nuclear pipe structure failure due to service vibration has been found in many nuclear power plants [1]. From the nuclear safety and economy point of view, this kind of malfunction is not acceptable and should be treated with great care. In the past years, many theoretical studies and engineering treatment [2-4] have been fulfilled in this field. This paper describes an engineering example for vibration analysis of the pipes with orifice.

High-level vibration and noise of the pipes was found in Daya Bay, a Nuclear Power Plant (NPP) in China that has been put into commercial running for about 8 years. Vibration has induced structure fatigue and pipe flaw appeared, which leads the leak of liquid. In order to investigate the cause of the structure damage, a research project was launched on 1999. On site vibration measurement gives the basic information including pipe vibration frequency, vibration response such as velocity and acceleration. Based on the field survey and spectrum analysis of vibration measurement result, resonance has been excluded. Computational Fluid Dynamics (CFD) codes were applied to calculate the fluid parameter on the region of violent vibration occurs, which finds the lowest pressure after a throttle orifice is reduced to the vapor pressure of the liquid and a phenomenon called "cavitation" happens. From these studies, researchers considered the cavitation caused by sharp pressure drop after orifice is the main reason for this issue. With the help of other factors such as turbulence, inappropriate pipe support design, the fatigue failure of the structure cannot be avoided. A laboratory hydrodynamic simulation test has been implemented to validate this judgment, and the system structure modification is schemed.

FIELD INVESTIGATIONS

In order to test containment spray system pumps, Daya Bay has set corresponding test line, which is equipped with an orifice to limit the flow rate of the line to around 300m3/h. Figure 1 shows the simplified system layout.

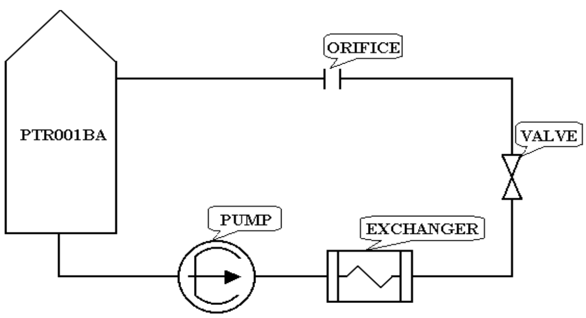

Fig. 1 The simplified system layout of test line

However, the periodic test appeared high level vibration and noise. Field investigation on 1997 and 1998 found that small branch lines connecting to the main pipe were failed due to fatigue flaw. The periodic test at the end of 1998 even caused flaw on the main pipe. Field treatment on 1999 was applied to eliminate the small branch lines from main pipe remaining the Boss head. Unfortunately, liquid leakage was found at the Boss head on 2000. Noise during the test is over 120dB and does great harm to the field workers.

An on site vibration measurement was arranged to obtain the basic information for the later detail analysis on Nov. 2001. When the system did not function, the natural frequency measurement was implemented. In spite of the abominable environment, the vibration response measurement was carried into execution when the system was running. Data treatment found the following results:

- The natural frequencies of the pipe have closely spaced;
- The high amplitude Power Spectrum Density (PSD) value of the vibration response was found at lower frequency range with closely spaced frequency.
- The vibration response is pulsed with very high pipe vibration velocity and noise at the position near the orifice.

FUNDAMENTAL REASON ANALYSES

Former analysis assumed that the high level vibration is due to resonance. On 1998, a 220Hz excitation frequency was found to be close to 218Hz natural frequency of the pipe during the quick field investigation using portable device. Based on this judgment, a design modification scheme was brought forward to change the natural frequency of the pipe by adjusting the pipe supports. To be circumspection, this design modification has been reviewed by NPIC and XJTU from 1999.

Engineering pipes conveying fluid may suffer from vibration and noise caused by different mechanisms. The source can be considered as fluid turbulence, fluid elastic instability, acoustic excitation, pulse pressure due to external excitation such as pump running and others. Since the vibration and noise is extremely high at the position near the orifice, it is straightforward to consider the orifice as the source of excitation. However, it is not an easy task to confirm the excitation mechanism.

In figure 1, we can see that pump induced pressure pulse is annihilated by a huge exchanger before it can reach the orifice. So the pump excitation can be eliminated from the main cause.

Field vibration measurement shows that both the frequencies of pipes and the peak response PSD are closely spaced. It is not likely to induce strong resonance with closely spaced frequencies.

When the liquid flows through the pipe restriction such as throttle orifice shown on figure 2, pressure drop will occur. It would be extremely severe with sharp pressure drop P1-P2 caused by high flow rate and small constriction.

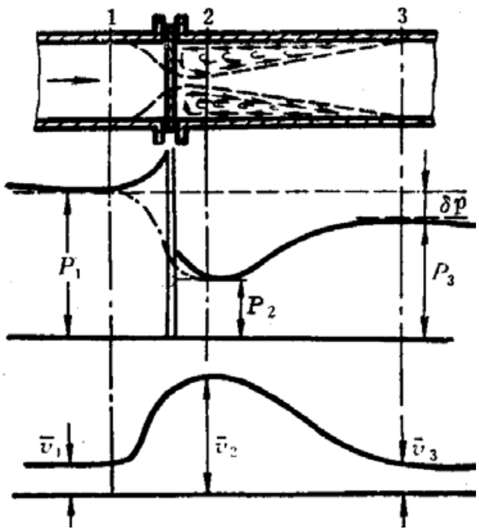

Fig. 2 Pressure and velocity profiles through an orifice

In case of the pressure P2 reduced to the vapor pressure of the liquid, the liquid may boil and form vapor bubbles. The bubbles are washed downstream where the liquid pressure P3 resumes. The bubbles collapsing at the high-pressure region may cause noise and damage [5]. Our first engineering judgment is focused on this phenomenon called “cavitation”.

In order to understand the flow pattern around the orifice, numerical calculation is firstly made with commercial CFD codes FLUENT and CFX. Using k-ε model and SIMPLC algorithm, the flow field is simulated for flow rate 300m^3/h, 330m^3/h and 350m^3/h. Figure 3 shows the velocity distribution for flow rate 300m^3/h. The corresponding lowest pressures are 0.98bar, -1.45bar and -3.76bar respectively, while the vapor pressure of the liquid at 40 ^{o}C is 0.075bar. Obviously, cavitation is possible to happen.

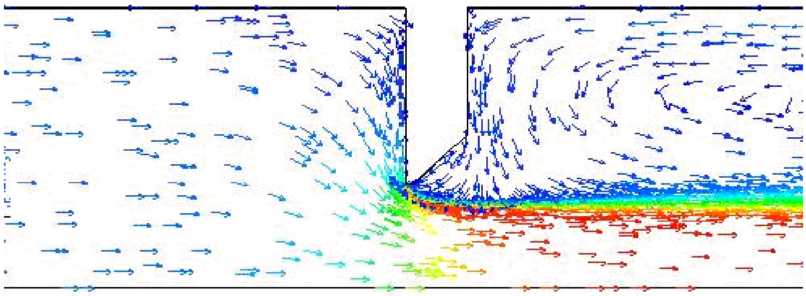

Fig 3 Velocity distribution through an orifice

LABORATORY TEST VALIDATIONS

To validate the above analysis, a thermal hydraulic simulation test has fulfilled on XJTU. As shown in figure 4, 1/4 scale test loop is set to model the field condition with different flow rate and β (the ratio of orifice hole and pipe diameter).

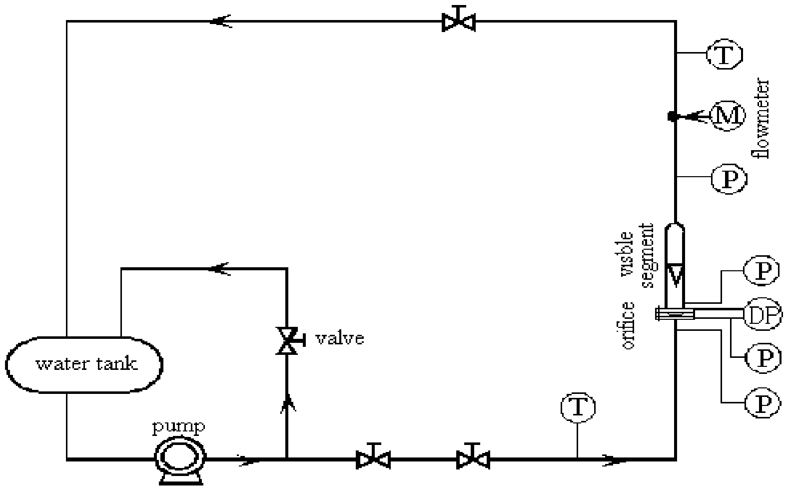

Fig. 4 Schematic diagram of the experimental apparatus

In literature, cavitation number σ is used to express the degree of cavitation, which is defined as

$$\sigma = \frac{P_3 - P_v}{0.5\rho V^2}$$

Where P_3 is the downstream pressure. P_v is the vapour pressure of the water. ρ is the density of the fluid and V is the average liquid velocity at the orifice.

The first step is made for the scaled field condition of 19.02 t/h flow rate and β=0.35. In order to observe the flow pattern, organic glass is used to make the test part. Figure 5 shows one of the visualization test result from which we can see a mass of bubbles after orifice. Cavitation number σ=0.494. Pipe vibration is visible and noise level reaches 105.5 dB. Organic glass pipes have been broken several times during the test. All these test results testify our engineering judgment of cavitation and numerical analysis results.

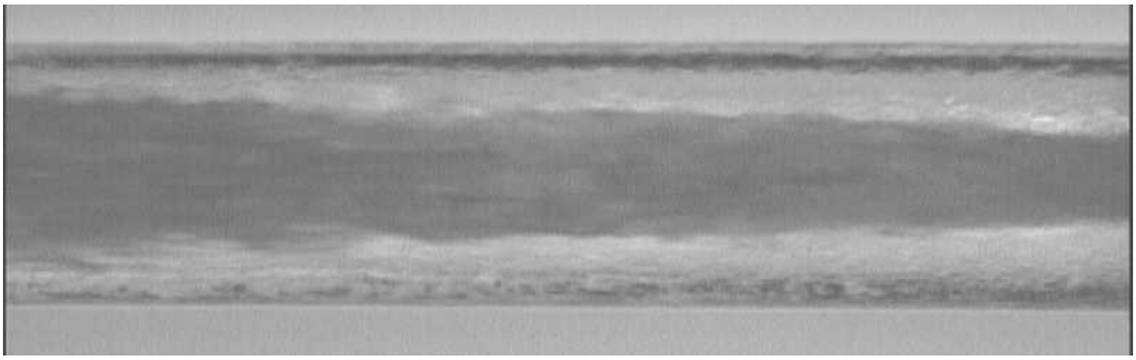

Fig 5 the visualization test result after an orifice

Cavitation should ascribe to sharp pressure drop after one single orifice. Considering field modification solution, we propose to use step orifice to replace the single orifice. To maintain the flow rate of the system, new step orifice should have same function as original orifice, whereas get rid of the damage of the cavitation. We have designed two schemes with two-step and three-step orifices respectively. Corresponding tests have been fulfilled on the same test loop. For the two-step scheme, the first step orifice has β=0.38 and σ=1.695, while the second step has β=0.47 and σ=1.561. Simulation test has shown that the vibration and noise level are significantly reduced. However, since the backpressure of the second orifice is relatively low, it is still possible to meet cavitation with high-pressure drop. Hence, three-step scheme is more likely to eliminate the cavitation phenomenon if the field condition permits.

CONCLUSIONS

High-level vibration and noise issues for a nuclear pipe system have been analyzed using numerical and experimental simulation methodologies. After field vibration measurement, engineering judgment has been made to assume cavitation instead of resonance and pump excitation as the fundamental reason. Numerical calculation shows that the pressure after orifice may drop to the vapor pressure of the liquid, while laboratory test simulating field condition recurs the vibration and noise caused by cavitation.

Regarding the technical modification on field, two-step or three-step orifices design has been proposed to maintain the original single orifice function and eliminate the cavitation phenomenon. Relevant simulating tests have been implemented to validate the design. Besides cavitation phenomenon, turbulence flow as well as acoustic excitation may also have contributed to the structure vibration. It is also necessary to strengthen the pipe supports to improve the endurance of the structure. Technical modification design has been provided by NPIC recently and the field implementation has just finished. A preliminary investigation shows that the vibration and noise level are both significantly reduced.

Vibration caused structure fatigue failure is a common occurrence in industry piping. It is still not easy to avoid this problem because of the lack of practical guidance and regulatory requirements. Especially for flow-induced vibration issue in nuclear piping, routine design process does not take it into consideration. The experience of the system designer is the only thing to rely on. Moreover, the vibration of the pipe conveying fluid cannot be totally eliminated. Hence, what is the acceptable limit for the vibration during the whole plant lifetime? NPIC and XJTU are still researching these issues focused on how to determine the vibration excitation as well as the response, and how to evaluate the structure integrity based on the vibration response.

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