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# FLOW INDUCED VIBRATION ANALYSIS OF THE THERMOWELL IN REACTOR COOLANT PIPE

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## ABSTRACT

There are mainly two excitation mechanisms for flow-induced vibration of thermowell in reactor coolant pipe under the cross flow: turbulence excitation and vortex shedding. The natural frequencies of the G1 ″ and G1 ″ 1/4 thermowell, and also the vortex shedding frequencies are calculated respectively in this paper. The vortex shedding lock-in is analyzed to the two different size thermowells, and then the study on flow induced vibratory fatigue analyses of the thermowell is performed using a simplified engineering approach.

**Keywords:** flow-induced vibration, turbulence excitation, vortex shedding, fatigue

## 1. INTRODUCTION

A Thermowell (thermometer well) is a receptacle for a temperature sensor, to be installed in a piping system as a part or fitting of that system. The thermowell stretches into the flowing coolant in the pipe with one end fixed on the boss and another end free. Nuclear reactor coolant temperature is directly measured in the hot leg and cold leg of the reactor coolant loop, by the resistance thermal detectors (RTD) inside the thermowell.

The thermowell is directly subjected to the cross flow of the reactor coolant, and cause vortices to be shed from the thermowell at a frequency, termed the vortex shedding frequency, proportional to the flow velocity. The lock-in synchronization will occur when the vortex shedding frequency is near the natural frequency of thermowell, the thermowell constantly absorb the energy from the flow fluid and result in high stress which finally cause the failure of RTD.

The coolant flow path and flow velocity can produce and maintain the turbulence; one part of flow energy will be converted into fluctuating pressures when the turbulence flows over the thermowell surface. The random surface pressure fluctuations produced by the turbulence velocity component can induce vibration of the thermowell.

The above-mentioned two primary flow excitations may cause the large vibration amplitude of the thermowell. Even if the thermowell does not fail, the RTD inside the thermowell may be subjected to severe levels of shock and vibration, resulting in erroneous readings or detector failure. The vortex shedding is predominating excitation for the thermowell vibration based on the theory and experiment investigations. Therefore the lock-in synchronization of vortex shedding should be avoided in the thermowell design.

The preliminary investigation is performed for flow-induced vibration analysis of the thermowell under cross flow. The natural frequencies and the vortex shedding frequencies of G1 ″ and G1 ″ 1/4 thermowell are calculated firstly, the lock-in phenomena of the two different size thermowells are discussed. The turbulence fluctuation pressure, the lift forces and the drag forces induced by vortex shedding are calculated using simplified engineering method based on the two main mechanisms: turbulence excitations and vortex shedding, and then the thermowell vibratory fatigue analysis are also performed.

## 2. THE THERMOWELL GOEMETRY

The two different size thermowells are considered: G1 ″ and G1 ″ 1/4. Both the inner radius of G1 ″ and G1 ″ 1/4 are 10mm, the outer radius of G1″is varied uniformly from 28mm at the fixed end to 24mm at the free end, the length between the two ends is 215mm; The outer radius of G1 ″ 1/4 is varied uniformly from 37mm at the fixed end to 18mm at the free end, the length between the two ends is 200mm.

## 3. PROPERTIES OF THE THERMOWELL MATERIAL AND THE COOLANT FLUID

For conservation, the material properties are considered at 350oC for thermowell and 300oC for coolant fluid respectively. The thermowell material is of austenitic stainless steel, which properties at 350oC are as flows

Elastic modulus E= 1.72E11 Pa
Poisson ratio $\upsilon$ =0.3
Allowable stress intensity $S_m$=114 MPa
Density $\rho_s$=7900 kg/m$^3$

When th a e pressure and temperature of coolant fluid in the main pipe are taken as 17.2MPand 300oC respectively, the fluid properties are

Kinematics viscosity $\mu$ =1.22E-7 m$^2$/s
Mass density $\rho_f$=726.7 kg/m$^3$

## 4. FREQUENCIES OF THERMOWELL AND VORTEX SHEDDING

The natural frequencies of G1 ″ and G1 ″ 1/4 thermowell in hot water (350oC) are calculated using the ANSYS code[1] respectively, The calculated results and related test results[2] are showed in Table 1.

*Table 1 the calculated and test results of the natural frequencies of thermowell*

| | Calculated results (in hot water) | | Test results (in air, room temperature) |
|---|---|---|---|
| | G1 ″ | G1 ″ 1/4 | G1 ″ |
| First order frequency/ Hz | 423.3 | 828.3 | 410 |
| Second order frequency/ Hz | 2264.6 | 3117.1 | - |

The calculated natural frequencies are higher than the test results because the boundary condition of the calculation model is completely fixed, which is more rigid than the real structure.

Reynolds Number of the fluid flowing across thermowell at 300oC can be written as

$$\mathrm{Re} = \frac{\mathrm{v}D}{\mu}$$

*D* is the mean outer radius of the thermowell subjected to the cross flow, v=17.73 m/s is the fluid velocity inside the main pipe.

The vortex shedding frequency is

$$f_S = \frac{S \times \mathrm{v}}{D}$$

Where, S is Strouhal Number. The Reynolds Numbers and the vortex frequencies for G1 ″ and G1 ″ 1/4 are list in Table 2.

*Table 2 The Reynolds Numbers and the vortex frequencies for G1 ″and G1 ″1/4*

| | G1 ″ | G1 ″ 1/4 |
|---|---|---|
| Reynolds Number | 3.7E6 | 3.4E6 |
| Strouhal Number | 0.3 | 0.3 |
| Vortex shedding frequency $f_s$/ Hz | 211.3 | 228.5 |
| Ratio of vortex shedding frequency to thermowell natural frequency | 0.50 | 0.28 |

## 5. RESPONSE OF THE THERMOWELL UNDER CROSS FLOW

Based on the large of test investigations, the characteristics law that two lock-in regions parallel to streamline and one lock-in region perpendicular to streamline is founded for a single cylinder response under cross flow, see Table 3[3].

*Table 3 the characteristics of the lock-in regions*

| Vibration direction | Vibration parallel to streamline | | Vibration perpendicular to streamline |
|---|---|---|---|
| | The first region | The second region | |
| Region | 1 | 2 | 3 |
| Reduced velocity $U_r$ | 1.25~2.5 | 2.5~3.8 | 3.8~10 |
| $U_r$ corresponding to the maximum response amplitude | 2.4 | 3.2 | 5.5~8 |
| Excitation frequency | Changed | Unchanged | Unchanged |
| Maximum response amplitude $a/D$ | 0.25 | 0.25 | 2.0 |
| Vortex | Symmetrical vortex pair | Stagger vortex pair | Stagger vortex pair |
| The upper bound of mass-damping parameter when lock-in occurs | 0.6 | 0.6 | 32 |

The reduced velocity and the mass damping parameter are calculated respectively according to the flowing formulas

$$U_r = \frac{v}{f_1 D} \qquad\qquad \delta_s = \frac{2\pi\zeta m}{\rho_f D^2}$$

Where, m, $\zeta$ are the thermowelll mass per unit length ( containing the added water mass ) and the damping ratio in water ( taken conservatively as 1% [4]) respectively. The calculated results of the reduced velocity and the mass damping parameter for the G1″ and G1″1/4 are list in Table 4.

*Table 4 the reduced velocity and the mass damping parameter*

| | G1″ | G1″1/4 |
|---|---|---|
| The reduced velocity / m/s | 1.61 | 0.92 |
| The mass damping parameter | 0.57 | 0.72 |

Comparing Table 4 to Table 3, it can be concluded that

(1) For the G1″ thermowell, the reduced velocity is in the 1st region of the vibration parallel to streamline, the mass damping parameter is less than 0.6, and the natural frequency of thermowell is approximately twice the vortex shedding frequency, the vortex shedding will be controlled by the thermowell vibration parallel to streamline, so the lock-in parallel to streamline occurs. The lock-in perpendicular to streamline does not take place because the vortex shedding frequency is far away from the thermowell frequency.

(2) For the G1″1/4 thermowell, the reduced velocity is less than that the lock-in occurs list on Table 3 and the mass damping parameter is more than 0.6, there is no enough energy to make the thermowell to vibrate, so both the lock-in parallel and perpendicular the streamline will not occur.

## 6 Vibratory Fatigue Analysis

The fluid fluctuation pressure power spectrum density (PSD) exerted on the thermowell surface is difficult to be obtained by calculation, which usually be measured by test. The thermowell alternative stress intensities are estimated by means of a simplified engineering method in this paper.

In uniform cross flow, the energy of vortex shedding occurs over a very narrow frequency band with a center frequency of vortex shedding, except over a transition band of Reynolds Number (2.0E5~3.0E6) where the character of the frequency content may vary from almost periodic to completely random.

It shows from test investigations [5] that the maximum root of mean square value of the turbulence fluctuation pressure in reactor coolant loop can be written as

$$\Delta p = 0.28(\frac{\rho_f \times \mathrm{v}^2}{2})$$

The peak value of the alternative lift force (pressure) [3, 4, and 6] is expressed as

$$p_L = \frac{C_L \times J \times \rho_f \times \mathrm{v}^2}{2}$$

Where, $C_L$ is the lift coefficient and $J$ is the joint acceptance. For conservation, $C_L$=1 and $J$=1[6].

Vortex shedding also induces a force in the drag direction. The drag force occurs at twice the vortex shedding frequency for single cylinders. However the magnitude of the oscillating drag force is typically an order of magnitude smaller than the oscillating lift force [6]. For conservation, the alternative drag force (pressure) peak value is taken as [4]

$$p_D = \frac{C_D \times \rho_f \times \mathrm{v}^2}{2}$$

Where, $C_D$ is the drag force coefficient and taken as 1 conservatively.

The dynamic amplified coefficient can be written as

$$Q = \frac{1}{\sqrt{(1-(\frac{f_s}{f_1})^2)^2 + (2\zeta(\frac{f_s}{f_1}))^2}}$$

The RSM value of loads should times 4 comparing the stochastic vibratory fatigue curve [7] with the high cycle fatigue curve of ASME code [6]. The total loads exerted on the thermowell can be written as

$$P_{total} = \sqrt{\left(\Delta p \times 4 + p_D \times Q\right)^2 + \left(p_L \times Q\right)^2}$$

According to Figure I-9.2.2 curve C in Division 1, Section III of ASME Code, the fatigue endurance limit of austenitic stainless steel is 13.6 ksi or 93.8MPa (10E11 cycles). The calculated alternative stress intensity of the thermowell under the cross flow are list on Table 5. The alternative stress intensity of the G1 ″ is larger than the endurance limit of ASME Code and the alternative stress intensity of the G1 ″ 1/4 is smaller than the endurance limit of ASME Code.

*Table 5 the calculated alternative stress intensity*

| | G1 ″ | G1 ″ 1/4 |
|---|---|---|
| Maximum alternative stress intensity/MPa | 96.6 | 65.6 |

## 7. CONCLUSIONS

The investigations on the flow induced vibration and vibratory fatigue analysis for the thermowell under the cross flow inside the main pipe are performed in this paper. The main conclusion can be drawn as follows

（1） For the G1 ″ thermowell, the lock-in perpendicular to the streamline does not occur, but the lock-in parallel to the streamline occurs, the calculated fatigue stress intensity is larger than the allowable value of ASME Code.

（2） For the G1 ″ 1/4 thermowell, the lock-in parallel and perpendicular to the streamline does not occur, the calculated fatigue stress intensity is smaller than the allowable value of ASME Code.

Flow-induced vibration analysis for thermowell is mainly concerned in this paper, so the influences of the main pipe vibration, the fluctuation of temperature and inner pressure of the coolant and so on to the thermowell fatigue analysis are not taken into account. The methodology for calculation of the loads induced by turbulence excitation and vortex shedding need further investigation.

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