FLUID – STRUCTURE INTERACTION (FSI) STUDY ON SODIUM LEAKAGE INCIDENT AT PROTOTYPE FAST BREEDER REACTOR MONJU BY USING ANSYS SOFTWARE

HOANG TAN HUNG, BUI THI HOA, HOANG MINH GIANG

Institute for Nuclear Science and Technology

Email: hoangtanhung1991@gmail.com

Abstract: Fluid – structure interaction (FSI) is the interaction of movable or deformable structure affected by fluid flow surrounding and takes an important role in many issues related to industry. Especially in nuclear engineering, the structures designed to work under high pressure and temperature can cause excessive force or stress to the structures resulting in mechanical damages that may eventually threaten the structural integrity. This research focuses on investigation of sodium leakage incident issue at prototype fast breeder reactor Monju by using engineering simulation ANSYS software.

Keyword: *FSI, Monju, ANSYS*

Introduction

Fluid - Structure interaction (FSI) is a multi – physics phenomenal which occurs in a system where flow of a fluid causes a solid structure to deform which, in turn, changes the boundary condition of the fluid system. FSI is an important area in many industrial fields such as mechanical engineering, process engineering, medicine technique, civil engineering and including the nuclear engineering. In nuclear power plants, reactor component systems are operating under hard condition (high pressure and high temperature) which can cause excessive force or stress to the structures resulting in mechanical damages that may eventually threaten the structural integrity. Therefore, FSI must be considered in the design of nuclear power plants to enhance nuclear safety.

In this paper, FSI simulation was performed to evaluate the flow loads and dynamic response of thermowell in the incident of sodium leakage from main pipe of secondary heat transport system of Monju fast breeder reactor. The break in the thermocouple was cause by the flow – induced oscillation with vortices shedding from the thermowell subjected to a cross – flow of sodium, allowing several hundred kilograms of sodium to leak out onto the floor below the pipe. The FSI simulation will be done with ANSYS Workbench coupling between ANSYS Mechanical and ANSYS Fluent.

The brief of Monju nuclear power plant

Monju is a fast breeder reactor (FBR) which has been developed in Japan in the long – term program for research, development and utilization of nuclear energy. FBR technologies can significantly increase the efficiency of uranium utilization, and, when they are commercialized in the future, can make it possible to continue using nuclear power for several hundred years with uranium resources currently known to be both technically and economically available for use, and can reduce the long-term radioactivity of high - level radioactive waste, decreasing the environmental load.

Construction of Monju nuclear power plant was started in 1985 and the reactor achieved criticality for the first time in April 1994. On 8th December 1995, sodium leakage from secondary circuit occurred in a piping room of the auxiliary building. The secondary sodium leaked through a temperature sensor, due to the breakaway of the tip of the thermowell tube. The incident was no released radioactive material. There were no adverse effects for personnel and the surrounding environment. The investigations confirmed that the breakage of the thermowell was caused by high cycle fatigue of the well tube tip due to Vortex – Induces Vibration (VIV). According to fatigue crack analysis on the flow rate history, it was estimated that cracks initiated at the early stage of the 100% flow operation, propagated in the subsequent operation, finally leading to the well tube failure in the last 40% flow operation.

Table 1: History of flow operation of Monju fast breeder reactor [1]

Period	May, 1992 – Aug, 1992	Sep, 1992 – Jun, 1993	Jul, 1993 – May, 1995	Jun, 1995 – Nov, 1995	Dec, 1995 –

Operation time	About 200 hours	About 500 hours	About 0.5 hour	About 2000 hours	About 20 hours	About 2000 hours	About 1000 hours	About 1,5 hours
Operation condition	Temperature: 200 ºC Flow rate: 100%	Temperature: 325 ºC Flow rate: 100%	Temperature: 325 ºC Flow rate: 100% → 40%	Temperature: 200 ºC Flow rate: 40%, 7%	Temperature: 200 ~325 ºC Flow rate: 100% ⇔ 40%	Temperature: 450 ºC Flow rate: 40%	Temperature: 485 ºC Flow rate: 40%	Temperature: 450 → 485 ºC Flow rate: 40%

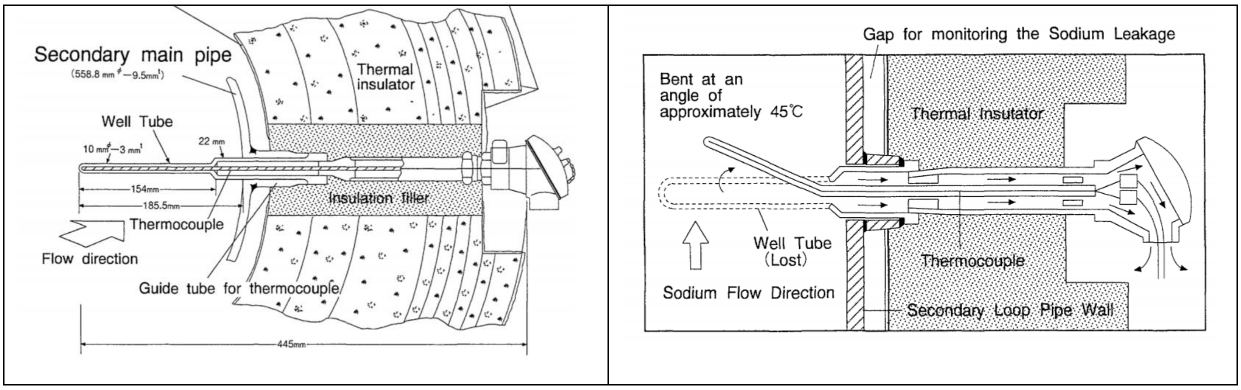


Figure1: Thermowell configuration before and after the incident [2]

Fluid – Structure Interaction theory

To solve FSI problems where VIV occurs, a theoretical understanding of both the structural and the fluid behavior, as well as the VIV phenomena is necessary. In this part, theory of fluid, structural and system coupling will be explained.

Fluid theory

The flow is fully described by conservation equations for mass, momentum, energy (equation 1).

$$\frac{\partial}{\partial t}\int_V \rho\phi dV + \oint_A \rho\phi \boldsymbol{V}.d = \oint_A \Gamma_\phi \nabla_\phi . dA + \int_V S_\phi\, dV \tag{1}$$

Where ϕ = 1 in continuity equations, ϕ = velocity u, v, w in momentum equation and ϕ = enthalpy h in energy equation. Partial differential equations are discretized into a system of algebraic equations then solved numerically to render the solution field.

Vortex shedding

Vortex shedding id an unsteady oscillating flow behind a body, especial around blunt cylindrical bodies. Vortices was formed and detach periodically from either side of the body. An asymmetrical flow pattern develops around the body due the periodic shedding and change the pressure distribution behind the body. A low pressure region will follow the vortices and create lift and drag forces on the body. The harmonically varying load that arises from the alternatively shedding induces vibrations with the same frequency as the frequency of the vortex shedding f_s. After separation, the regular pattern of vortices moves further downstream and the energy of the vortices is consumed by viscosity and the regular pattern gets dissolved.

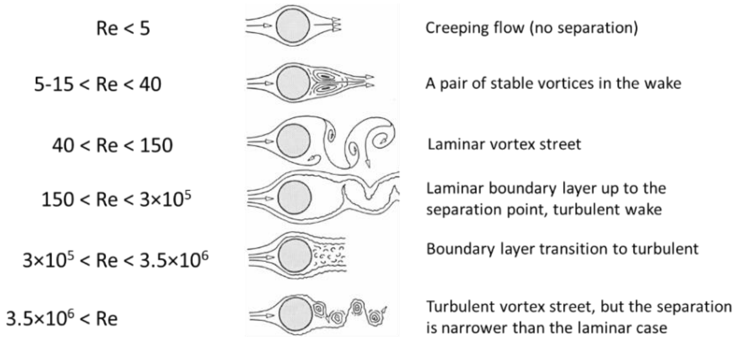


Figure 2: Vortex shedding pattern for different Reynolds number [3]

The vortex shedding process is defined by the Reynolds number and shedding frequency by the Strouhal number $St = f_s D/U$ where f_s is the shedding frequency, D is the diameter of cylinder and U is the free stream velocity. The Reynolds number can be used to indicate a number of flow regimes. Vortex shedding appears in all these regimes, but with different pattern. Figure 2 show approximately how the vortex pattern depends on the Reynolds number.

Structural theory

In the study, transient dynamic was used for analysis behavior of structures under application of loads. The equation of motion for structural is [4]:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K(u)]\{u\} = \{F(t)\} \tag{2}$$

Where M, K and C are the mass, stiffness and damping matrix and u, $\dot{u}$ and $\ddot{u}$ are the displacement, the velocity and the acceleration, accordingly. The right term is the forces apply, in this case is the lift and drag force.

Another tool was used is modal analysis to determine the vibrational characteristic of the structure. The vibrational characteristics contain natural frequencies and mode shapes of the structure are important in designing a structure subjected to a dynamic load. The basic equation used in modal analysis which is given [4] as:

$$([K]) - \omega_i^2 [M]\{\phi_i\} = \{0\} \tag{3}$$

Where ϕ_i is a mode shape vector (Eigen vector) of mode i and ω_i is a natural frequency of mode i. As the mention above, the harmonically varying load is a dynamic response of structures. If the frequency of vortex shedding (f_s) is close to natural frequency of structures can lead to the resonance and failure of the structure. So it is an essential process to find out the natural frequencies and mode shapes of a structure to find most dangerous case of flow operation of Monju reactor.

Fluid – Structure Interaction

In FSI problems, solid structures interact with surrounding fluid flow. The solid structure displacement will be caused by pressure differences in the fluid, and these pressure differences will force, or damp, the motion of the structure. There are different numerical methods for solve these types of problems. The monolithic approach solves the fluid and structure dynamics as one system of equations, this method require conforming mesh and a specialized code. The partitioned approach solves the fluid and structure system separately with different meshes and codes. The advantage with this approach is that common and well-known codes can be used and connected together. The partitioned approach is the method used in the simulations in this paper, connecting ANSYS Mechanical with ANSYS Fluent. A partitioned FSI simulation can also be one-way or two-way coupled. In a one-way coupled simulation data is only transferred from one solver to the other, but not the opposite way. In two-way coupled FSI both part is affected by each other and data is transferred both from fluid solver to structure solver and from structure solver to fluid solver.

FSI analysis on thermowell

Because Monju reactor has operated under several conditions, it is necessary to find the most dangerous case to perform FSI analysis. Firstly, modal analysis was performed to determine natural frequency (f_n) and mode shape of structure. Secondly, 2D flow analysis was perform by Fluent to determine vortex shedding frequency of different flow conditions. Comparison between natural frequency of structure (f_n) and vortex frequency can show the most dangerous case to perform FSI analysis. Finally, FSI calculation was performed to analysis location and value of stresses concentrate on the thermowell tube. The value of stresses concentrate will be compared with endurance limit of material (S_E). The diagram of analysis process show in figure 3.

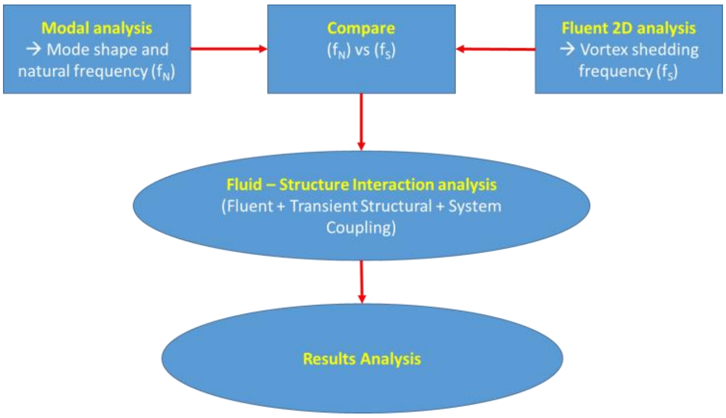


Figure 3: Analysis process

Geometry and mesh

The geometry and computational domain for FSI analysis of thermowell were showed in Figure 4. The whole length of the tube is 185.5 mm and 3mm thickness. Thermowell in Monju incident is type of step – shank with length of small part is 154 cm, with outlet diameter of 10 mm, transient part is 5 mm of length, and root part is 26.5 mm with outlet diameter of 22 mm.

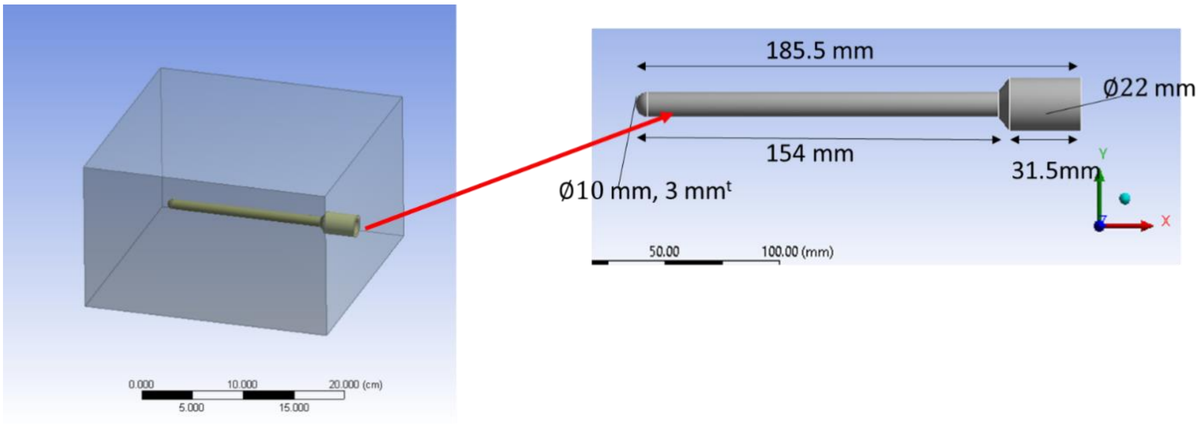


Figure 4: Geometry of thermowell

Material properties

The material for thermowell is 304 stainless steel, the density is 8000 kg/m^3, Young modulus is E_S = 193 – 200 GPa and the Poisson ration ν_S = 0.29 [5]. From history operation of Monju reactor, the flow properties of sodium can divide in 4 cases summary in table 2:

Table 2: Test matrix for 2D Fluent analysis [6]

	Temperature (℃)	Velocity (m/s)	Dynamic viscosity (Pa.s)	Diameter D (m)	Density (kg/m^3)	Reynold number
Case 1	200	5.2	4.52E-04	0.01	903.0352	1.04E+05
Case 2	200	2.08	4.52E-04	0.01	903.0352	4.15E+04
Case 3	450	2.08	2.55E-04	0.01	846.2525254	6.92E+04
Case 4	485	2.08	2.41E-04	0.01	838.1427074	7.23E+04

Modal analysis

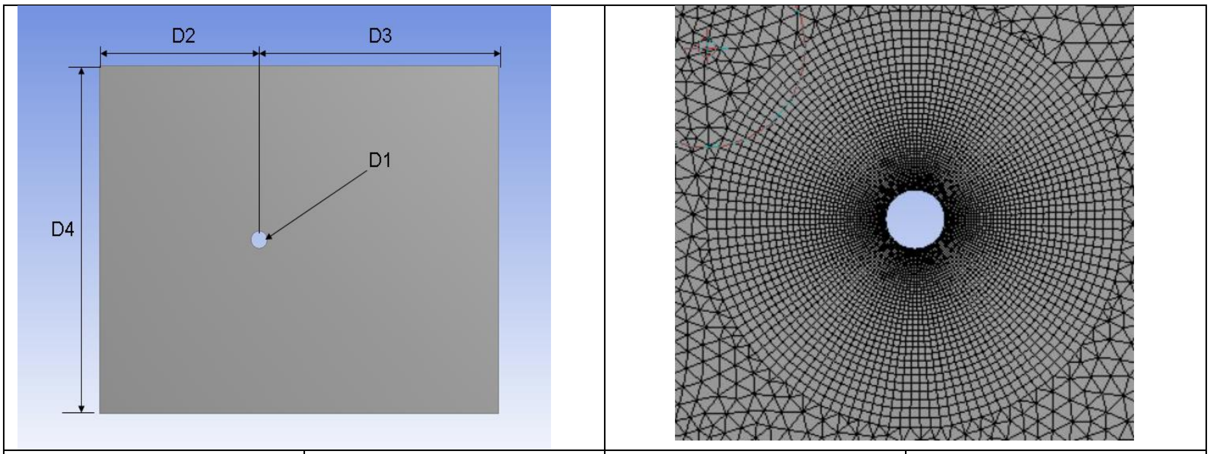
In modal analysis, the root part of thermowell was fixed and the set up to find first six natural frequency and mode shape of thermowell. The table 3 show the results of modal analysis.

Table 3: Natural frequency of thermowell

Mode	1	2	3	4	5	6
Natural frequency f_N (Hz)	261.15	261.22	1611.7	1612.	4327.2	4327.5

2D Fluent analysis

The 2D Fluent analysis was performed with typical cross section of thermowell. 2D model of thermowell and mesh was showed in Figure 5. Because all of cases have Reynold number greater than 10^4 so we chose the standard k - ω turbulence model for near – wall interactions model rather than k – epsilon model.



D1 = 0.01 m (D)	D2 = 0.14 m = 14 D	D3 = 0.16 m = 16 D	D4 = 0.15 m = 15 D

Figure 5: Model of 2D Fluent analysis at typical cross section of thermowell

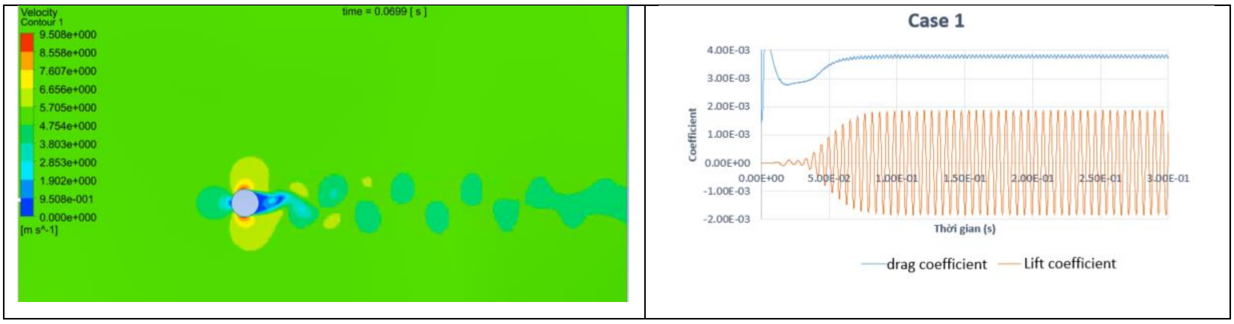


Figure 6: 2D Fluent vortex shedding (case 1)

The shedding frequency of thermowell and the comparison with average natural frequency of y and z direction are presented in Table 4. The case 1 with ratio f = f_S/ f_N = 0.654468 is the most dangerous because the vortex shedding frequency is close the natural frequency of the thermowell, it causes resonance and the thermowell starts to vibrate with same frequency as the shedding frequency.

Table 4: Comparison of natural frequency of thermowell and vortex shedding frequency

	Vortex shedding frequency f_S (Hz)	**Natural frequency f_N (Hz)**	**Ratio f = f_S/ f_N**
Case 1	170.94	261.185	0.654468
Case 2	64.10	261.185	0.245426
Case 3	64.10	261.185	0.245426
Case 4	64.10	261.185	0.245426

FSI analysis

From previous study, the most dangerous case was selected for FSI analysis is the case 1. The analysis was divided in two part are one-way FSI coupled and two-way FSI coupled to compare structural response to static and dynamic load.

One-way coupled

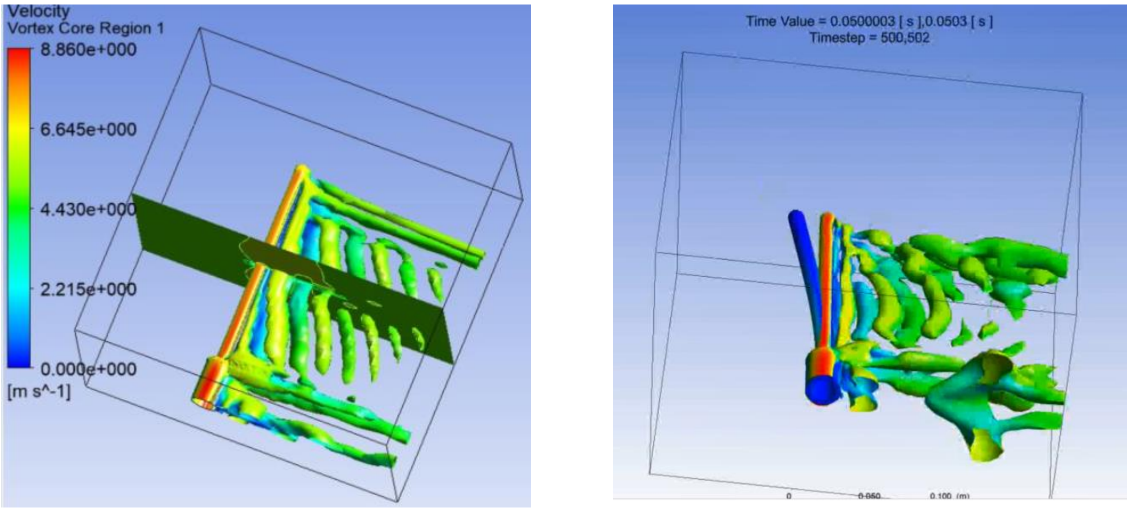
In one – way coupled simulation, we focus on affect from sodium flow to the thermowell, so the load data only transferred from Fluent solver to the Static structure solver. In Static structure setup, we need to import pressure from Fluent solver.

Two-way coupled

The two – way coupled simulation is more complicated, the motion of thermowell simulation using Transient structure, the motion of flow using Fluent are solved at the same time with the System Coupling coordinating the solution process as well as data transfers between the two analysis systems. The data transfer are: force data from the motion of flow is received by the Transient structure as it solves the structural behavior over time and displacement data from motion of thermowell is received by the Fluent as it solves the fluid behavior over time.

Results and discussion

The vortex shedding appear behind the thermowell in both scenario of FSI analysis (Figure 7). Due to change of diameter along the thermowell, the size and time appear of vortex shedding are different from the root to the top. In one –way FSI coupled, the flow pressure will be mapped on the thermowell surface to calculate the deformation and stress concentration and don’t have any feedback to flow field. In case two – way FSI coupled, the deformation information will be feedback to the flow field to calculation influence of deformation to the flow.



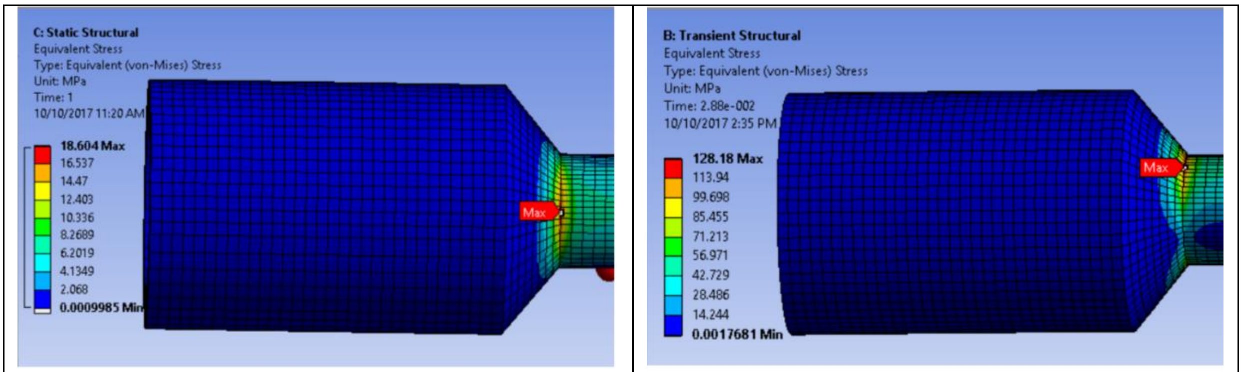
a) One – way FSI coupled

b) Two – way FSI coupled

Figure 7: Vortex shedding appear behind the thermowell

Figure 8 show that the location of stress concentration on the thermowell in FSI analysis is the same broken location of thermowell in incident for both cases one – way and two – way FSI coupled. But the value of stress concentration is very different between two types of FSI, in one – way coupled the maximum equivalent stress is 18.6 MPa much smaller than case of two – way coupled and endurance limit of structural steel is 86.2 MPa. The results show that have a big difference between structural response of static and dynamic load. In static load of sodium flow on the thermowell, the value of maximum equivalent stress cannot cause the fatigue damage on thermowell. Another way, the result of two – way FSI coupled, the value of maximum equivalent stress are greater than endurance limit (Figure 9) and vibration of thermowell can cause the fatigue damage, close to phenomena actually happened in Monju incident. This different of results can be caused by pressure load in one – way coupled is static load couldn’t have resonance effect like dynamic load in two – way coupled, which phenomena lead the system to oscillate with larger amplitude and maximum stress.

In one – way coupled do not updated the fluid domain related to the thermowell deformation, differences in pressure field lead to more conservative deflection values, , whereas two-way FSI simulations updated the fluid domain related to the thermowell deformation at each time step so this approach need higher computational cost.



a) One – way FSI coupled

b) Two – way FSI coupled

Figure 8: Stress concentration on thermowell

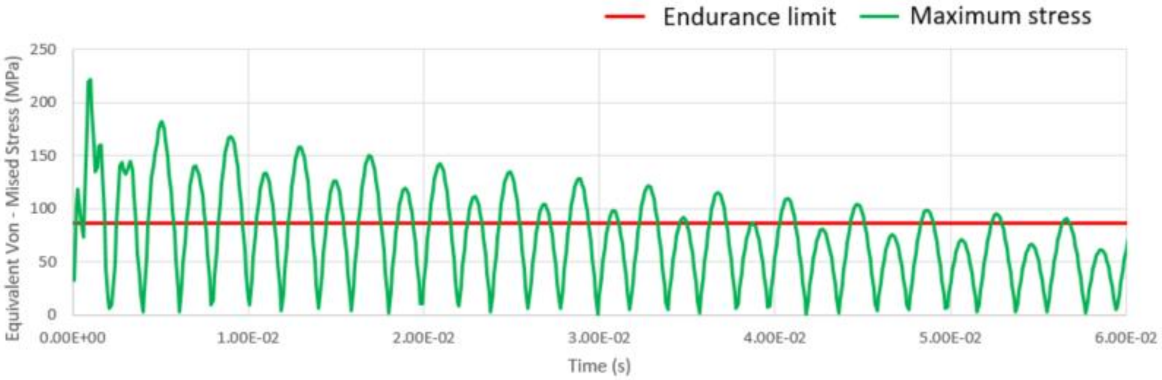


Figure 9: Maximum equivalent stress (Two – way FSI coupled)

Conclusion

FSI analysis was performed to simulation sodium leakage incident at prototype fast breeder Monju reactor. The study find to the most dangerous case to FSI analysis by comparison the natural frequency of thermowell versus vortex shedding frequency in several flow condition of reactor. The most dangerous case was selected for FSI analysis were solved with one – way and two – way coupling method. The simulation results show that:

- In both scenario, the vortex shedding appear behind the thermowell, and due to the change of diameter along the thermowell, the size and time appear of vortex shedding are different from the root to the top.
- The stress concentration location in both case has good agreement with broken of thermowell in Monju incident.
- The value of maximum equivalent stress in one – way FSI coupled is smaller than endurance limit and cannot cause the fatigue damage on thermowell, while in two – way FSI coupled, the value of maximum equivalent stress is greater than endurance limit by vibration of thermowell can cause the fatigue damage. Overall, the results of the simulation thermowell showed significant differences between the one – way FSI coupled solution and the real condition in Monju incident, whereas the two – way FSI coupled results that were close to reality.

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PHÂN TÍCH TƯƠNG TÁC CHẤT LƯU – KẾT CẤU (FSI) TRONG TAI NẠN RÒ RỈ NATRI TẠI LÒ PHẢN ỨNG HẠT NHÂN MONJU BẰNG CHƯƠNG TRÌNH TÍNH TOÁN ANSYS

HOÀNG TÂN HƯNG, BÙI THỊ HOA, HOÀNG MINH GIANG

Viện Khoa học và Kỹ thuật Hạt nhân

Email: hoangtanhung1991@gmail.com

Tóm tắt: Tương tác chất lưu – kết cấu (FSI) là tương tác giữa sự giữa sự dịch chuyển hoặc biến dạng của kết cấu với chất lưu bao quanh đóng vai trò quan trọng trong nhiều ngành công nghiệp. Đặc biệt trong công nghiệp hạt nhân, nơi các kết cấu phải hoạt động trong điều kiện khắc nghiệt như áp suất và nhiệt độ cao thì việc đảm bảo tính toàn vẹn của các kết cấu đóng vai trò quan trọng đối với an toàn của lò phản ứng hạt nhân. Mục tiêu của nghiên cứu này là mô phỏng lại tai nạn gãy ống chứa cảm biến nhiệt độ do hiện tượng FSI xảy ra tại lò phản ứng hạt nhân Monju thông qua chương trình tính toán ANSYS.

Từ khóa: *FSI, Monju, ANSYS*