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An evaluation of the fluid-elastic instability for Intermediate Heat Exchanger of Prototype Sodium-cooled fast Reactor

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1. Introduction

The sodium-cooled fast reactor (SFR) module consists of the vessel, containment vessel, head, rotating plug (RP), upper internal structure (UIS), intermediate heat exchanger (IHX), decay heat exchanger (DHX), primary pump, internal structure, internal components and reactor core [1]. The IHXs transfer heat from the radioactive sodium coolant (primary sodium) in the primary heat transport system to the nonradioactive sodium coolant (secondary sodium) in the intermediate heat transport system [2]. Each sodium flows like Fig. 1. Primary sodium flows inside of tube and secondary sodium flows outside.

During transferring heat two sodium to sodium, the fluid-elastic instability is occurred among tube bundle by cross flow. Large amplitude vibration occurred by the fluid-elastic instability is caused such as crack and wear of tube. Thus it is important to decrease the fluid-elastic instability in terms of a safety.

The purpose of this paper is to evaluate the fluid-elastic instability for tube bundle in the IHX following ASME code.

2. Nomenclatures

V_c	: Critical cross flow velocity (m/s)
f_n	: Natural frequency of nth vibration mode (Hz)
D	: Tube outer diameter (m)
m_t	: Total mass per unit length of tube (kg/m)
ξ_n	: Fraction of critical damping for nth mode
ρ	: Fluid mass density (kg/m)
C_n	: Frequency constant
r	: Radius of gyration of cross section (inch)
L	: Tube length (inch)
K_m	: Material constant
P	: Pitch of tube to tube (m)
T	: Sodium temperature (K)

3. Methods and Results

3.1 A method to evaluate instability

The fluid-elastic instability is evaluated to compare the critical velocity with the gap velocity of tube bundle. When the Critical velocity is less than the gap velocity or equal to, the instability is increased [3].

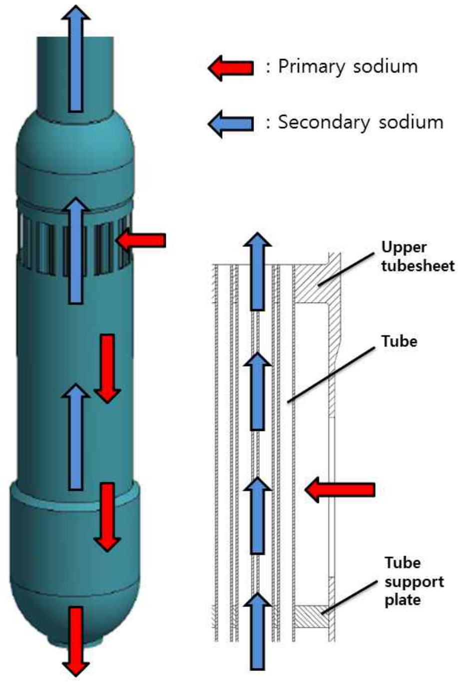

Fig. 1 a shape of IHX and flow direction of sodium

The critical velocity of tube bundle is calculated by eq. 1 [4]. The Critical velocity is related to natural frequency, total mass per unit length, damping, and fluid density of outside of tube. Fluid density is in inverse proportion and the others are in proportion. It is more conservative that fluid density has a high value and the others have a low value in terms of the critical velocity.

$$V_c/f_n D = C[m_t(2\pi\xi_n)/\rho D^2]^a \qquad (1)$$

In equation, a and C are functions of the tube array geometry. a = 0.5 has been recommended [4]. Fig. 2 shows that C is determined by a tube array type. This paper applies C = 4 because tube array type of IHX is rotated triangle type.

	Triangle	Rotated Triangle	Rotated Square	Square	All
C_{mean}	4.5	4.0	5.8	3.4	4.0

Fig. 2 Mean values of C for each tube array type [4]

3.2 A method of calculation

Natural frequency is calculated by eq. 2 [5]. Eq. 2 is a method of calculating natural frequencies of beams in flexure. This paper evaluates the fluid-elastic instability at a tube array of IHX upper slot like Fig. 1. IHX upper tube is welded at upper tubesheet and lower is supported by tube support plate (TSP). Thus a boundary condition of IHX tube can assume clamped-hinged condition. In clamped-hinged condition, frequency constant is 49.57. Material constant determined by material's temperature applies 0.912 in case of steel.

$$f_n = C_n \frac{r}{L^2} \times 10^4 \times K_m \qquad (2)$$

Total mass means sum of structural mass per unit length, contained fluid mass per unit length and added fluid mass per unit length. A calculating an added fluid mass uses the FAMD code. FAMD means Fluid Added Mass and Damping [6]. It was developed for practical applications calculating the fluid added mass and damping. In order to compare with FAMD code result, another added fluid mass is calculated eq. 3, 4 [4]

$$m_a = \frac{\rho\pi D^2}{4}\left[\frac{(D_e/D)^2+1}{(D_e/D)^2-1}\right] \qquad (3)$$

$$D_e/D = \left(1+0.5(P/D)\right)(P/D) \qquad (4)$$

Fig. 3 shows the finite element (FE) model for using FAMD code. A FE model consists of 1st~18th tube to demonstrate rotated triangle array type. Fig. 4 shows calculated results using FAMD code. In terms of conservation, lowest added mass of FAMD code is 0.28. In the other hand, an added mass calculated using eq. 3, 4 is 0.278. Two results are similar with each other. This paper applies results of FAMD code.

The table 1 shows critical damping ratio of tube installation type. Tube installation of case 1 is that thermowells and single span tube supported by welded or rolled in ends. Case 2 is that multi-span heat exchanger tubes supported by passing through oversized holes in plates. Comparing case 1 with case 2, case 1 is more conservative than case 2. Low value is that mid-span RMS vibration amplitude less than 1% of tube diameter and smaller than the diametrical clearance between the tube and the support plate. High value is that mid-span RMS amplitudes comparable to or larger than the diametrical clearance between the tube and the support plate. A clearance of IHX tube and TSP is approximately corresponded to high value due to allowing thermal expansion of IHX tube. On balance, damping ratio applied this paper is 0.005.

Fluid mass density is calculated by eq. 5 [7].

$$\rho = 219 + 275.32\left(1-\frac{T}{2503.7}\right) + 511.58\left(1-\frac{T}{2503.7}\right)^{0.5} \qquad (5)$$

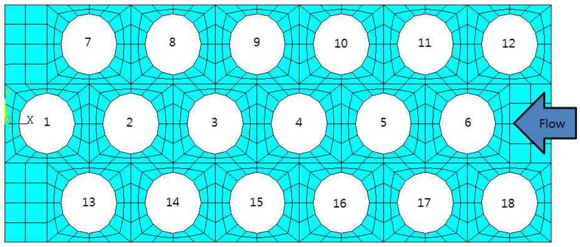

Fig. 3 The FE model of IHX tube array for FAMD code

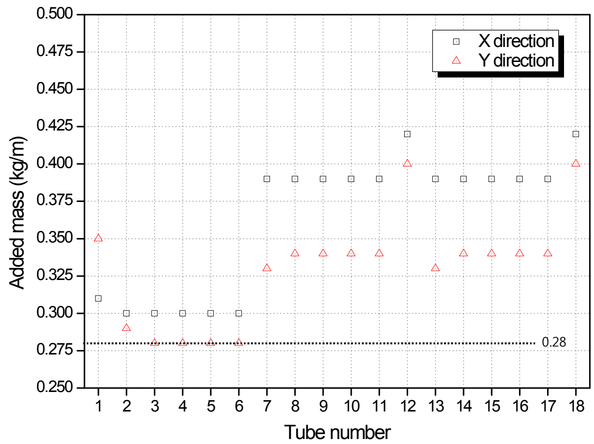

Fig. 4 Added masses calculated by using FAMD code

Table 1 Guidelines for damping of flow-induced vibration [4]

	Low value	Typical Design value	High value
Case 1	0.0005	0.002	0.005
Case 2	0.01	0.02	0.03

3.3 results

Table 2 shows calculated the critical velocity and instability ratio. For the fluid-elastic instability evaluation the gap velocity of tube bundle assumes 1.5 m/s. According results, though the critical velocity doesn't less than gap velocity, but the instability ratio is approximately 1. It means the critical velocity equal gap velocity. Therefore, the probability of occurring fluid-elastic instability at IHX tube bundle is high.

Table 2 Results of critical velocity and instability ratio

	Critical velocity (m/s)	Instability ratio
Clamped - Hinged	1.66	0.91

In order to decrease the probability, this paper suggests adding a TSP under the upper tubesheet so that natural frequency increases. Of course, changing a height between upper tubesheet and existing TSP shortly helps increasing natural frequency. But it is not recommend because it makes upper tubesheet to be undergo high thermal stress.

Once a TSP is added, a boundary condition of IHX tube is changed from clamped-hinged condition to hinged-hinged condition. In hinged-hinged condition, frequency constant is 31.73. As adding a TSP, though the Natural frequency decreases, but tube length can shorten. A range of increased natural frequency by adjusting tube length is larger than a range of decreased natural frequency by changed boundary condition of IHX tube. Thus it is more effective to add a TSP than not.

Fig. 5 shows tube length with respect to a variation of the critical velocity about an additional TSP location. If an additional TSP is located a tube length to become lower about 750 mm, the critical velocity becomes high than 1.5 m/s. Therefore, it can prevent to be occurred the fluid-elastic instability at tube bundle.

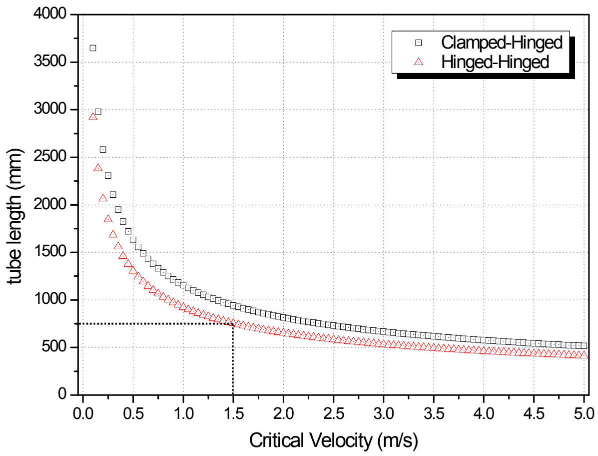

Fig. 5 Tube length with respect to a variation of the Critical velocity

4. Conclusions

This paper evaluated the fluid-elastic instability of tube bundle in the SFR IHX. According evaluation results, the fluid-elastic instability of IHX tube bundle is occurred. A installing an additional TSP under the upper tubesheet can decrease a probability of fluid-elastic instability. If a location of an additional TSP does not exceed tube length to become a 750 mm, tube bundle of IHX is safety from the fluid-elastic instability.

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