Flow induced vibration of inverted U-shaped piping containing flowing fluid of top entry system for LMFBR

T.Inagaki
Japan Atomic Power Company, Tokyo
T.Umeoka
Kansai Electric Power Company, Osaka, Japan
K.Fujita, T.Nakamura & T.Shiraishi
Takasago Research & Development Center, Mitsubishi Heavy Industries Ltd, Hyogo, Japan
T.Kiyokawa
Kobe Shipyard, Mitsubishi Heavy Industries Ltd, Japan
Y.Sugiyama
University of Osaka Prefecture, Japan

1 INTRODUCTION

One of the major points to decrease the cost of the Loop-type Fast Breeder Reactor is performed by minimizing the length of the connecting pipings. The inverted U-shaped piping is proposed to complete it by setting the supports flexible, see Fig. 1.

However, it makes the natural frequencies of the pipings lower, and some vibrational problems of the inverted U-shaped pipings should be checked. In this paper, the flow-induced vibration problem caused by the fluid flow inside the piping is examined.

2 VERIFICATION TEST

2.1 Test Equipments

In this test, the following two items are especially checked.

i) Some reasonance between the pipings and the pressure pulsation caused by curved parts.

ii) An unstable oscillation at the outlet region of the pipings.

For this purpose a simulation test was done to verify the safety of the inverted U-shaped piping.

The Reynolds number should be the same as the practical one, however the capability of test facility is limited. So the dynamic pressure is kept the same as the actual one by keeping the fluid velocity inside the piping constant while the Reynolds number is about 1/6 of the practical one.

The similarity law of this model is shown in Table 1. The shape of the piping are the same as the actual piping, and the shape and the size of the RV (Reactor Vessel) and IHX (Intermediate Heat Exchanger) is modified simply from the actual ones.

In addition, this model keeps the following parameters constant, which are related to an unstable vibration of axial flow in the piping.

$$UL\left[\frac{\rho A}{EI}\right]^{\frac{1}{2}}, \quad \frac{\rho A}{M}$$

where, ρA denotes the mass of fluid per unit length inside the piping. EI the bending rigidity of the piping, M the mass of the piping per

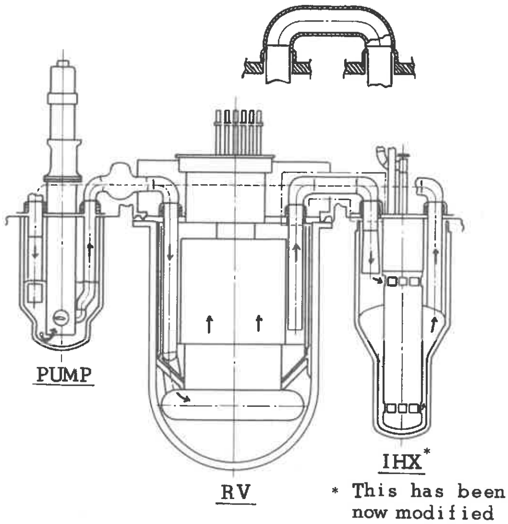

Fig. 1 Schematic view of the inverted U-shaped piping

Table 1 Similarity law of the model

No.	Items	Dimension	Scale	Scaling law *	Practical ones	Model
1	Diamater of piping D	L	a	0.45	1016 mm	157 mm
2	Fluid mass density ρ_t	$M \cdot T^2 \cdot L^{-4}$	b	1.2	0.85×10^{-6} $Kg \cdot S^2/cm^4$	1.0×10^{-6} $Kg \cdot S^2/cm^4$
3	Fluid velocity U	$L \cdot T^{-1}$	c	1.0	5.2 m/s	5.2 m/s
4	Length of piping L_t	L	a	0.45		
5	Thickness of piping t_t	L	a	0.45	11.1 mm and 15.9 mm	5 mm and 7.2 mm
6	Young's modulas of piping E_t	$M \cdot L^{-2}$	bc^2	1.2	1.68×10^4 Kg/mm^2	2.0×10^4 Kg/mm^2
7	Mass density of piping ρ_t	$M \cdot T^2 \cdot L^{-4}$	b	1.2	8.07×10^{-6} $Kg \cdot S^2/cm^4$	3.0×10^{-6} $Kg \cdot S^2/cm^4$
8	Length of Support skirts L_s	L	a	0.45		
9	Thickness of support skirts t_s	L	a	0.45	11.1 mm	5 mm
10	Young's modulas of support E_s	$M \cdot L^{-2}$	bc^2	1.22	1.68×10^4 Kg/mm^2	2.0×10^4 Kg/mm^2
11	Frequency f_r	T^{-1}	c/a	2.22		
12	Acceleration α_t	$L \cdot T^{-2}$	c^2/a	2.22		
13	Stress σ_t	$M \cdot L^{-2}$	bc^2	1.22		

* Model/Practical

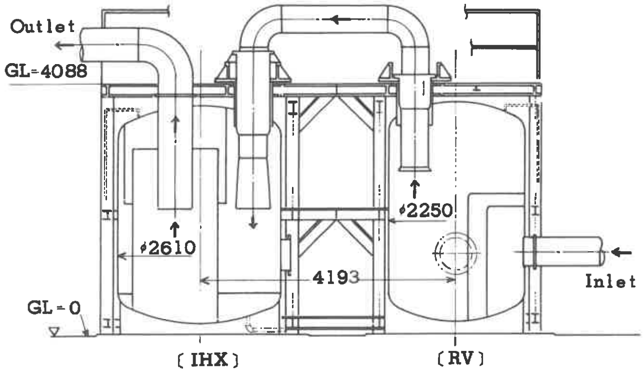

Fig. 2 Structure of piping model

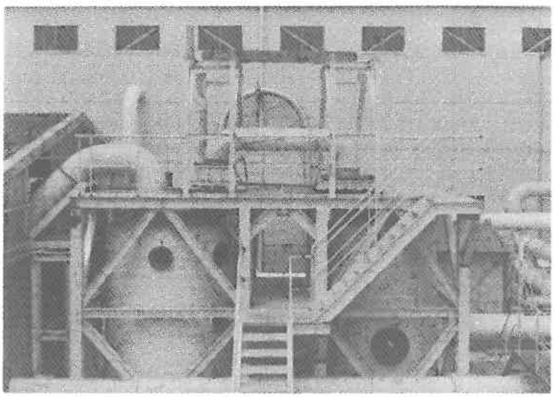

Fig. 3 Test apparatus

unit length.

The piping model is shown in Fig. 2 and Fig. 3. The supports of the piping are positioned on the two tanks which are modelled for the actual IHX and RV, respectively.

The pump which can flow the water at 1 m^3/s is used at room temperature.

The rigidity of the supports is changed to three levels including a similar model of the actual one. As a result, the most flexible case is 1/2.26 of the similar model in the rigidity.

By these models the vibrational responses of the piping are measured by varying the flow velocity up to 1.45 times the actual 5.2 m/s.

The accelerometers and the strain gages are used to measure the response of the piping, the pressure fluctuation and the flow velocity disctrubtion are also measured.

2.2 Test Results

(1) Vibrational Characteristics

The fundamental characteristics of the piping in the three different support conditions are shown in Table 2 which are obtained by the tapping test in air and in water, respectively. Figure 4 shows the first modes to each direction, for examples.

The distribution of the stress of the piping is checked by the shaker test, and it is revealed that the fixed point of the support has the greatest stress, which is also proved by an analysis.

(2) Vibrational Response

Figure 5 shows an example of the relation between the fluid velocity and the response of the piping in which no diversing large vibration is observed in all cases.

The representative frequency response characteristics by the flowing fluid is shown in Fig. 6. In these figures, only low cycles frequencies are dominant, which include the natural frequencies of the piping.

(3) Characteristics of the flow

The pressure loss of the piping and the time averaged pressure distribution inside the piping are not varied with the change of Reynolds number.

Case	Mode	In Air		In Water	
		Frequency	Damping	Frequency	Damping
1	1	32.0 Hz	0.74 %	15.8 Hz	0.20 %
(Similar)	2	35.0 Hz	0.85 %	17.3 Hz	-
2	1	28.5 Hz	0.66 %	15.0 Hz	0.52 %
(Flexible)	2	34.5 Hz	1.00 %	17.8 Hz	1.36 %
3	1	20.8 Hz	0.25 %	10.8 Hz	0.45 %
(Most flexible)	2	28.3 Hz	0.35 %	15.0 Hz	0.31 %

Table 2 Measured vibrational characteristices of the model

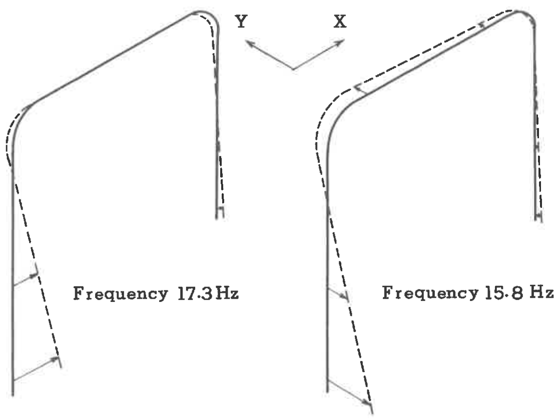

Fig. 4 Natural modes

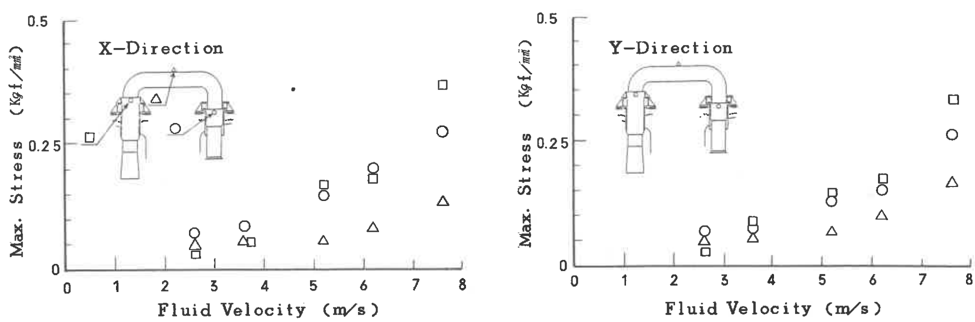

Fig. 5 Response of piping and fluid velocity

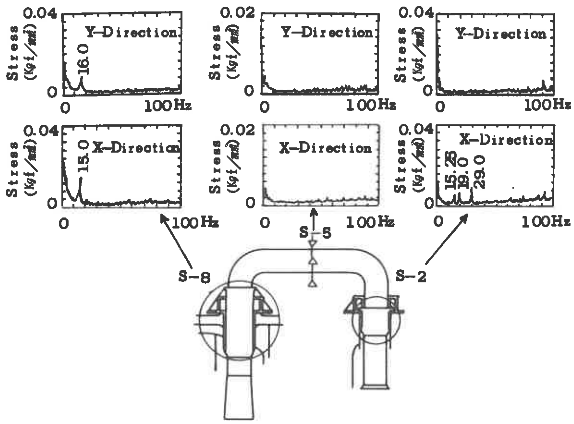

Fig. 6 Frequency component of response stress of piping (V=5.2 m/s, case 1)

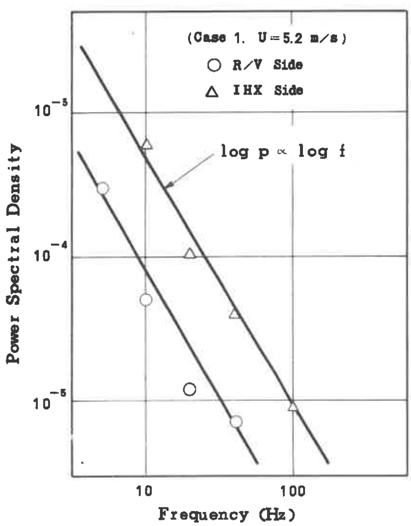

Fig. 7 Pressure fluctuation at elbow portion

Figure 7 shows the freqeuncy component of the pressure fluctuation at the elbow portion which says that the low cycle component are considered to be the main exciting source component of the piping.

2.3 Estimation of Test Results

Test results show the small random vibration only, so here it is to estimate the order of the exciting force acting on the piping of the flow inside the piping.

The model piping is modelled as a FEM model by using NASTRAN code, and the fundamental vibrational characteristics are shown in Fig. 8. This shows a good coincidence with the test result.

The response of the piping is expressed by the following statistical form.

$$Sj(\omega) = |Hj(\omega)|^2 \cdot Sa(\omega)$$

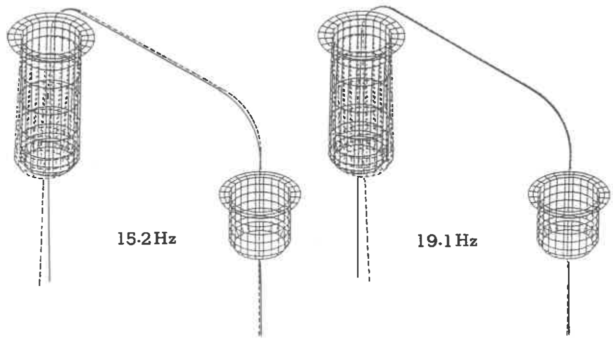

Fig. 8 Eigenvalue calculation of the model

where, $Sj(\omega)$ denotes the power spectral density of the response of the piping, $S_a(\omega)$ the power spectral density of the exciting force, $H_j(\omega)$ the transfer function.

The response of the piping is obtained as the integral of the power spectral density in the form of squared averaged value $\overline{U}j^2$.

Here, the components of the exciting force are estimated by using the other experimental values.

$$\overline{U}j^2 = \frac{1}{2\pi}\int_0^\infty Sj(\omega)\,d\omega$$

The response of the piping $\overline{U}j^2$ is used as the test results, and the slope of the frequency component of the exciting force $S_j(\omega)$ is assumed by using the slope of Fig. 7. By an assumption of the damping of the piping to an adequate value, the transfer function can be fixed. So, the rms value of the exciting force can be estimated.

As a result the exciting force acting on the elbow of the piping is computed as 10~30% of the theoretical dynamic pressure at the elbow which is statically estimated by the following equation

$$F = \sqrt{2}\rho A U^2$$

where, A denotes the area inside the piping,

3 MARGIN OF THE ACTUAL PIPING TO AN UNSTABLE OSCILLATION

The vertical outlet part of the inverted U-shaped piping can be thought to be modelled with the vertical cantilever pipe which conveys the fluid at which the end is immersed in water. It is useful to estimate the safety of the inverted U-shaped piping by checking the stability of the simple vertical pipe caused by the internal fluid flow. From pervious papers[(1)(2)], it is well known that the cantilever pipe conveying the fluid with high velocity has the possibility to cause the beam-type flutter and the shell-type flutter. It is verified by the verification test that the inverted U-shaped piping simulating the actual model does not cause these kind of flutters. However, it is important to estimate the margin of the piping for these flutters.

The parameters used to stability assesment of the actual inverted U-shaped piping are shown in Table 3. The best way to estimate the safety margin initially is by using the simplified model. It should be detailed if the result shows the critical value.

(1) Beam-type flutter

At first, the beam-type flutter is checked. As the most simple case, the vertical outlet part of inverted U-shaped piping is considered to be the horizontal pipe conveying the fluid at which one end is fixed and another is free. This case corresponds to the case neglecting the effect of gravity. The stability of this case is studied by Gregory and Paidoussis.[1] The important key of this case is the mass ratio β which is the ratio of the fluid to the pipe. This ratio is 0.74 from Table 3. Then the order of the critical velocity of the beam-type flutter is:

$$U_b = 2900 \text{ m/s}$$

This is an exttemely high velocity compared with the operating flow velocity U_n = 5.2 m/s for actual plants. The gravity has the effect supressing the flutter. The inverted U-shaped piping should be considered to have a lot of margin to the beam-type flutter.

The secondaly, the vertical pipe conveying the fluid at which the free end is immersed in water is examined,[3] especially the effect of the depth of the pipe in water for the stability. By the observation of the test, once the beam-type flutter occured, the pipe could not keep the straight shape and oscillate with rotating motion in water. One of the results of the test is shown in Fig. 9.

Table 3 Characteristic value and parameter of the vertical pipe

Terms	Nomen-clature		Unit	Note
Density (liquid)	ρ_f	1.0×10^3	Kg/m³	Water
Density (pipe)	ρ_s	7.8×10^3	Kg/m³	Steel
Density ratio	$\bar{\rho}$	7.8	—	$= \rho_s / \rho_f$
Liquid mass per unit length	m_f	776	Kg/m	$A_f \times \rho_f$
Pipe mass per unit length	m_s	273	Kg/m	$A_s \times \rho_s$
Mass ratio	β	0.74	—	$m_f / (m_f + m_s)$
Poisson's ratio (pipe)	ν	0.3	—	—
Young's modulus (pipe)	E	206	GPa	21000 Kgf/mm²
Parameter of dead load	γ	8.47×10^{-4}	—	$=(m_f+m_s)gL^3/EI$
Parameter	α_1	1.86×10^{-4}	sec/m	$= \sqrt{\rho_s (1-\nu^2)/EI}$
Parameter	α_2	4.62×10^{-3}	sec/m	$= L \sqrt{m_f / E}$
Mass parameter	ε	5.90	—	$= R \rho_f / h \rho_s$

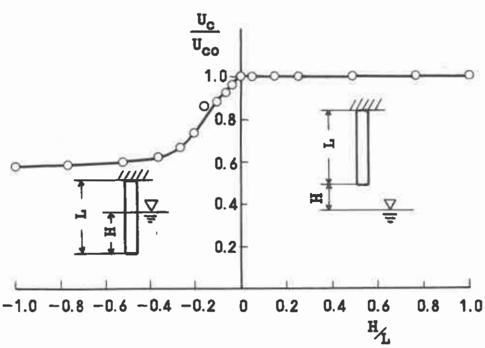

Fig. 9 Effect of the depth of the pipe in water for the flow velocity of flutter

This shows that the pipe is destabilized when the free end of the pipe is immersed in water. Even if the critical flow velocity decreases, at most, to half of the above value by this effect, the margin of the stability of the inverted U-shaped piping is extremely great.

(2) Shell-type flutter

The critical flow velocity of the cantilever shell is checked. Extrapolating the result[2] of Paidoussis, the critical flow velocity of the shell-type flutter is:

$U_S = 700$ m/s

This is lower than that of the beam-type flutter. However, this is also an extremely great value compared with the operating flow velocity of 5.2 m/s. So, it can be said that the shell-type flutter to not occurred.

In conclusion, the inverted U-shaped piping is qualitatively estimated to have the greater margin for the unstable oscillation caused by conveying fluid. Considering the more practical model, it shows some interesting problems scientifically, such as the development of the more suitable elastic support system and the detail study for the flow-induced vibration of the half-immersed cylindrical shell. These problems are also being studied now.

4 CONCLUSION

(1) No unstable oscillation of the inverted U-shaped piping is observed in this test, even in the case of the 1.5 times the actual operating fluid velocity and the 0.4 times the rigidity of piping.

(2) No resonance is observed between the pressure fluctuation and the frequency of the piping.

(3) These results are also supported by the analytical estimations.

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(1) R. W. Gregory & M. P. Paidoussis. "Unstable oscillation of tubular cantilevers conveying fluid 1. Theory". Proc. Rov. Soc. London A. 293. pp. 512-527 (1966)

(2) M.P. Paidoussis. "Dynamics of tubular cantilevers conveying fluid". J. Mechanical Engineering Science. Vol. 12. pp. 85-103 (1970)