EXPERIMENTAL AND ANALYTICAL STUDIES ON THE MULTI-SURFACE SLOSHING CHARACTERISTICS OF A TOP ENTRY LOOP TYPE FBR

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ABSTRACT

Sloshing tests were conducted on the 1/8 scale model of the top entry loop type FBR with multiple free liquid surfaces, which are connected to each other by inverted U-shaped pipings. The sloshing characteristics of the top entry loop type reactor was established by these tests. Applicability of the analytical code and effectiveness of the anti-sloshing devices were also evaluated.

1. INTRODUCTION

The top entry loop type FBR is a system with multiple liquid surfaces. The coolant liquid sodium flows in vessels through inverted U shaped pipings which connect these free liquid surfaces. In-vessel structures are installed in these vessels.

The following effects on the sloshing characteristics have to be cleared for the anti-seismic design of the top entry loop type reactor:

- (1) Effect of in-vessel structures
- (2) Effect of multi-surface connection
- (3) Effect of in-reactor forced flow

Studies are in progress on the effect of in-vessel structures on the sloshing characteristics [1], [2]. It has not been cleared yet, however, on the effects of the multi-surface connection and in-vessel forced flow on the sloshing characteristics. Accordingly, the authors have conducted vibration tests with a 1/8 scale model of the entire system of the top entry loop type reactor to clear the above mentioned sloshing characteristics of the reactor. Analytical studies were also conducted to evaluate the applicability of the analytical code based on comparison between test results and the analysis. Ring plates were mounted on the testing model to clear their effectiveness as an anti-sloshing device. The paper presents results of the vibration tests and the analytical studies conducted by the authors to clear the sloshing characteristics.

2. TESTING METHOD

2.1 Testing apparatus

The test employed a 1/8 scale 3-loop model, made of acrylic resin, of the entire primary loop of the top entry loop type FBR (electric output 600 MWe). The 3-loop model tested was composed of the reactor vessel, intermediate heat exchanger (IHX) vessel, pump vessel, and top entry piping, as shown in Fig.1. The tested model had a rigid structure to prevent the vibration of fluid structure interaction since the tests were aimed at investigating the sloshing effect of the top entry loop type reactor. Major structures in vessels were simulated. Water was used as the working fluid as it had nearly equal density to the liquid sodium and it was forced to circulate by a pump.

2.2 Testing condition

The purpose of tests were to study the effects of three important parameters, in-vessel structures, multi-surface connection and in-vessel forced flow on the sloshing characteristics of the top entry loop type reactor. Tests were conducted with three different testing arrangement, i.e. individual vessels, 3-loop connection without flow of fluid and 3-loop connection with forced flow of fluid, as shown in Fig.2.

In order to simulate the liquid level difference between the reactor vessel and IHX vessel under the in-vessel forced flow condition and the response wave height in tests equal to 1/8 of that in actual system, tests were conducted under the following conditions so that the Froud numbers Fr in testing and actual conditions agree to each other ($Fr = U/\sqrt{gD}$, where U : Flow velocity in vessel; g : Acceleration of gravity, and; D : Typical length):

- (1) Simulation ratio between testing apparatus and actual system: $1/n = 1/8$
- (2) Sloshing wave height: $1/n$ of actual system = $1/8$
- (3) Input velocity: $1/\sqrt{n} = 1/\sqrt{8}$ of actual system
- (4) Input acceleration : $1/1$ of actual system

2.3 Vibration test

Vibration tests were conducted using a three-dimensional shaking table. Sloshing wave height were measured in the tests with additional measurement of the pressure, flow rate and acceleration.

Fig. 1 Tested model

Fig. 2 Experimental conditions

Vibration tests were conducted to clear the sloshing characteristics of the top entry loop type reactor as follows:

- (1) Sine wave sweep test (evaluation of natural frequency, vibration mode)
- (2) Free vibration test (evaluation of damping)
- (3) Sine wave test (evaluation of response wave height)
- (4) Seismic wave test (evaluation of response wave height)

The excitation were applied mainly in the parallel direction to the hot leg piping, in which the effect of the vessel interconnection is significant. Additional tests were conducted in the normal direction to the hot leg piping.

3. TEST RESULTS

3.1 Test on individual vessel

Tests on individual vessels were carried out with the presence/absence of in-vessel structure as a parameter, aiming at clearing the effect of in-vessel structure on the sloshing characteristics.

Test results from the reactor vessel are shown in Fig.3 as a typical example for the transfer function obtained by the sine wave sweep test. Results of sloshing natural frequency are shown in Table 1. From test results of sloshing natural frequency shown in Table 1, it is found that values of the sloshing natural frequency for reactor and IHX vessels with in vessel structures are lower than those without in-vessel structures under the effect of these structures. Since the IHX layout is eccentric in the IHX vessel, values of sloshing natural frequency vary depending upon the direction of excitation, demonstrating the significant effect of the location of in-vessel structure on the sloshing.

Table 2 shows results of the damping ratio for small wave height as obtained by the free vibration test. From the table, the values of the damping ratio for reactor and IHX vessels with in-vessel structures are higher than those without in-vessel structures under the effect of these structures. Table 3 shows results of the response wave height of the third input wave as determined by the sine wave tests of the reactor and IHX vessels. It is found, from the table, that the response wave heights of the reactor and IHX vessels are small as compared with those without in-vessel structures due to the effect of these structures.

3.2 3-loop connection test without fluid flow

To find the effect of the multi-surface connection on the sloshing characteristics, tests were carried out on the 3-loop connection system without fluid flow.

Results of response wave height are shown in Tables 1 - 3 on the sloshing natural frequency, damping ratio and sine wave transient response. As shown in Tables 1 - 3, significant difference is not found in the sloshing natural frequency, damping ratio and sine wave transient response between the 3-loop connected system and individual vessels with in-vessel structures. Showing the insignificant effect of the multi-surface connection on the sloshing characteristics.

3.3 3-loop connection test under in-vessel forced flow condition

To find the effect of the in-vessel forced flow on the sloshing characteristics, tests were carried out on the 3-loop connection system under the in-vessel forced flow condition.

Tables 1 - 3 show results of by tests on the sloshing natural frequency, damping ratio and sine wave transient response. The damping ratio with the in-vessel forced flow is found to be high as compared with that without fluid flow by the effect of the flow, as shown in Table 2. A slight decrease of the response wave height is found by the sine wave test under the in-vessel flow condition as compared with wave height without fluid flow, as shown in Table 3.

Change of sloshing characteristics is found between the 3-loop connection system with and without the in-vessel forced flow due to the effect of the forced flow. Namely, few difference is found in the 1st and 2nd order sloshing natural frequency between conditions with and without in-vessel forced flow, whereas the sloshing mode of the 3rd order frequency disappear when the forced flow is present in the vessels as shown in Fig. 3.

Fig. 3 Transfer function of reactor vessel

Table 1 Measured natural frequencies

		Unit: Hz											
Tested vessel	Exciting direction	Individual vessel without in-vessel structure			Individual vessel with in-vessel structure			3-loop model without flow			3-loop model with flow		
		1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Reactor vessel	①	0.85	1.46	1.85	0.78	1.38	1.55	0.78	1.39	1.55	0.78	1.37	1.68
	②	—	—	—	0.81	1.39	2.35	0.80	1.38	—	0.80	1.35	—
IHX vessel	①	1.13	1.93	2.44	1.05	1.60	2.01	1.05	1.59	—	1.05	1.58	—
	②	—	—	—	0.90	2.23	2.52	0.91	2.27	2.55	0.92	2.21	—

Note: ①direction (along the hot leg pipings)
②direction (normal to the hot leg pipings)

Table 2 Measured damping ratio

Unit: %				
Condition	Individual Vessel without in-vessel Structure	Individual Vessel with in-vessel Structure	3-loop Model without Flow	3-loop Model with Flow
Tested vessel				
Reactor vessel	0.05	0.50	0.48	1.31
IHX vessel	0.12	0.81	0.77	1.66

Table 3 Response wave height in the sine wave transient response test (Response of third input wave)

Unit: mm					
Tested vessel	Point of measure- ment	Individual vessel without flow	Individual vessel with flow	3-loop model without flow	3-loop model with flow
Reactor vessel	WRV07	82.1	59.3	60.2	59.1
	WRV03	-62.9	-53.0	-53.2	-49.2
IHX vessel	WAI04	80.4	43.2	43.1	42.8
	WAI02	-43.2	-46.4	-46.3	-42.9

3.4 Test on anti-sloshing devices

To investigate the effect of the anti-sloshing devices on the sloshing characteristics, a ring plate [3] shown in Fig.4 was mounted on the reactor vessel and tests were conducted with the 3-loop connection model with and without the forced fluid flow.

Tables 4 - 6 show results in the tests on sloshing natural frequency, damping ratio and sine wave transient response. From test results of the sloshing natural frequency shown in Table 4, the effect of anti-sloshing devices is demonstrated by a slight decrease of the sloshing natural frequency when the ring plate is mounted on the reactor vessel. The damping ratio is found to increase by about 1 to 1.5% under the influence of the anti-sloshing devices with and without in-vessel forced flow as compared with those without anti-sloshing devices, as shown in Table 5. The response wave height in the sine transient response test with the anti sloshing devices mounted is lower than those without the anti-sloshing devices as shown in Table 6, which demonstrates the effectiveness of the ring plate.

Fig. 4 Anti-sloshing device

Table 4 Sloshing natural frequency of reactor vessel
(Direction of excitation: ①)

		Unit: Hz					
		3-loop model, without fluid flow			3-loop model, with forced fluid flow		
		1st order	2nd order	3rd order	1st order	2nd order	3rd order
With anti-sloshing device	Test	0.78	1.39	1.55	0.78	1.37	1.68
	Analysis	0.78	1.37	—	—	—	—
Without anti-sloshing device	Test	0.76	1.34	1.53	0.76	1.33	1.50
	Analysis	0.73	1.33	—	—	—	—

* Analysis: Potential analysis

Table 5 Damping ratio of reactor vessel

	Unit: %	
	3-loop model, without fluid flow	3-loop model, with forced fluid flow
With anti-sloshing devices	0.48	1.31
Without anti- sloshing devices	1.43	2.83

Table 6 Effect of anti-sloshing devices in the sine transient wave response test
(Response wave height of reactor vessel, 3rd input wave)

		Unit: mm	
		3-loop model, without fluid flow	3-loop model, with forced fluid flow
With anti-sloshing devices	WRV07	60.2	59.1
	WRV03	-53.2	-49.2
Without anti-sloshing devices	WRV07	46.7	41.8
	WRV03	-35.8	-35.7

4. NUMERICAL ANALYSIS

4.1 Analytical method

Analytical studies were conducted by the 3-dimensional analytical code based on the potential flow theory in order to clear the sloshing characteristics of the top entry loop type reactor and to validate the analytical code. In the analytical model, the in-vessel structure and the anti-sloshing devices were simulated. The analysis was carried out with individual vessels since the effect of multi-surface connection is insignificant as stated in Paragraph 3.2. The values of damping ratio obtained in tests were used in the analysis.

4.2 Analytical results

4.2.1 Analytical results of sloshing natural frequency and sloshing mode

Table 4 presents results of the analysis of the sloshing natural frequency of reactor vessel by the analysis of the 3-dimensional analytical FEM code based on the potential flow theory, together with test results of individual vessels with in-vessel structure. The analytical results of the sloshing natural frequency are given in Table 4 for cases with the anti-sloshing devices (ring plate) mounted on the reactor vessel. A good agreement with test results is shown by analytical results of the sloshing natural frequency using the 3-dimensional analytical code based on the potential flow theory shown in Table 4, which demonstrates the capability of the analysis to evaluate the effects of in-vessel structures and the anti-sloshing devices. The analytical results also demonstrate that the sloshing natural frequency is decreased by the effects of the in-vessel structures and the anti-sloshing devices.

4.2.2 Analytical results of response wave height

Fig.5 shows results of the sine wave transient response of wave height of the reactor vessel by the 3-dimensional analytical code based on the potential flow theory and compares them with test results. Fig.6 shows analytical results of wave height of reactor vessel without the fluid flow with the anti-sloshing devices mounted on the reactor vessel, together with test results.

From the above results, a good agreement is demonstrated between the test results and the analytical results. The capability of the analysis in the sloshing response is also demonstrated concerning with the effect of in-vessel structures and anti-sloshing devices.

Fig. 5 Comparison between test results and analytical results of response wave height

Fig. 6 Comparison between test results and analytical results of response wave height with anti-sloshing device

5. DISCUSSION

5.1 Sloshing characteristics

(1) Sloshing natural frequency

The sloshing natural frequency is decreased by the effect of in-vessel structure as shown in Table 1. A good agreement with test results is shown by analytical results of the sloshing natural frequency by the 3-dimensional analytical code based on the potential flow theory shown in Table 4, which validates the analytical code. It is found by the analysis that the sloshing natural frequency decreases under the effect of in-vessel structures. The decrease of sloshing natural frequency by the effect of in-vessel structure is similar to the sloshing with co-axial cylinders, showing more decrease of the sloshing natural frequency as the proportion of in-vessel structure increases [5]. The decrease of the sloshing natural frequency is estimated to be caused by the increase in the additional mass by the in-vessel structure. With the in-vessel forced flow, the sloshing modes of higher order are disappear, as shown in Fig.3. The difficulty in the generation of sloshing modes of higher order agrees with results by a rectangular tank [6].

(2) Damping characteristics

The damping ratio increases under the effect of in-vessel structure as compared with those without in-vessel structure, as shown in Table 2, because the area in contact with the liquid increases, which, in turn, increases the friction at the boundary layer [7]. On the other hand, the difference in values of the damping ratio between the 3-loop connected system without fluid flow and individual vessels with in-vessel structure is insignificant, as shown in Table 2, suggesting little effect of multi-surface connection on the damping.

With the in-vessel forced flow, the damping ratio increases under the effect of the in-vessel flow as shown in Table 2. The disappeared sloshing mode of higher order and the increase of the damping ratio under the presence of the forced flow coincide with the results of a rectangular tank [6]. It has been known that the damping ratio under the sloshing varies depending upon the response wave height. Fig. 7 shows result of the damping ratio of the reactor vessel for the response wave height of individual vessel, without fluid flow. It is found that the damping ratio becomes larger as the response wave height increases, demonstrating the dependence of the damping on the wave height.

(3) Sloshing response

The response wave height decreases by the effect of in-vessel structure as compared with those without in-vessel structure. This decrease is believed to be caused by increased damping ratio due to the in-vessel structure and reduced mode participation factor of the sloshing response by the effect of the in-vessel structure [1]. No significant difference in the response wave height is found between the 3-loop connection system without fluid flow and individual vessels with in-vessel structure, demonstrating little effect of the multi-surface connection on the sloshing response.

It is confirmed that the analysis of individual vessels is sufficient for evaluation of the sloshing characteristics and the response wave height of the top entry loop type reactor since the multi-surface connection has little effect on them.

Fig.7 Relationship between response wave height and damping ratio (Individual reactor vessel, without fluid flow)

5.2 Effect of multi-surface connection

Little difference is shown in test results of the sloshing natural frequency, damping ratio and response wave height between the 3-loop connected system without fluid flow and individual vessels, as shown in Tables 1 - 3, proving that the effect of multi-surface connection on the sloshing characteristics is insignificant.

While the little effect of multi-surface connection on the sloshing characteristics was approved by the test, presence of the manometer vibration is supposed in the entire system. Therefore, the sine wave sweep test in a low frequency region (0.06 - 0.12 Hz) was conducted on the 3-loop connected model without fluid flow for the purpose of demonstrating the presence of manometer vibration in the entire system. Fig.8 shows results of tests on the natural frequency. As a result, it was confirmed that the manometer vibration at low frequencies of 0.08 - 0.09 Hz occurred between IHX vessels. The mode of manometer vibration between multi-surface connection was that the liquid in the IHX vessels vertically oscillated by in- and out-flow of the liquid through the reactor vessels and the inverted U-shaped pipings, while the liquid level in the reactor vessel did not vary significantly. When the in-vessel forced flow is present, on the other hand, no manometer vibration was observed between connected vessels, proving the dependence of the manometer vibration between vessels on the flow condition in the inverted U-shaped pipings.

The manometer vibration at the frequency of 0.08 - 0.09 Hz between vessels as observed without fluid flow is equivalent to the vibration at the frequency of about 0.03 Hz ($0.08 - 0.09 \text{ Hz} / \sqrt{8}$, period of 33 sec.) in

the actual system, according to the similarity rule. The natural frequency of the manometer vibration in the actual system is very low, therefore, no special attention for the aseismic design is required to be paid on the manometer vibration between vessels.

Fig. 8 Results of 3-loop connection model low frequency sine sweep

5.3 Effect of in-vessel forced flow

The damping ratio was determined by changing the flow rate in the reactor in order to investigate the effect of the in- vessel forced flow on the damping ratio. It was found that the damping ratio generally increases in proportion to the square of in-vessel flow rate.

To investigate the effect of the in-vessel forced flow on the sloshing response, the seismic wave test was conducted with varying rate of in-vessel flow. Results of the test are shown in Figs.9 and 10. Fig.9 shows change of the response wave height to the in-vessel flow rate, from which the response wave height is found to decrease with the increase of in-vessel flow rate. Fig.10 shows results of the Fourier spectrum analysis of the response wave height by the seismic waves test. It is found that the sloshing response of the 1st and 2nd order decrease and those of the 3rd order or higher hardly occur as the in-vessel flow rate increases.

Fig.9 Relationship between in-vessel forced flow and response wave height in seismic wave test

Fig.10 Fourier spectra of response wave height in the seismic wave test (S1 seismic wave excitation)

Fig.11 Relationship between the mounting position of anti-sloshing devices and damping ratio (Reactor vessel, without fluid flow)

5.4 Effect of anti-sloshing devices

The presence of anti-sloshing devices causes damping ratio to increase as shown in Table 5 and the response wave height to decrease as shown in Table 6 as compared with those without the anti-sloshing devices. The decrease of the response wave height under the presence of anti-sloshing devices is affected by the increased damping ratio as well as the effect of the anti-sloshing devices.

The damping ratio under the presence of the anti-sloshing devices is affected by the mounting height of the anti-sloshing devices (distance from the free liquid level to the anti-sloshing devices). Therefore, the damping ratio was determined by the free vibration test in which the mounting height of the anti-sloshing devices was varied in order to find the effect of mounting height of the structure. Results of the test are shown in Fig.11, from which the damping ratio is found to increase as the mounting position of the anti-sloshing devices approaches the free liquid level. With the anti-sloshing devices mounted near the free liquid level, decrease of the response wave height to the sloshing is expected by the effect of anti-sloshing devices itself and the increase of the damping ratio.

6. CONCLUSION

The authors conducted the vibration test using the 1/8 model of the top entry loop type reactor in order to investigate the sloshing characteristics of the reactor. The applicability of the analytical code to test results was also evaluated. Further investigation were made on the effect of ring plate mounted on the test model as a anti-sloshing device. As a result, conclusions are drawn as follows:

- (1) The sloshing natural frequency decreases and the damping ratio increases under the effect of in-vessel structure. The response wave height decreases under the effect of the in-vessel structure.
- (2) Generation of manometer vibration at low frequencies are confirmed between vessels. However the effect of the multi-surface connection on the sloshing characteristics is low.
- (3) The damping ratio increases and the sloshing mode of 3rd order or higher disappear under the effect of the in-vessel forced flow.
- (4) The effectiveness of ring plate for anti-sloshing device was evaluated. As a result, the ring plate was confirmed to be effective as a anti-sloshing device.
- (5) The 3-dimensional analytical code based on the potential flow theory is capable of evaluating the sloshing characteristics of top entry loop type reactor.

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