A study on non-linear sloshing of pool type LMFBR coolant

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1. Introduction

The pool type LMFBR contains a large amount of liquid sodium in the large reactor vessel. Therefore, sloshing becomes more important for the LMFBRs than for the LWR or loop type FBR.
An earthquake has frequency components (5 to 10 sec) corresponding to the natural period of liquid sodium sloshing contained in the pool type LMFBR. This means that the sloshing may occur when the pool type LMFBR is subjected to an earthquake. Also, the wave height of free surface during sloshing may rise significantly when the earthquake has a large amplitude in long period. In this case, the liquid surface will strike at the roof slab, which is the reactor vessel upper cover, producing a high impact pressure. To date, the sloshing behavior during an eathquake has been studied extensively [1] [2]. Most of the papers, however, are concerned with the linear sloshing. Few studies concern the phenomenon of nonlinear sloshing.
The authors carried out non linear sloshing experiments, to study the impact pressure occurring inside a reactor vessel.

2. Experiment

It is difficult to theoretically determine high impact pressure produced when the free surface of liquid in a tank strikes at the roof slab as the result of sloshing. On this problem, several experiments have been performed [3]. According to the results of those experiments, the impact pressure is proportional to 1.6~2.0 power of the free liquid impact velocity . However, in those experiments, neither a clear definition of conditions under which maximum impact pressure occurs nor an explanation of the propagation of impact pressure through the tank interior is given. In the present experiment, the relation between the impact velocity and the impact pressure was studied by varied excitation level. Also, the impact pressure propagating through the water was measured.

(1) Method of experiment

The test model is shown in the Fig. 1. This model is a boxlike vessel. The length and height of the model correspond approximately to one-third of the hot plenum of an actual reactor vessel. Water was used instead of liquid sodium. The lowest three sloshing natural periods of the model were 3.3 seconds. Since the primary natural period of

sloshing in an actual pool type LMBFR is 5.7 seconds, the ratio is 0.58.
The waves used for the test were resonant sine waves, Niigata earthquake, Hachinohe earthquake and Great Kanto earthquake which are typical examples of earthquakes having strong long period components.

(2) Results of experiment

Fig. 2 shows the impact pressure that occurred at the roof slab edge. After the maximum impact pressure occurs, the impact pressure does not increase even the exicitation continues.

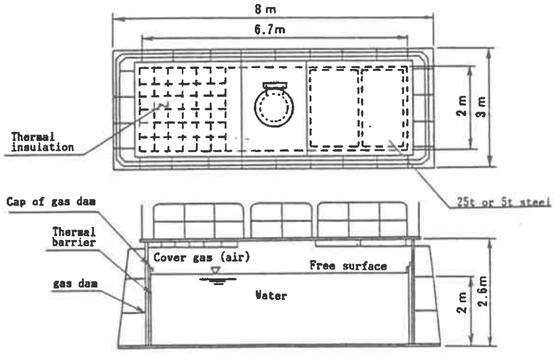

Fig 1 Schematic illustration of test equipment

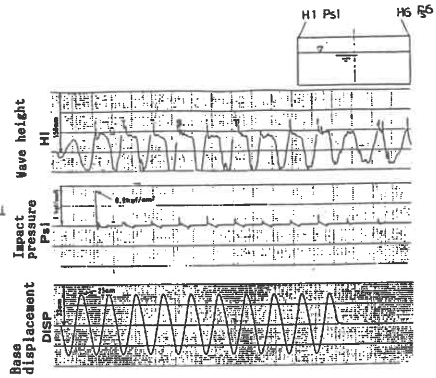

Fig 2 Oscillogram of impact pressure (T=3.3sec D=25cm^{0-P})

The free water surface after the maximum impact pressure occured is markedly disturbed due to the breaking of waves. Thus, conceivable reasons why the suceeding impact pressure becomes smaller than when the water surface strikes at the roof slab for the first time include: ① decrease of impact velocity of free water surface, ② change in effective mass of striking liquid, and ③ decrease of elastic modulus of liquid due to gas caught in the liquid. Supposing that the drop of impact pressure is ascribable to a decrease in impact velocity of free water surface (reason ①), it is possible that certain earthquake waves excite nonlinear sloshing after the breaking of waves, thereby increasing the impact pressure. In view of this, the relationship between impact velocity and impact pressure at the striking of water surface at different levels of sine wave excitation was studied. The experimental results are shown in Fig. 3(a) and (b). As shown, the impact velocities of the second and third waves are equal to or slightly higher than the impact velocity of the first wave at which the maximum impact pressure occurs. The impact pressures of the second and subsequent waves are evidently lower than the impact pressure of the first wave. Thus, the drop of impact pressure after the maximum impact pressure occured is considered ascribable not to reason ① , but to the change in effective mass of liquid and/or the decrease of elastic modulus of liquid.

Next, the relationship between impact velocity and impact pressure when the maximum impact pressure occured was studied. The results are shown in Fig. 4. The empirical formula released as a result of a study on liquid surface impact pressure occurring with an oil tank is also shown in Fig. 4. According to literature [3], this empirical formula was obtained in an excitation experiment in which the impact velocity of free liquid surface was in the range about 100 to 150 kine. The data shown in Fig. 4 was obtained by using a steel plate of 25 mm thickness and 5 mm thickness respectively, as the roof slab at which free liquid surface struck, together with a thermal insulator. When the roof slab is rigid (a steel plate of 25 mm thickness), the maximum im-

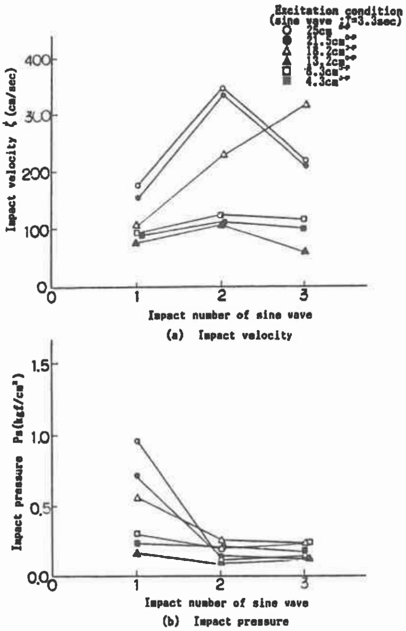

Fig 3 Relationship between impact pressure and impact velocity

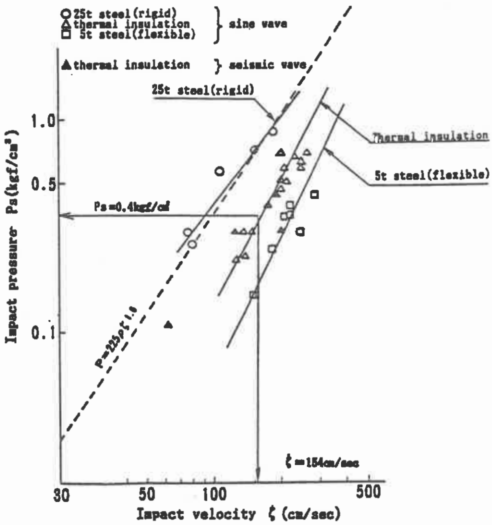

Fig 4 Relationship between impact pressure and impact velocity at the maximum impact pressure

pact pressure nearly corresponds to the value calculated by the empirical formula at the impact velocity around 200 kine.

Another study was performed on conditions under which maximum impact pressure would occur. In existing literature, it has been defined that the maximum impact pressure occurs when the first effective wave strikes at the roof slab. However, connorete conditions under which such maximum impact pressure would occur have not been shown. Fig. 5 shows the impact pressure of liquid surface obtained when a sine wave of 17 cm^{0-P} amplitude was applied. In this case, the maximum impact pressure occurred at the mid-point between the first and second sine waves. This suggests that under certain excitation conditions, the maximum impact pressure can occur some time after the first wave strikes at the roof slab. Fig. 6 shows the calculated free liquid wave heights and liquid surface impact pressures obtained by the empirical formula and those measured by varying the level of sine wave excitation. In Fig. 6, during excitation at 50 kine, the maximum impact pressure (○) occurs at the first wave of free liquid, while the impact pressure at the mid-point between the first and second waves (●) is lower. Conversely, during excitation at 30 kine, the impact pressure at that mid-point (●) becomes the maximum one. In this case, the pressure rise at the mid-point is due to the fact that the free liquid surface was not disturbed much because the first wave struck the roof slab only slightly, causing the effective striking at the mid-point between the first and second waves. On the other hand, in sine wave excitation at 50 kine, the first wave height of free liquid becomes nearly double the cover gas space height, causing marked disturbance in the liquid surface when the wave strikes at the roof slab.

From the above-mentioned, the striking of the first effective wave is considered to occur when the height of the free liquid surface becomes double the height of the cover gas space.

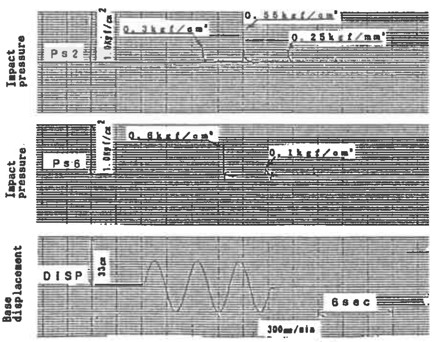

Fig 5 Oscillogram of impact pressure (T=3.3sec D=17cm^{0-P})

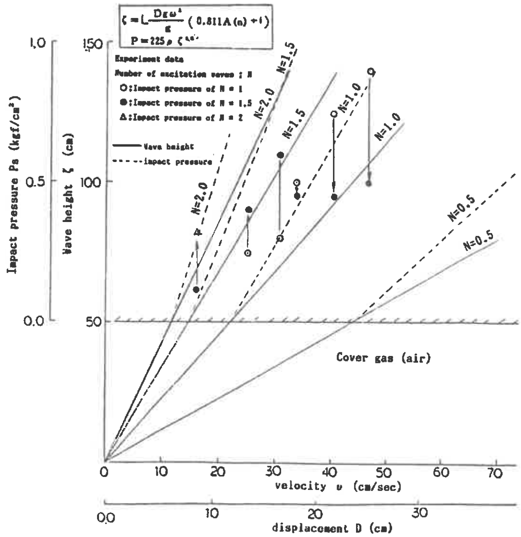

Fig 6 Relationship between excitation level and impact pressure

When the free liquid surface does not strike at the roof slab during sloshing, the dynamic pressure acting on the vessel is nearly equal to the head pressure of free liquid surface. However, when the free liquid surface strikes at the roof slab, linear calculation does not give the actual dynamic pressure. In the study, the distribution of dynamic pressure during nonlinear sloshing was studied by an experiment. Experimental results show that unlike in the linear sloshing, the maximum dynamic pressure at the wall occures due to the propagating impact pressure in the nonlinear sloshing.

3. Analysis

It was confirmed by an experiment that in the case of sine wave excitation, the maximum impact pressure occurs when the height of free liquid surface becomes about double the height of the cover gas space.

During excitation by an earthquake wave, the free liquid surface heaves at random, hence a calculation progarm is needed to estimate the height of free liquid wave. In the present analysis, the free liquid wave height during an earthquake was obtained by a linear sloshing program, and the time at which the maximum impact pressure occurs and the maximum impact pressure value were calculated.

Fig. 7 shows experimental data and calculated wave height when Niigata NS waves were applied to the water tank. From the calculated wave height, it is expected that the maximum impact pressure will occur at point C where the free liquid wave height nearly doubles. The impact pressure at this point is estimated to be 0.4 kgf/cm^2 from the calculated impact velocity and experimental data. On the other hand, the waves at points A and B strike at the roof slab only slightly, hence the impact pressure is expected to be small.

According to the experiment data, the maximum impact pressure occurs at the time of point C estimated by calculation, and the maximum pressure value almost coincides with the estimated value.

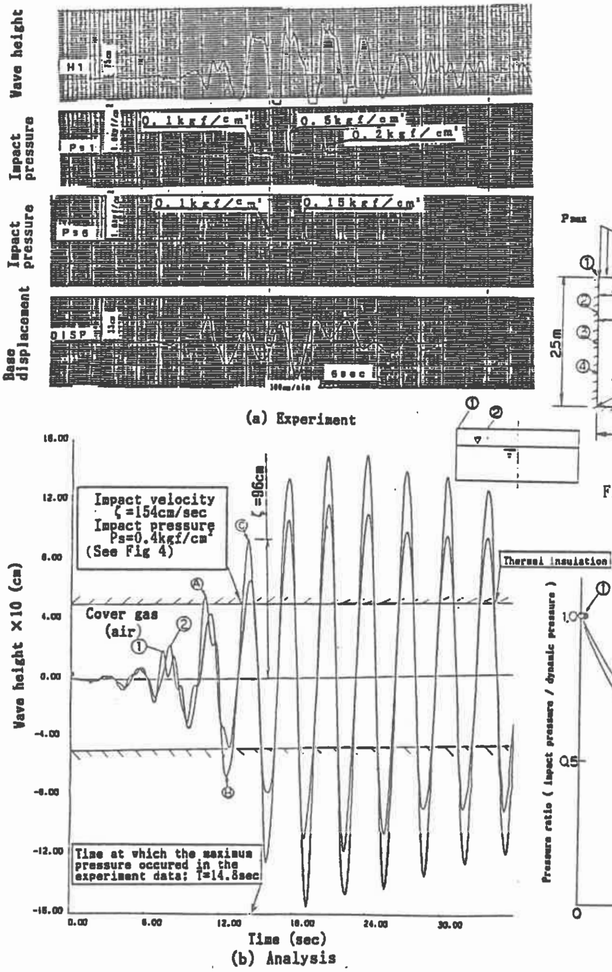

Fig 7 Comparison impact pressure between experiment and analysis

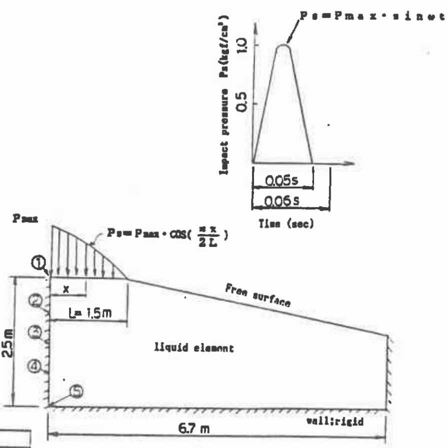

Fig 8 Analysis model of wave propagation

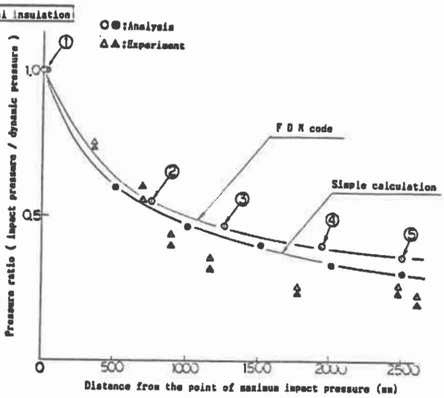

Fig 9 Comparison dynamic pressure between experiment and analysis

When the wave height during excitation by an earthquake wave can be estimated by linear sloshing calculation as shown above, it is possible to estimate the time at which the maximum impact pressure occurs and the maximum impact pressure value.

It was found by an experiment that the maximum pressure occuring on the thermal barrier of water tank during nonlinear sloshing is ascribable to the propagation of impact pressure. In the present analysis, the pressure distribution on the thermal barrier was estimated using an analytical program. Fig. 8 shows a calculation model using a finite difference method program. The impact pressure was applied to free liquid surface. From the experimental data, the distribution of liquid surface impact pressure was assumed to be a cos distribution. Also, the impact pressure was assumed to be a sine wave having a time interval of 50 ms. Fig. 9 shows the experimental data (△,▲) and calculated value of dynamic pressure on the thermal barrier. In this figure, the vertical axis represents the ratio of liquid surface impact pressure to dynamic pressure on the thermal barrier, and the horizontal axis represents the distance from the point of maximum impact pressure.
The calculated values almost coincide with actual values.

4. Structural Integrity Evaluation of Actual Plant

As an example of structural integrity evaluation of an actual plant of pool type LMFBR under a sloshing load, the buckling strength of thermal barrier subjected to an earthquake wave of 50 kine sloshing primary resonant wave analyzed.

The velocity at which the liquid sodium surface strikes at the roof slab during sloshing is about 190 kine. From experimental data, the maximum impact pressure occurring at this moment is estimated to be about 0.8 kgf/cm^2. In this case, the maximum impact pressure propagating to the thermal barrier, calculated by a theoretical formula for 3-dimensional wave propagation, is about 0.75 kgf/cm^2.

Fig. 10 shows the pressure distribution on the thermal barrier, obtained as shown above. The figure also shows the buckling load when a 30 mm thick thermal barrier was used. This buckling load was obtained by a buckling eigen value analysis on the assumption that the above-mentioned sloshing load distribution would act on the thermal barrier. The buckling mode is shown in Fig. 11.

From the above-mentioned, it was confirmed that a thermal barrier having a thickness of about 30 mm is sufficient to withstand sloshing loads.

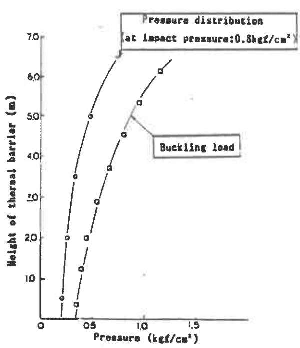

Fig 10 Pressure distribution on the thermal barrier

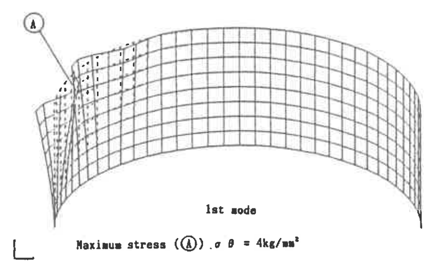

Fig 11 Buckling mode

5. Conclusion

(1) The maximum impact pressure occurs when the first effective wave strikes at the roof slab. There-after, the impact pressure drops irrespective of impact velocity.

(2) The first effective wave by which maximum impact pressure occurs refers to the case in which the height of free liquid surface becomes nearly double the height of cover gas space.

(3) It was confirmed that the impact pressure propagating to the thermal barrier can be estimated by a wave propagation analysis.

(4) Structural integrity evaluation of actual plant against sloshing load was confirmed

Reference

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[2] Y. W. Chang, et al; EPRI/CRIEPI Joint Program on Seismic Sloshing of LMR Reactors:Part II - Numerical Simulations, 9th SMIRT Conference (1987)

[3] O. Asai, et al; Proposals for the Earthquake-Proof Designs of Cylindrical Liquid Storage Tank with Fix ed Roof (II), JHPI Vol.17 No4 (1979)