Evaluation of Dynamic Loads Due to Bubble Oscillation Caused by S/RV Actuation

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ABSTRACT

An analysis code BUBBLE has been developed for the evaluation of the dynamic loads due to bubble oscillations in the pressure suppression pool of a BWR caused by safety-relief valve actuations. BUBBLE has been coupled with the analysis code ACERON which analyze the pressure field in the pool.

The characteristics of the dynamic loads due to bubble oscillations have been examined using BUBBLE/ACERON, and the applicability of BUBBLE/ACERON has been confirmed.

The dynamic load evaluation method based on BUBBLE/ACERON is expected to give consistent load evaluation methodology with that proposed by the authors for LOCA steam condensation loads.

BUBBLE/ACERON gives reasonable pressure distributions, and is expected to give reasonable load assessments.

1. Introduction

In a boiling water reactor, each safety-relief valve (S/RV) through which steam escapes into the pressure suppression pool where it condenses, automatically opens as soon as the pressure in the reactor pressure vessel (RPV) exceeds its own set pressure. When the valve actuates, high pressure non-condensable gas and steam are discharged in the suppression pool through a discharge line. Both of them may produce pressure oscillation which will cause vibrations in the submerged equipments and in the containment walls. However, by using a quencher as the discharge device, steam is expected to condense smoothly and dynamic loads due to steam condensation at the quencher holes seem to be negligible.

The pressurerized non-condensable gas expelled from the discharge line forms bubbles, which expand and propagate pressure disturbances through the suppression pool. The dynamics involved in the expanding bubbles result in pressure oscillations caused by expansion and contraction of the bubbles coupled with inertial effects imposed by the surrounding water. The dynamic load due to the bubble oscillations is still one of the problems of concern especially when the dominant frequency of the induced pressure oscillation is near or equal to that of the pool wall or a submerged equipment.

In the case of BWR Mark II containments, dynamic loads due to non-condensable gas bubble oscillations are usually assessed based on the DFFIR[1]. However, the evaluated loads seem to be very conservative in some cases. On the other hand, the authors proposed a method to evaluate the dynamic loads due to chugging or condensation oscillation[2],[3] which are assumed to occur in the case of a loss of coolant accident (LOCA). The dynamic phenomena caused by the bubble oscillations are very similar to those caused by chugging and condensation oscillation from the view point of the analytical model. Therefore, it is reasonable to evaluate the dynamic loads due to the bubble oscillations by a method similar to that used for chugging or condensation oscillation.

This paper proposes an analytical model for the evaluation of the dynamic loads due to the bubble oscillations caused by S/RV actuations. Characteristics of the dynamic loads have also been examined using the analytical model.

2. Analytical Model

Assuming a spherical bubble oscillation in infinite fluid, the following equations have been obtained.

$$\beta \frac{d^2\beta}{dt^2} + \frac{3}{2}\left(\frac{d\beta}{dt}\right)^2 + \frac{4\mu}{\rho_w R_0^2}\,\frac{1}{\beta}\frac{d\beta}{dt} = \frac{P_0}{\rho_w R_0^2}\left(\beta^{-3\kappa} - 1\right) \qquad (1)$$

$$\beta = R/R_0 \qquad (2)$$

Where R_0 is the equilibrium radius for the spherical bubble, P_0 the equilibrium pressure, κ the specific heat ratio of the bubble, ρ_w the water density, and μ the friction coefficient of water. The relationship between the bubble radius and pressure is given as

$$P = P_0\,\beta^{-3\kappa} \qquad (3)$$

Eqs. (1) ∿ (3) describe the bubble dynamics in infinite fluid, and the irrotational motion of the fluid has not been assumed in those equations.

On the other hand, an analysis code ACERON was developed by the authors[2] for calculating the pressure field excited by steam condensation in water. In the analysis code ACERON, irrotational motion of the pool fluid was assumed. That is,

$$(\nabla^2 - \frac{1}{c_w^2}\frac{\partial^2}{\partial t^2})\, p(\vec{r}, t) = f(\vec{r}, \vec{r}_i, t) \tag{4}$$

$$\partial p/\partial n = 0 \text{ at the boundary, } p = 0 \text{ at the free surface} \tag{5}$$

were solved in the pool. Where $p(\vec{r}, t)$ is the dynamic pressure, $f(\vec{r}, \vec{r}_i, t)$ the contribution of bubble collapse or oscillation at $\vec{r} = \vec{r}_i$, c_w the sonic velocity in water, and n the normal at the boundary. Function $f(\vec{r}, \vec{r}_i, t)$ can be related to the volumetric source as

$$f(\vec{r}, \vec{r}_i, t) = -4\pi\rho_w \frac{dm(t)}{dt}\,\delta(x-x_i)\delta(y-y_i)\delta(z-z_i) \quad , \tag{6}$$

where m(t) is the strength of the source and δ the Dirac's delta function.

If m(t) is given by

$$m(t) = R^2\frac{dR}{dt} = R_0^3\beta^2\frac{d\beta}{dt} \quad , \tag{7}$$

eqs. (1) ∿ (2) including rotational motion of the fluid and eqs. (4) ∿ (5) can be coupled by the hypothetical source given by eq. (7).

3. Characteristics of the Dynamic Loads

Analysis code BUBBLE has been developed to solve the eqs. (1) ∿ (2) and is coupled with ACERON by the eq. (7). In order to confirm the applicability of the analysis codes for the evaluation of the dynamic loads, 1/10 scale test results for ramshead devices performed by the authors, have been simulated. A simulation example is shown in Figure 1. The calculated dynamic pressure shows features similar to those observed. However, non-linear effects seem to be stronger in observed pressure than calculated pressure. Comparing the calculated pressure with observed pressure in Figure 1, the proposed analytical model is basically satisfactory for the evaluation of the dynamic loads due to the bubble oscillations.

Since the dynamic responses of the structures depend on the magnitudes and frequency components of the dynamic loads applied, the dominant frequency and the peak pressure amplitude of the dynamic pressure have been examined using the analytical model. Equilibrium bubble radius R_0 and initial bubble velocity $(dR/dt)_{t=0}$ have been chosen as parameters, since both of them have been expected to influence the peak pressure magnitude and the dominant frequency of the induced pressure.

Figure 2 shows the relationship between the dominant frequency of the induced pressure and the equilibrium bubble radius. If the small (linear) vibration of a spherical bubble in infinite water is assumed, the frequency of the pressure oscillation induced can be obtained as

$$f = \frac{1}{2\pi R_0}\sqrt{\frac{3\kappa P_0}{\rho_w}} \tag{8}$$

The frequencies estimated by eq. (8) are also shown in Figure 2. The dominant frequencies obtained by BUBBLE/ACERON show tendency similar to those estimated by eq. (8). The influences of the initial bubble velocity have also been examined. However, the effects seem to be negligible as far as the parameters examined. Therefore, the dominant frequencies are expected to depend mainly on the equilibrium bubble radius. Since the equilibrium bubble radius depends on individual discharge line volumes, the dominant frequency or the equilibrium radius expected under the normal conditions may be predicted using the correlation between the equilibrium radius and the discharge line volume.

Figure 3 shows the influence of the initial bubble velocity and the equilibrium bubble radius on the peak pressure amplitude. The peak pressure amplitude increases as the equilibrium bubble radius or the initial bubble velocity magnitude increases. Since the equilibrium bubble radius is related to the discharge line volume, the dependence of the peak pressure amplitude on the equilibrium bubble radius agrees with the reported observations[1]. On the other hand, what is related to the initial bubble velocity is not so clear as in the case of the equilibrium bubble radius.

Figure 4 shows the influence of the initial bubble velocity on the peak pressure amplitude. The tendency shown in this figure is similar to the relationship between the steam pressure (reactor pressure) and peak pressure amplitude observed in 1/10 scale tests performed by the authors. In the 1/10 scale tests, the normalized peak pressure amplitude increased almost in proportion to an increase in the normalized steam pressure (reactor pressure). Therefore, the correlation may be obtained between the reactor pressure and the initial bubble velocity.

4. On the Dynamic Loads Induced in BWR Mark-II Containments

In order to obtain the optimum energy transfer and steam condensation, quenchers are used as discharge devices. However, the dynamic loads due to non-condensable gas vibrations in water are still the problems of concern, even though quenchers are employed. In order to confirm the integrity of the primary containment vessel, in-plant tests have been performed and part of the obtained results have been reported by Olivieri et al.[5]

The dominant dynamic loads observed seem to be classified into two categories. One type is represented by damping pressure oscillations. The other has a rather complex portion before damping pressure oscillations. This complex portion is caused by the non-condensable gas discharge process, where the non-condensable gas has begun to expand into the water. These two categories have been simulated by BUBBLE/ACERON and are shown in Figure 5 for a representative Mark-II containment. In the case of type II shown in this figure, a few more modifications seem to be necessary in order to simulate the observed pressure oscillation precisely. However, the characteristics of the dynamic loads are expected to be well simulated.

Bedrosian et al. proposed pressure distributions based on Caorso in-plant test and their acoustic methodology[4], which were different from those proposed by DFFIR[1]. Figure 6 shows the vertical pressure distribution on the outer wall of the containment obtained by BUBBLE/ACERON. For comparison purposes, the distributions proposed by Bedrosian et al. and by DFFIR are also shown in this figure. The vertical distribution proposed by Bedrosian et al. is based on the in-plant test data. The distribution obtained by BUBBLE/ACERON is in good agreement with that reported by Bedrosian et al., which shows that BUBBLE/ACERON can produce a reasonable vertical pressure distribution. Comparing the calculated distribution with that proposed by DFFIR, the resultant dynamic loads are expected to be reduced markedly by using BUBBLE/ACERON.

Figure 7 shows the peripheral pressure distributions obtained by BUBBLE/ACERON and proposed by DFFIR in the case of single valve actuation. The calculated distribution agrees with that by DFFIR. Therefore, it seems to be reasonable to use the proposed methodology by DFFIR for multiple valve actuations, that is, to evaluate the peak pressure amplitude using SRSS method based on the proposed pressure distribution for the case of single valve actuation.

The dynamic loads caused by the bubble oscillations are expected to depend on many conditions such as the set pressure of the actuated S/RV, discharge pipe volume, temperature in the discharge line and so on. These conditions may differ from one S/RV to another and from one actuation to another. In these conditions, set pressure and discharge line volume can be related to the equilibrium bubble radius and initial bubble velocity as mentioned. However, the other conditions such as temperature in the discharge line and the valve opening time cannot be given a priori. In the case of a first actuation of single valve under the normal conditions, the induced dynamic load can be assessed in rather deterministic way based on the correlations between the valve actuation and calculation conditions, since the valve opening time has no significant effects on the resultant loads if it opens fully within a certain time. In the case of subsequent actuations, the deviations both in the magnitude and the dominant frequency of the load caused by undetermined parameters can be assessed based on the statistical analyses of the data if enough data can be obtained.

If the dynamic loads are defined to envelope the representative loads observed, in frequency domain, for a certain containment using BUBBLE/ACERON, the loads for any other containment can be assessed by using BUBBLE/ACERON. The dynamic load evaluation process above mentioned is now still under development by the authors.

Since the dynamic load evaluation method, based on BUBBLE/ACERON, is similar to that proposed by the authors for the dynamic loads due to chugging and condensation oscillation, the dynamic loads due to bubble oscillations caused by S/RV actuations can be evaluated in a consistent manner with those due to chugging and condensation oscillation by using BUBBLE/ACERON.

5. Conclusions

The analysis code BUBBLE has been developed for evaluating the dynamic loads induced by the bubble oscillations in water and the characteristics of the dynamic loads have been examined by using BUBBLE/ACERON. Obtained concluding remarks are as follows.

(1) The applicability of BUBBLE/ACERON has been confirmed for the evaluation of the dynamic loads due to bubble oscillations caused by S/RV actuations, since the characteristics of the calculated loads show the features similar to those observed.

(2) Non-linear effects seem to be insignificant in the bubble oscillations.

(3) The dynamic load evaluation method for S/RV actuations based on BUBBLE/ACERON is expected to give a consistent load evaluation methodology with that for the steam condensation loads.

(4) BUBBLE/ACERON gives reasonable pressure distributions and is expected to give reasonable load assessments.

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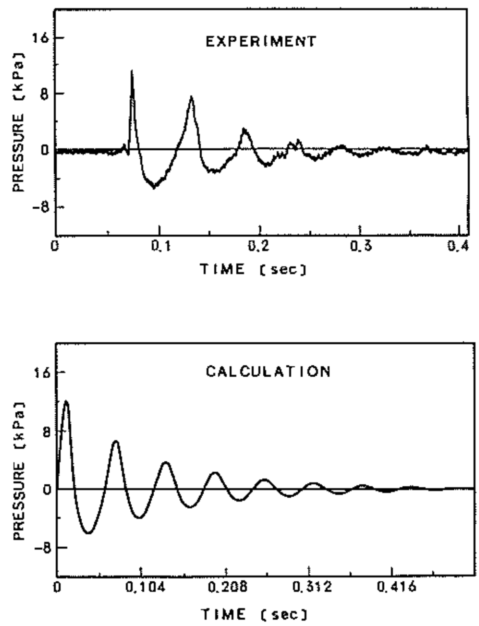


Fig. 1 Comparison of 1/10 Scale Test Pressure Time History with Calculated Values

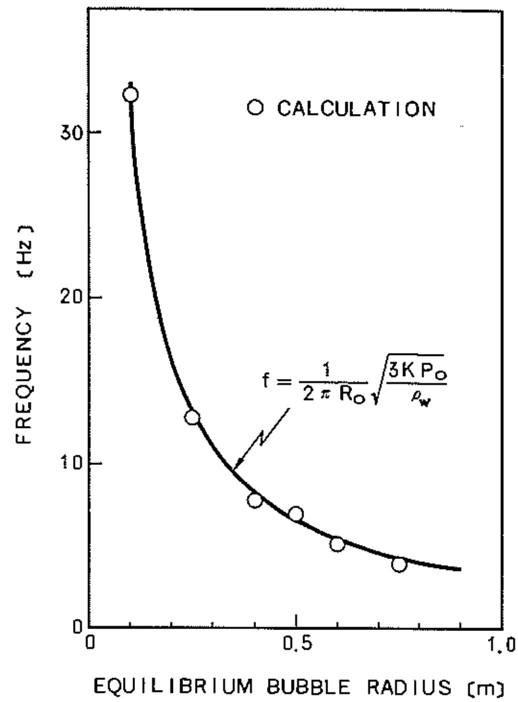


Fig. 2 Influence of Equilibrium Bubble Radius on Bubble Oscillation Frequency

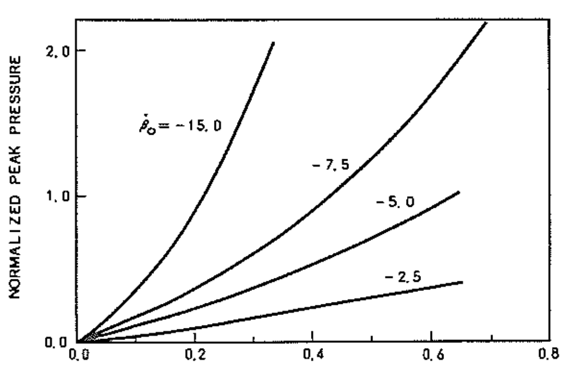


Fig. 3 Influence of Equilibrium Bubble Radius and Initial Bubble Velocity on Peak Pressure Amplitude

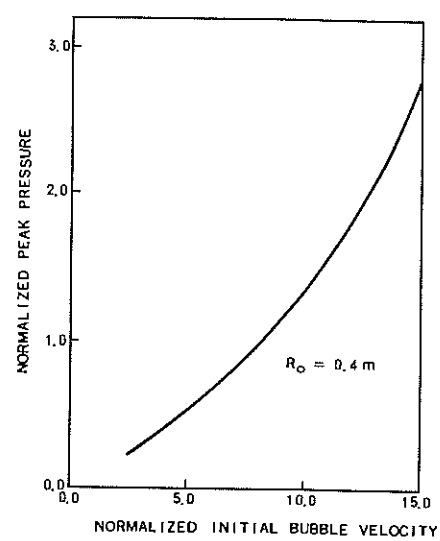


Fig. 4 Influence of Initial Bubble Velocity on Peak Pressure Amplitude

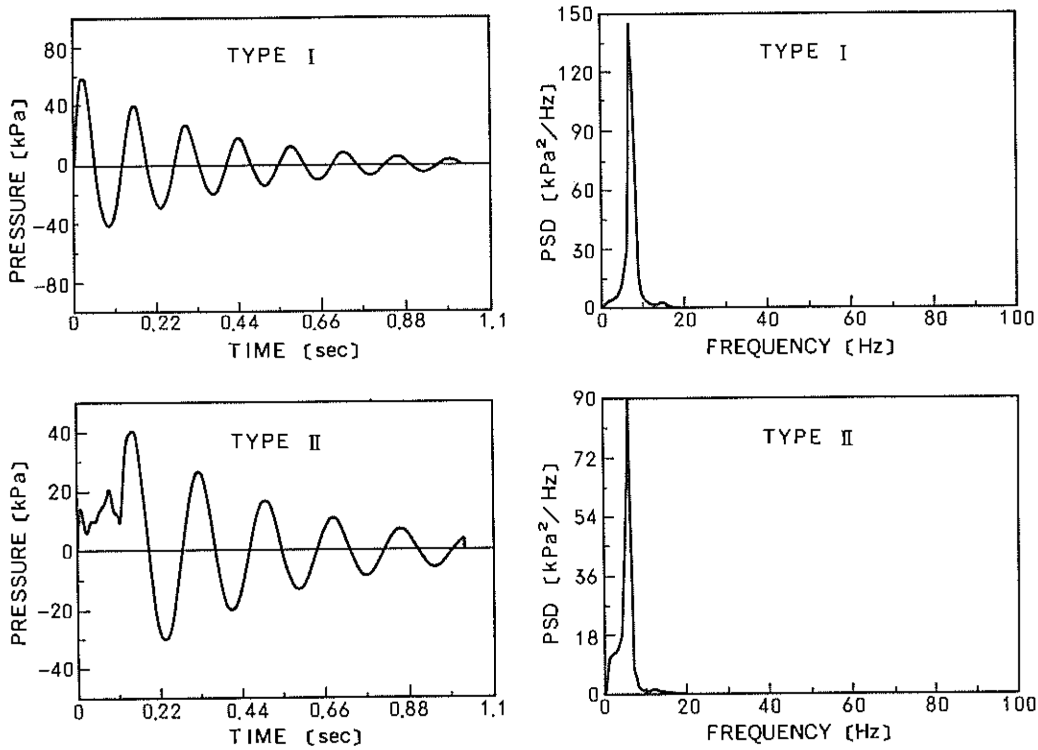
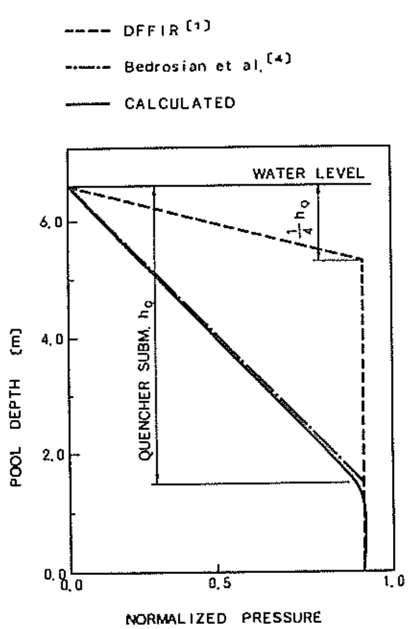


Fig. 5 Simulation Example for Two Types of Pressure Time Histories



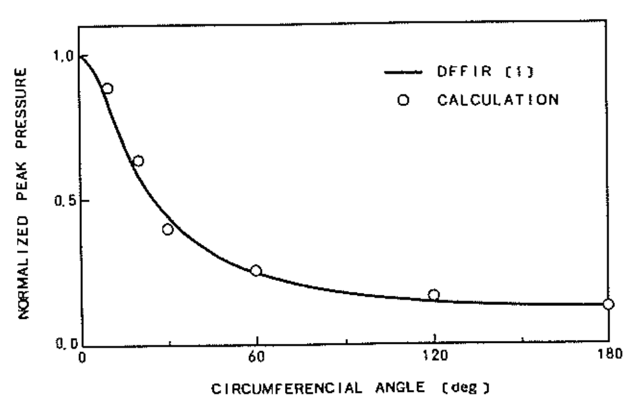


Fig. 7 Circumferential Pressure Distributions

Fig. 6 Vertical Pressure Distribution