Damping and Peak Period Shortening of a Water Hammer in Collapse of a Cooling Cavity*

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This paper presents some waveform analyses of the recorded pressure fluctuation in a water hammer due to collapse of a cooling cavity and the estimated velocity of the liquid column in collision with the blind end of a pipe. Real damping and peak period shortening, whose effects are similar in appearance on a graph of the change with time, are separated from each other by drawing graphs of the change with cycle number. The discussion on the damping is generalized using logarithmic decrements. It is proved that the air in the cavity strengthens the damping, the strengthening is greater earlier in the water hammer cycle, and the peak period shortening takes place rapidly not later than between the 2nd and the 3rd peaks in the case where the initial air concentration is over 30%, and is almost completed within this interval. In addition, considering the minor fluctuation in pressure bottoms, physical mechanisms of the damping and the peak period shortening are discussed.

Key Words: Water Hammer, Cooling Cavity Collapse, Damping, Peak Period Shortening, Waveform Analysis, Logarithmic Decrement, Air Concentration, Minor Fluctuation

1. Introduction

In a closed pipe forming a cooling cavity⁽¹⁾⁻⁽³⁾ because of the contraction of hot liquid upon cooling, rapid opening of a valve at an end of the pipe causes line pressure or atmospheric pressure to suddenly collapse the cavity, whose pressure has been reduced nearly to the saturation vapor pressure, and this gives rise to an unexpected water hammer^{(1),(4),(5)}, presenting danger. The above phenomena must be investigated not only as the cause of plant accidents but also to devise preventive measures against secondary accidents related to large earthquakes.

In our previous paper⁽⁴⁾, a water hammer in which a cooling cavity formed in a blind end of a short pipe collapsed was modeled using the rigid column theory

as shown in Fig.1, and a model experiment was performed employing an idealized system.

It is verified that the maximum pressure rise reaches an unusual magnitude of more than ten times the impression pressure difference. The values of the above maximum pressure rises are quantitatively discussed using new estimation formulas conforming with essential features of the phenomenon.

In this study, we discussed the damping and peak period shortening of the above water hammer after the generation of the maximum pressure rise as the first peak of pressure fluctuation, based on experimental data. Though the previous paper deals with the phenomenon before the first collision of the liquid column with the blind end of the pipe, the focus of this

Fig. 1 Rigid column model for the collapse of a cooling cavity

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study is the phenomenon after the first collision.

In the fluid transients relating to both gas and liquid phases, the damping and peak period shortening have been ignored. Nevertheless, they are important subjects to understand and elucidate, because of the coupling or interaction of plural two-phase systems in the response analyses of bubble train systems^{(3),(5)}, complex systems and large-scale plants, and also because the damping and peak period shortening of transients influence solutions in the numerical analysis of steady pulsation two-phase flows by means of time-marching-like methods.

Accordingly the purposes of the present paper as the first report are to analyze the waveforms of the pressure fluctuation experimented with in the previous paper and the collision velocity of the liquid column estimated from the above pressure fluctuation, to grasp the actual damping and peak period shortening in the presence of a cavity or bubble, to discuss their physical mechanisms, and to obtain some interpretations and views of useful for the modeling and simulation that will be reported in the following papers.

2. Outline of Experiment

We present an outline of the experiment in our previous paper⁽⁴⁾, as the following section 2.

2.1 Apparatus

A schematic of the apparatus is shown in Fig. 2. The closed pipe used in the experiment is supported on a rack set at a slope of 1/50, with foam polystyrol pieces for heat insulation. The closed pipe is 20 mm in inside diameter, 5 mm in wall thickness, 1 m in length and made of transparent acrylic. One end terminates with a ball valve and the other is a blind end. By employing a ball valve with the same orifice diameter as the pipe, 20 mm, valve loss in full admission can be neglected. The end plate of the pipe blind is equipped with a K-type sheath thermocouple 0.5 mm in diame-

Fig. 2 Experimental apparatus

ter and 500 mm in length and a temperature-compensated pressure transducer. Outputs of both sensors are recorded using a pen recorder, together with the output of another thermocouple for room temperature measurement.

2.2 Method

After forming a cooling cavity and measuring the cavity fraction in the thermal equilibrium state (refer to the previous paper⁽²⁾), the ball valve was quickly opened and the pressure fluctuation at the closed end (the blind end) was recorded using an electromagnetic oscillograph.

2.3 Results

The initial conditions in a series of present experiments were 5 ± 2 kPa pressure, $\phi (=l/L) = 2.2 \pm 0.1\%$ cavity fraction and $47 \pm 24\%$ air concentration (partial pressure ratio P_{air}/P standing for mol concentration). The final conditions were atmospheric pressure 101.3 kPa and 97.5% air concentration. For the impression pressure difference of 96 ± 2 kPa, the first peak pressure reached 912 ± 77 kPa.

Figure 3 shows an example of a chart recorded by the electromagnetic oscillograph. The pressure fluctuation is characterized by taking the maximum at the first peak, and 23 ± 3 ms (44 ± 6 Hz) as the period between 1st and 2nd peaks, and is damped within about 0.2 - 0.3 s.

Surprisingly, the maximum surge pressure reached 992 kPa (9.8 kgf/cm^2). The maximum pressure rise of 989 kPa is 10.1 times the impression pressure difference (96 ± 2 kPa).

3. Waveform Analysis

3.1 Approach

Because the water hammer treated in this study has the perfect stationary state as both initial and final conditions, it is the most suitable object for discussions of damping (i.e., energy dissipation), in the capacity of the pure transient free from consideration

Fig. 3 An example chart of the electromagnetic oscillograph

of the energy inflow from steady flows.

The volume of the cavity and the air concentration in the cavity are to be considered as the significant factors which influence the damping and peak period shortening of pressure fluctuation in the water hammer due to the collapse of the cavity itself.

The volume of the cavity is normalized by the volume in the pipe and dealt with in the form of cavity fraction. In our experiment, the initial cavity fractions have almost the same value (within $\pm 5\%$) in all data, as described in section 2.3. The final cavity fractions naturally have a positive correlation with the initial air concentration (the figure is omitted).

Consequently in this paper, the air concentration results in the principal parameter of significance. Fortunately, the initial air concentrations measured in our experiment are scattered in a suitable range (22–57%), and are hence satisfactory for the principal parameter.

Furthermore, the experimental values of the impression pressure difference (=atmospheric pressure as the final pressure—the initial pressure; see section 2.3) and the estimated values of the first collision velocity, $w_{\text{coll}}(1)$, (See section 3.5) are almost the same for each datum (within $\pm 2\%$, $\pm 7\%$ respectively); hence the only experimental parameter of significance is the initial air concentration.

Accordingly in section 3, dividing all experimental data into 5 groups with initial air concentration as the principal parameter, waveform analyses of the measured pressure fluctuation and the estimated collision velocity are performed with regard to their damping and peak period shortening.

3.2 Damping of pressure overshoot

Pressure overshoots are the differences between the peak values in a transient pressure fluctuation and the final value (atmospheric pressure). In order to observe the damping, we normalize them by the first overshoot (the maximum overshoot) as expressed in Eq. (1).

$$\Psi_i = [P_{pk}(i) - P_{\infty}] / [P_{pk}(1) - P_{\infty}] \quad (1)$$

Figure 4 shows the change of the normalized pressure overshoot, Ψ , with time. The time axis as abscissa is made dimensionless, using the peak period between the 1st and 2nd peaks as a standard time. Because the 1st peak is exactly at the half-period ($t^*=0.5$) of the motion of the liquid column, the dimensionless time of the 2nd peak is always $t^*=1.5$. The dimensionless times at and after the 3rd peak are obtained through the sequential integration of each dimensionless peak period thereafter (See section 3.3).

By comparison of the changes of Ψ 's before about $t^*=4$, while the damping shows the gentle and approx-

Fig. 4 The change with dimensionless time in the normalized overshoot of pressure

imately linear gradient in the 20% level of the low initial air concentration, when the initial air concentration is higher than the above level, the damping increases as each curve becomes so concave that bending points are conspicuous. However, beyond $t^*=5$, the initial air concentration is not observed to have much effect.

Particularly, the fixed point comparison of Ψ 's can be performed by observing the values of the 2nd peak, which is fixed at $t^*=1.5$ by definition. Comparing the values of this point with $\Psi=0.6$ as a standard, we find that these values tend to decrease with increasing initial air concentration. In other words, it is found that the damping tends to increase with increasing initial air concentration. Consequently, it is assumed that the air has the effect of increasing the damping.

However, Fig. 4 shows not only the pure damping but also that with the shortening of peak period admixed, so it is difficult to distinguish between the two effects, which are similar in appearance in terms of the damping and convergency. Therefore it is necessary to investigate the damping and the peak period shortening separately as originally different phenomena.

3.3 Shortening of pressure peak period

To begin with, we consider the shortening of peak period of pressure fluctuation, as shown in Fig. 5. Taking the peak number as the abscissa, we discuss the period in terms of cycle number. Accordingly, peak periods are plotted midway between the

Fig. 5 The change with cycle number in the peak period of pressure

graduations of the abscissa, or peak number.

Let us compare the peak periods normalized using the peak period between the 1st and 2nd peaks (the raw values of all data had no dependency on the initial air concentration) as the standard. At the 20% level of the low initial air concentration, the shortening is almost reduction by half, to the extent of 0.5 - 0.6 finally, and is slow in convergence.

In the range of 35-60% of the initial air concentration, the shortening rapidly reaches 0.7 - 0.8 midway between the 2nd and the 3rd peaks, as the plots between the 2nd and the 3rd peaks are conspicuous for bending points. After that the shortening becomes slight and gentle, and finally the shortening reaches 0.65 - 0.75. The values of the bending point between the 2nd and 3rd peaks and the final values tend to remain higher for higher initial air concentration.

From the above comparison, we find that when the initial air concentration is over 30%, the shortening of peak period occurs rapidly not later than between the 2nd and the 3rd peaks, and is almost completed during this interval. The final shortening has a tendency to retain narrower breadth, the higher the initial air concentration.

3.4 Logarithmic decrement of pressure overshoot

The discussion of damping can be generalized by using the logarithmic decrement. This value, as expressed by the following equation,

$$\delta = \ln(\Psi_i / \Psi_{i+1}), \quad (2)$$

is defined in the interval between two neighboring

Fig. 6 The change with cycle number in the logarithmic decrement of pressure overshoot

peak numbers, so the graph naturally employs the peak number for the abscissa and displays physically not the change with time but the change with cycle number. These graphs are shown in Fig. 6. Such an employment of the peak number for the abscissa in succession to section 3.3 has made it possible to separate the superficial damping in Fig. 4 into the peak period shortening in Fig. 5 and the pure damping in Fig. 6, as pointed out in the closing of section 3.2.

In the 20% level of the low initial air concentration, $\delta \approx 0.4$, that is almost constant (horizontal) or increasing slightly (a slight rightward ascent) for the cycle number. At 35 - 41% of the initial air concentration, it changes as $\delta = 0.55 \rightarrow 0.35$. At 42 - 46% of the initial air concentration, it also changes as $\delta = 0.55 \rightarrow 0.25$, and the gradient of rightward descent declines a little more than in the case of 35 - 41%. At 47 - 49% of the initial air concentration, there is a change of $\delta = 0.5 \rightarrow 0.3$, as well as a rightward descent gradient. At the 50% level of the initial air concentration, there is a sharp rightward descent as $\delta = 0.6 \rightarrow 0.2$.

Summarizing the change of δ with the initial air concentration as a parameter, while it is almost constant at the 20% level of the low initial air concentration, as the initial air concentration increases, δ , and therefore damping, tends to be higher earlier in the water hammer cycle, and to be lower for larger cycle numbers. Judging from these facts, it is considered that the air strengthens the damping in pressure fluctuation and such an action is stronger earlier in the water hammer cycle.

3.5 Reynolds' number of collision velocity

It is inferred that each pressure peak discussed up to section 3.4 is generated by the cyclic collision of the liquid column with the closed end of the pipe. Then, regarding the difference between each pressure peak value and the just-before=bottom value as the pressure rises at each peak, and calculating it using the inverse Joukowski formula, the collision velocity just before the generation of each pressure peak (the liquid column velocity peak), can be evaluated as follows.

$$w_{cll} = \Delta w_{cll} = \Delta P_{cll} / \rho a \quad (3)$$

where ρ : density 998 kg/m³, a : sonic velocity 700 m/s⁽⁴⁾.

Furthermore, using this value and obtaining the Reynolds' number at each collision velocity (peak Reynolds' number), as follows, the flow condition and the pipe friction can be estimated.

$$Re_{cll} = D \cdot w_{cll} / \nu \quad (4)$$

where D : diameter of pipe 0.02 m, ν : coefficient of kinematic viscosity 1×10^{-6} m²/s.

Both values are essentially identical, so they are shown in the same Fig. 7.

The scale graduations of Reynolds' number in the ordinate are not logarithmic but regular in order to make the proportion of the turbulent flow intelligible. Each hatched belt in Fig. 7 indicates the transition zone ($2\,300 < Re_{cll} < 5\,000$), and the pairs of arrows indicate the ranges of each data curve intersecting the

upper and lower sides of the transition zone.

Figure 7 shows that the velocity fluctuation of the liquid column is also as intense as the pressure fluctuation and that the flow is mainly in the full turbulent zone, at the earlier stage in the water hammer cycle, when the damping is strengthened by the air as pointed out in section 3.4. (From this finding, it is also confirmed that the approximation of the liquid column by a rigid column used in the previous analysis is satisfactory.) Consequently, its damping can be estimated mainly by turbulent pipe friction.

In contrast, because the previous analysis⁽⁴⁾ tells us that the pipe friction term has no effect at least under the positive flow condition (the phase when the liquid column moves toward the closed end of the pipe and comes into collision with it), it follows that in fact mechanisms other than the pipe friction contribute to the damping.

Furthermore, the disposition of the twin arrows in Fig. 7 indicates that the damping is slower, the lower the initial air concentration, and that the damping is faster, the higher the initial air concentration. As for the data in the present paper, because the values of the collision velocity at the 1st peak, which is the starting point of each data curve, are all very similar, it is evident that the causes by which the damping of the collision velocity is strengthened depending on the air in the above way are not such flow conditions as the laminar/turbulent and the pipe friction.

Accordingly, there are undoubtedly some mechanisms other than pipe friction in which the air strengthens the damping.

3.6 Logarithmic decrement of collision velocity

With regard to the collision velocity, in the same manner as in section 3.4, its logarithmic decrement, δ_w , is evaluated and shown in Fig. 8. Similarly to δ in Fig. 6, it remains almost constant (horizontal) as $\delta_w = 0.3 - 0.4$ at the 20% level of the low initial air concentration. As the initial air concentration increases, δ_w tends to be larger earlier in the water hammer cycle, and to be smaller, the larger the cycle number. Accordingly, with regard to the collision velocity, that is, the velocity peak of the liquid column, likewise the pressure fluctuation in section 3.4, it is considered that the air strengthens the damping in the velocity fluctuation and such an action is stronger earlier in the water hammer cycle.

3.7 Minor fluctuation of bottom pressure

Figure 9 shows an enlargement of part of Fig. 3 showing the waveform of minor fluctuations that were observed in the pressure bottoms after the 1st and before the 3rd - 4th peaks for all the initial air concentrations.

The features of such minor fluctuations were, at

Fig. 7 The change with cycle number in the Reynolds' number of collision velocity

Fig. 8 The change with cycle number in the logarithmic decrement of collision velocity

Fig. 9 A magnified example of the minor fluctuation of bottom pressure

the first bottom where they were especially noticeable, 24 ± 10 kPa inception pressure, 14 ± 7 kPa average pressure, 21 ± 5 kPa (peak to peak) maximum amplitude (about 22% of the impression pressure difference), and 1.8 ± 0.2 ms period (nearly 560 ± 60 Hz frequency). The upper limit of the occurrence was 30 ± 7 kPa during the transients reducing the pressure rapidly for the bottom just after the 2nd-3rd peak.

560 ± 60 Hz corresponds to the natural frequency of a bubble with the diameter of 3.7 ± 0.4 mm under the above average pressure. However, the cavity fraction of a bubble with the diameter within these bounds is of the order of 0.01% and one-tenth as small as 0.1%, the final cavity fraction. Therefore, judging from this fact, and additionally considering that the pressure bottom is in the phase when the cavity volume is maximum, such phenomena of the minor pressure fluctuation suggest the existence of no few

bubbles which are of uniform diameter within the bounds noted above. Furthermore, from this suggestion, it is surmised that the cavity is disrupted into a crowd of bubbles with uniform diameter within the bounds noted above under the pressure bottoms after the 1st and before the 3rd - 4th peaks.

Moreover, noting the inception point, it is found that the pressure response curve under the steep pressure reduction has, suddenly at the inception pressure, jumped as high as the maximum amplitude noted above. Remembering that the pressure in the cavity is the sum of the steam pressure and the partial pressure of air, and because it is difficult to postulate the sudden increase of the steam pressure at the pressure bottom in the phase of pressure reduction and cooling, it can be considered that the reason for such a sudden increase of pressure response must be the sudden increase of the partial pressure of air, that is to say, the abrupt desorption of the dissolved air in the liquid column into the cavity. Incidentally, since it is considered that the average values of bottom pressures were not affected by the minor pressure fluctuations, such an abrupt desorption of the dissolved air is interpreted as having been completed within the short interval from the inception pressure to the average pressure of bottoms.

4. Discussion

4.1 Mechanism by which air strengthens damping

Summarizing the closing remarks in sections 3.4 - 3.6 on the damping, we can say that there are some mechanisms other than pipe friction in which the air strengthens the damping, and that the damping is strengthened more earlier in the water hammer cycle.

Then, taking note of the fact that the fluctuating range of pressure, that is, the pressure difference between each peak and its just-before-bottom (and thus collision velocity, also), is larger earlier in the water hammer cycle, we can propose the pressure rise and fall between peaks and bottoms, namely the compression/expansion of the air, as the mechanism of the damping strengthened by the air.

As a concrete mechanism, it is assumed that, in the liquid column collapsing the cavity, the heat dissipates from the air in the cavity with temperature up to the surrounding liquid and pipe wall of ordinary temperature, and that the heat dissipation due to the temperature difference brings about the energy loss. Such heat dissipation will waste the energy that has been transformed from the kinetic energy of the liquid column before the collision, through the compression work of the air in the cavity, into the form of peak pressure once in store and must be returned again to

the liquid column. Heat absorption in the expansion phase will also waste the energy that has been transformed into the form of bottom pressure in store and must be returned again to the liquid column. Consequently, it is considered that the heat transfer between the air undergoing repeated compression/expansion in the cavity and the surroundings suppresses the pressure fluctuation as it clips those peaks and bottoms, and strengthens the damping of the water hammer with the compression/expansion of the air.

Another considerable mechanism is transient dissolution/desorption of the air. First, in the pressure peak, the transient dissolution of the air in the cavity into the liquid column will restrain the rise of peak pressure. In the pressure bottom, the transient desorption of the dissolved air in the liquid column into the cavity as described in section 3.7 will also restrain the fall of bottom pressure. Consequently, it is considered that transient dissolution/desorption of the air restrains the pressure fluctuation sandwiched between the falling peaks and the rising bottoms, and strengthens the damping of the water hammer with them.

4.2 Mechanism of peak period shortening

Generally speaking, the cause of the change in fluctuation period is often the characteristic change in the inertia element or restoration element in a system. In the present system (Fig. 1), while the mass of the liquid column of the inertia element is regarded as constant, the increase of the partial pressure of the air in the cavity which is regarded as an air spring of the restoration element, that is, the rise of the air concentration, will harden such an air spring and bring about the shortening of peak period.

Then, reading the closing remarks of section 3.3 while substituting the hardening of air spring for the shortening of peak period, we find that the rapid hardening of the air spring, namely, the rise of air concentration, occurs during the 1st - 3rd peaks in the case where its initial concentration is over 30% and has been almost completed within this interval.

However, it is impossible for the rise of air concentration to be almost completed within the 1st - 3rd peaks because of the still intense fluctuation. Accordingly, another mechanism causing the rise of air concentration to be almost completed must exist within the 1st - 3rd peaks.

To such a mechanism raising the air concentration, the transient desorption of the dissolved air in the pressure bottoms after the 1st and before the 3rd-4th peaks, as related in section 3.7, is well applicable. In the cooling cavity, the higher the initial air concentration, the larger the amount of initial dissolved air in the liquid column, so it is assumed that the amount

of transient desorbed air is greater and the air concentration rises faster. Therefore, as in the closing remarks in section 3.3, it is considered that the higher the initial air concentration, the faster, and the earlier in the water hammer cycle, are the hardening of the air spring and the shortening of peak period almost completed.

5. Conclusions

In the present paper, the waveform of the pressure fluctuations measured in the experiments on the water hammer produced by collapse of a cooling cavity, and that of the estimated values of the collision velocity of the liquid column were analyzed, using the initial air concentration as the principal parameter. The actual damping and peak period shortening were elucidated, and their physical mechanisms were discussed. The concluding remarks are summarized as follows.

(1) By considering not the change with time but the change with cycle number, we separated the damping and the peak period shortening from each other, that take similar effects in appearance on damping and convergency, and generalized the discussion of the damping, using the logarithmic decrement.

(2) While the logarithmic decrement is almost constant at the 20% level of the low initial air concentration, as the initial air concentration increases, the logarithmic decrement tends to be larger earlier in the water hammer cycle, and to become smaller as the cycle number increases. From these findings, it is considered that the air in the cavity strengthens the damping and such an action is stronger earlier in the water hammer cycle.

(3) When the initial air concentration is over 30%, the shortening of peak period occurs rapidly not later than between the 2nd and the 3rd peaks, and has been almost completed within this interval. The final shortening has a tendency to have a narrower breadth, the higher the initial air concentration. Therefore, it is considered that the rise in air concentration early in the water hammer cycle brings about the peak period shortening.

(4) Based on the above findings, as a concrete mechanism of the damping and peak period shortening in the water hammer in collapse of a cooling cavity, the energy loss by the heat transfer between the air undergoing repeated compression/expansion in the cavity and the surroundings, and the transient dissolution/desorption of the air have been discussed.

In particular, though the concept of energy loss by compression/expansion of the air in the cavity has already been seen in the discussion on a pipeline transient with column separation/rejoining⁽⁶⁾ similar

to the present phenomenon, such discussion has been within the confines of a technique resulting ultimately in equivalent shear stress, so we consider that the concept will become important in analyses of fluid transients.

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