Influence of Gas Diffusion on Fluid Transient Phenomena Associated with Column Separation Generated during Decompression Operation*

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A mathematical model is presented for numerical simulation of the fluid transients in the return line during the decompression operation of a hydraulic system. Particular attention has been paid to clarification of the influence of gas diffusion on the fluid transients because in such a system, part of the separation cavity consists of a gas-liquid two-phase flow containing a number of minute gas (air) bubbles. Experiments using sump oil and deaerated oil as a test fluid showed that the generation mechanism of the separation cavity and the fluid transients are significantly affected by the gas diffusion. Values calculated from the proposed "bubble-diffusion model", which takes into consideration the effects of gas diffusion as well as the amount of gas bubbles released from the oil flowing out of the valve before column separation occurs, the change of state of gas and the surface tension applied to the gas bubble, agreed well with the measured values over a wide range of tests.

Key Words : Fluid Power Systems, Fluid Transients, Diffusion, Column Separation, Decompression, Dissolved Air, Transient Cavitation, Bubbly Flow

1. Introduction

We previously investigated in detail two kinds of fluid transient phenomena associated with column separation generated in some typical fluid power pipelines, in which one was related only to flow in a single pipeline⁽¹⁾ and the other was affected in a complex manner by the other system components other than the pipe in question^{(2),(3)}. In those papers, the generation mechanism of column separation, the flow pattern in a separated part of the liquid column, and the effects of system parameters on the duration of the cavity after column separation and on the surge pressure upon the collapse of the first cavity, which are of great interest in engineering problems, were elucidated, and the mathematical models capable of simulating the phenomena with sufficient accuracy were also developed. However, regarding the effects of secondary factors, such as released gas, on the fluid

transient phenomena⁽⁴⁾⁻⁽⁷⁾, further investigation is necessary.

Of these secondary factors, regarding the effects of the released gas in the separation cavity on the fluid transient phenomena associated with column separation generated in the return line during the decompression cycle of a hydraulic machine press, we have pointed out that a number of minute gas bubbles generated in the separation cavity have a significant effect on the fluid transients, and that when the duration of cavitation is relatively long (this rarely occurs under ordinary operating conditions of a hydraulic machine press), the proposed "bubble model" which takes into consideration the effects of partial pressure of the air in the gas bubbles (provided that the amount of air was assumed constant) and surface tension of the gas bubbles cannot explain the fluid transients sufficiently, especially the surge pressure upon the collapse of the first cavity [as shown in Figs. 1(a) and (b)]⁽²⁾. Since the decompression operation is very common in other hydraulic systems and fluid transient phenomena in which the cavitation duration is relatively long are often produced in various systems, the development of a physical model which can simulate

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these phenomena accurately over a wide range of operations is of interest and value.

This study deals with the fluid transient phenomena associated with column separation generated in the return line during the decompression operation, in which the separation cavity is made up of a number of minute gas bubbles, and examines experimentally the effects of diffusion between the air dissolved in the oil and the air bubbles in the separation cavity on the phenomena using the two kinds of oil, sump oil and deaerated oil, as test fluids under a wide range of operating conditions.

Nomenclature

Pressures are all expressed as absolute pressure

A_i : Cross-sectional area of pipe i

a_v : Effective orifice area of the decompression valve

B : Universal gas constant

B_e : Equivalent bulk modulus of elasticity of the oil in the pressure vessel

c : Speed of sound in the fluid in the pipeline

D : Diffusion coefficient of air in the oil

G : Molar density of air

K_d : Coefficient for the void fraction of air released from the oil flowing out of the valve (refer to Fig. 5)

(a) Case of relatively short cavitation duration (ordinary operating conditions)

(b) Case of relatively long cavitation duration

Fig. 1 Pressure variations generated in return line during decompression cycle of hydraulic machine press

L_i : Length of pipe i

p_c : Initial pressure in the pressure vessel and high-pressure line (initial working pressure)

$p_{i,j}$: Pressure at grid point j of pipe i

$p_{\max}$: Surge pressure upon the collapse of the first cavity

p_t : Reservoir pressure (constant)

p_v : Saturated vapor pressure of the oil

p_0 : Atmospheric pressure

R : Bubble radius

R_0 : Averaged radius of the air bubbles released from the oil flowing out of the valve (measured at n.t.p.)

T : Absolute temperature

t : Time

T_{col} : Time at which the first separation cavity collapses

$u_{i,j}$: Cross-sectional averaged velocity of the oil at the grid point j of pipe i

V_a : Volume of the separation cavity

V_c : Volume of the oil in the pressure vessel

V_g : Total volume of the released air in part of the separation cavity (measured at n.t.p.)

α_d : Void fraction of the air released from the oil flowing out of the valve

α_0 : Percentage content of air dissolved in the oil

χ : Polytropic coefficient

ν : Kinematic viscosity

ρ : Surface tension of the oil

Subscripts

i : Pipe number ; the high-pressure line and the return line are represented by $i=1$ and $i=2$, respectively

j : Grid point number (used in $p_{i,j}$)

m : Value of j at the valve end of the high-pressure line (in this study, $m=25$)

n : Value of j at the reservoir end of the return line (in this study $n=13$)

2. Experimental Considerations

2.1 System and experimental apparatus

We consider the fluid pipeline shown in Fig. 2 and discuss the fluid transient phenomena associated with column separation in the return line when the high-

Fig. 2 System configuration

pressure oil in the pressure vessel and in the high-pressure line enclosed under the initial working pressure is discharged into the reservoir through the return line by opening the decompression valve (decompression operation). The layout of the experimental apparatus is shown in Fig. 3. In order to examine the effects of diffusion between the air dissolved in the oil and the air bubbles in the separation cavity on the fluid transient phenomena, a sealed tank (made from transparent acrylic resin, volume of about 20 L) fitted with a vacuum pump for changing the amount of air dissolved in the test oil, was used as the reservoir, and thus the oil in the circuit was isolated from the external atmosphere. The other system components are the same as those used in the previous study⁽²⁾. The percentage content of air dissolved in the test oil was measured by means of a general-purpose dissolved-oxygen meter by sampling the oil in the reservoir immediately after every experiment. The relationship between the indicated value of this dissolved-oxygen meter and the percentage content of dissolved air was examined by using the oils of various known amounts of dissolved air, which had been measured by reading the pressure change in the evacuated vessel after injection of the test oil according to Yamaguchi's method⁽⁸⁾.

Experiments were carried out using two kinds of oil, that is, oil exposed to air for a few days ($\alpha_0 = 10.2\%$, hereafter called saturated oil) and oil deaerated under about 1 Pa ($\alpha_0 = 2.3\%$, hereafter called deaerated oil), and various initial pressures in the pressure vessel p_c at the temperature of $30 \pm 2^\circ\text{C}$. The values of the system parameters are as follows: $A_1 = 158 \text{ mm}^2$, $A_2 = 285 \text{ mm}^2$, $B_e = 1310 \text{ MPa}$, $c = 1375 \text{ m/s}$, $L_1 = 5.0 \text{ m}$, $L_2 = 2.5 \text{ m}$, $p_t = 102 \text{ kPa}$, $p_v = 0.1 \text{ Pa}$, $V_c = 3.54 \text{ L}$, $\nu = 42.0 \text{ mm}^2/\text{s}$, and $\rho = 857 \text{ kg/m}^3$. For the test decom-

Fig. 3 Experimental apparatus

pression valve, a spool-type directional valve whose spool end was machined into a four-stage taper was used, which was the same as that used in the previous study⁽²⁾, and was opened at a constant speed by a hydraulic cylinder whose speed was adjusted by the flow control valve.

2.2 Pressure variation waveforms

Figures 4(a), (a)' and (b) show the measured pressure variations at the pressure-vessel end, $p_{1,1}$, and at the valve end of the return line, $p_{2,1}$, when the initial working pressure p_c is 15.2 MPa, and also show the magnified records for the low-pressure part of $p_{2,1}$. The observed pressure variations in each experiment differed slightly from one another in the case of saturated oil even under the same operating conditions, as shown in Figs. 4(a) and (a)' (two examples of this difference being relatively large), but were almost the same in the case of deaerated oil, as shown in Fig. 4(b). It can be seen from a comparison of Figs. 4(a) and (b) that the amount of air dissolved in the oil (in other words, the amount of diffusion) has a considerable effect on the fluid transients. In addition, the characteristics of the pressure waveform of $p_{2,1}$ are as follows.

(1) Before formation of the first cavity, an extremely high-frequency pressure oscillation is produced.

(2) In the early stage of growth of the first cavity, the pressure falls to less, on the order of some kPa, than absolute zero pressure.

(3) The pressure in the separation cavity during the growth and decay sequence increases monotonically in the case of saturated oil, whereas it is maintained almost constant in the case of deaerated oil.

(4) The pressure curve of saturated oil is fairly rounded at the collapse of the first cavity compared to that of deaerated oil.

(5) The period of the water hammer after the collapse of the first cavity of saturated oil is longer than that of deaerated oil.

(6) The surge pressure upon the collapse of the first cavity of deaerated oil is higher than that of saturated oil.

2.3 Photographic observations of separation cavity

The growth and decay sequences of the separation cavity at the downstream side of the valve were observed by means of a high-speed camera by replacing the return line with a transparent tube made of acrylic resin. The behavior of the separation cavity was almost the same as that in the previous study⁽²⁾, except for the differences between the case of saturated oil and that of deaerated oil, shown as follows.

(1) A number of minute air bubbles are

(a) Saturated (sump) oil

(a)' Saturated (sump) oil

(b) Deaerated oil

Fig. 4 Waveforms of measured pressure variations

generated in the form of a mist and carried downstream from the valve end until the pressure at the downstream side of the valve falls below atmospheric pressure

after valve opening, but the total volume of these bubbles is relatively small (less than 1% in cross-sectional averaged void fraction in the case of saturated oil) and almost negligible in the case of deaerated oil.

(2) The appearance of the separation cavity, which is composed of a number of these air bubbles without coalescence, resembles uniformly thick white smoke (a group of air bubbles of some μm in diameter) in the case of saturated oil. In the case of deaerated oil, the degree of cloudiness of the separation cavity gradually becomes low downstream from the valve end, and a definite number of visible bubbles are observed near the top of the separation cavity. In addition, the maximum length of the cavity in the case of deaerated oil is shorter than that in the case of saturated oil.

(3) After completion of the phenomenon, a large number of air bubbles remain throughout the region of maximum length of the cavity in the case of saturated oil, whereas no visible residual bubbles remain in the case of deaerated oil. In addition, no cavitation formation was observed in any part of the pipeline except for the vicinity of the valve end, as far as the camera and visual inspection could cover.

From the above observations of pressure variations and the examinations of photographs, the mechanism of the growth and decay of the cavity produced in the present system can be explained as follows. An indefinite number of air bubbles with a diameter on the order of several μm are released from the oil flowing out of the valve in the early stage of valve opening when the flow through the valve is subjected to a high shearing force [section 2.2 (1) and (2)], and these bubbles expand and contract without coalescence to form the separation cavity [section 2.3 (1)]. The amount of air in the cavity in the expansion process increases by diffusion of the air dissolved in the oil, and hence increases as the amount of air in the oil increases [section 2.2 (3) to (5) and section 2.3 (3)]. Therefore, it may be conjectured that the time at which the first cavity collapses and the surge pressure at this time are significantly affected by the diffusion of the air dissolved in the oil and the air bubbles, as well as by the change of state and the surface tension of the air bubbles, in other words, by the states of the air bubbles (diameters and total number or total volume of bubbles) released in the early stage of valve opening.

Little quantitative research has been undertaken on the behavior of air bubbles released from the liquid flowing out of a valve when the fluid is subjected to a shearing force, although a few studies have been conducted with regard to inception and growth of a

relatively large air bubble in shear flow⁽⁸⁾⁻⁽¹⁰⁾. In those investigations, from the observation of a flow with a simple shear-flow pattern and a stepwise reduction in pressure, the mechanism of bubble inception was examined by measuring the time when an air bubble of 100 to 200 μm in diameter appeared, and the relationship between the Peclet number and Sherwood number was considered by observing the time history of the bubble radius after the inception⁽⁸⁾⁻⁽¹⁰⁾. However, in the case of the present system, since the flow pattern of the shear flow is very complicated and the diameter of the released air in question is on the order of several μm , the state of the released air may not be exactly represented by those results. Furthermore, with regard to parameters related to bubble behavior, it was pointed out from the examination of the diffusion with respect to a stationary single air bubble in oil, that the values of diffusion coefficient and surface tension may be changed by the effect of substances adsorbed on the interface between the oil and the bubble when the bubble radius is on the order of a few μm ^{(11),(12)}. In the present system, since a number of air bubbles of various radii are nonuniformly distributed in oil of a definite volume, it may be difficult to estimate the values of the parameters of the bubble by considering those results.

However, since the observed pressure waveforms (that is, fluid transients) of every experiment are almost the same, as discussed in section 2. 2, it may be conjectured that, even if the values of the parameters of the released air change within a certain range, these changes may have no appreciable effects on the fluid transients.

Therefore, in this study, the approximate values of the parameters of the released air bubbles related to cavity formation were obtained in the following manner. The volume of air released from the oil flowing out of the valve was measured by collecting the oil downstream of the valve into a vessel through an attached capillary tube and reading the volume change based on the change in the height of the oil column in the capillary tube due to the disappearance of bubbles in the oil. The measurement was carried with various pressure difference across the valve (the pressure downstream of the valve is maintained at atmospheric pressure) and valve opening. In this study, the void fractions of air α_d were estimated as the ratio of the measured air volume to the sampled oil volume. Figure 5 shows the measured values (average value of several measurements) of α_d of saturated oil, together with the obtained empirical formula. The average diameter of released air bubbles was estimated by comparing the measured value of the minimum pressure at the valve end of the return

Fig. 5 Measured values of void fraction of released air from oil flowing out of valve

Fig. 6 Measured variations of diameter of air bubble in oil under atmospheric pressure

line during the decompression operation with the value calculated from the mathematical model (to be discussed in section 4). As a result, the averaged diameter of the bubbles was found to be in the range of 2 to 4 μm , under the range of operating conditions in this study. The diffusion coefficient of the dissolved air in the oil was calculated from Epstein-Plesset's equation⁽¹³⁾ using the measured time at which an air bubble of an initially specified diameter in saturated oil under atmospheric pressure disappeared by diffusion. The behavior of the air bubble was observed using a microscope. Figure 6 shows the observed time-history traces of the bubble diameters, together with the ones calculated from Epstein-Plesset's equation. It can be seen from the figure that the diffusion coefficient of the test oil is between about 1×10^{-10} and $3 \times 10^{-10} \text{ m}^2/\text{s}$. Surface tension of the test oil was measured using a copper ring and Jolly's spring balance, and was about 25 mN/m.

3. Mathematical Model

From the results in section 2, we can express the physical model for the formation mechanism of the

cavity produced in the present system, as given below. After the decompression valve is opened, the air bubbles of a constant diameter ($2R_0$ at atmospheric pressure) are released from the oil flowing out of the valve at the void fraction proportional to the square root of the pressure difference across the valve (conforming to the empirical formula shown in Fig. 5). These bubbles change their state owing to the pressure change and surface tension, but diffusion between the bubbles and the air dissolved in the oil does not occur. This air-release process continues until the pressure at the valve end in the return line $p_{2,1}$ falls to less than atmospheric pressure first (label this time t_d and the total volume of the released air at atmospheric pressure $V_{g,d}$). Subsequently, no air is released from the oil flowing out of the valve because the shearing force applied to the flow through the valve orifice becomes considerably low, while diffusion between the air dissolved in the oil and the air bubbles which have been already released, occurs. We assume that the dynamics of this diffusion is governed by the same physical model as that of a stationary single bubble in oil without a boundary, and that the concentration of the air dissolved in the oil at the bubble surface is in accordance with Henry's law (e.g., Ref. (12)). However, the maximum value of the volume of released air should be limited ($V_{g,max}$) because the volume of oil containing an indefinite number of air bubbles is finite. In this study, this value of $V_{g,max}$ is equal to the product of the percentage content of the air dissolved in the oil and the total volume of the oil flowing out of the valve until the pressure in the pressure vessel falls to less than atmospheric pressure.

Using the above assumptions for the cavity formation, the fluid transient phenomena generated during the decompression operation of the present system can be expressed by a mathematical model as follows (hereafter, called the "bubble-diffusion model").

For the liquid columns in the pipeline $0 < x_i < L_i$ assuming that the motion of the liquid column in each pipe can be given by the equation of motion and continuity equation governing one-dimensional transient flow, these equations can be expressed by the method of characteristics using a specified grid (length of pipe section: Δx , time increment: $\Delta t = \Delta x/c$) as given below:

$$\rho u_{i,j} + p_{i,j}/c = f_{A,i,j-1} \quad (1)$$

$$\rho u_{i,j} - p_{i,j}/c = f_{B,i,j+1}, \quad (2)$$

where, using $p_{i,j}$ and $u_{i,j}$ at time $t - \Delta t$,

$$f_{A,i,j} = \rho u_{i,j} + p_{i,j}/c - \Delta t h_{i,j}$$

$$f_{B,i,j} = \rho u_{i,j} - p_{i,j}/c - \Delta t h_{i,j}$$

and $h_{i,j}$ is the pressure drop per unit length when the flow in the pipe is two-dimensional, unsteady and laminar⁽¹⁴⁾.

The boundary conditions for the pipeline can be expressed as follows.

At the end of the decompression valve ($x_1 = L_1$ and $x_2 = 0$),

$$\rho u_{1,m} + p_{1,m}/c = f_{A1,m-1} \quad (3)$$

$$\rho u_{2,1} - p_{2,1}/c = f_{B2,2} \quad (4)$$

$$A_1 u_{1,m} = \text{sign}(p_{1,m} - p_{2,1}) a_v \sqrt{2|p_{1,m} - p_{2,1}|/\rho} \quad (5)$$

$$p_{2,1} = p_v + p_0 \left(\frac{V_g}{V_a} \right)^k - \frac{2\sigma}{R_0} \left(\frac{V_{g,d}}{V_a} \right)^{1/3} \quad (6)$$

$$\frac{dV_a}{dt} = A_2 u_{2,1} - A_1 u_{1,m} \quad (7)$$

$$\left. \begin{aligned} \frac{dV_g}{dt} &= A_1 u_{1,m} K_d \sqrt{p_{1,m} - p_{2,1}} \\ &(: 0 < t \leq t_d) \\ \frac{dV_g}{dt} &= K(p_0 - p_a) R \left\{ 1 + \frac{R}{\sqrt{\pi D(t - t_d)}} \right\} \\ &(: t > t_d) \end{aligned} \right\} \quad (8)$$

and

$$\left. \begin{aligned} V_g &= V_{g,min} = \text{const.} \quad (: V_g < V_{g,min}) \\ V_g &= V_{g,max} = \text{const.} \quad (: V_g > V_{g,max}), \end{aligned} \right\}$$

where

$$p_a = p_v + p_0 \left(\frac{V_g}{V_a} \right)^k$$

$$R = R_0 \left(\frac{V_a}{V_{g,d}} \right)^{1/3}$$

$$K = \frac{3BDGT V_{g,d} \alpha_0}{p_0^2 R_0^3}$$

$$V_{g,max} = \left(\frac{V_c}{B_e} + \frac{A_1 L_1}{\rho c^2} \right) (p_c - p_0) \alpha_0$$

and $V_{g,min}$ is the minimum volume of air at the valve end introduced for convenience of calculation and is very small so that it has minimal effects on the calculated results (in this study, $V_{g,min} = 0.01$ mL).

At the end of the pressure vessel ($x_1 = 0$),

$$\left. \begin{aligned} \frac{V_c}{B_e} \cdot \frac{dp_{1,1}}{dt} &= -A_1 u_{1,1} \end{aligned} \right\} \quad (9)$$

and

$$p_{1,1} = p_v = \text{const.} \quad (: p_{1,1} < p_v).$$

At the reservoir end ($x_2 = L_2$),

$$p_{2,n} = p_t = \text{const.} \quad (10)$$

The mathematical models proposed in the previous studies^{(1),(2)}, namely, the "vapor model", the "gas model" and the "bubble model", can be expressed as special forms of the present "bubble-diffusion model". For example, the "bubble model" corresponds to the bubble-diffusion model in which $K_d = 0$, $K = 0$ (that is, $D = 0$) and $V_g = \text{constant}$.

In this study, the numbers of pipe sections of the characteristic grid were selected as $m = 25$ and $n = 13$, and the equations of the boundary condition with differential terms were solved numerically by the Runge-Kutta method.

The values of the parameters related to the behavior of the air bubble are as follows, except for values specifically indicated in the figures: $B =$

8.31 J/(mol·K), $D=1 \times 10^{-10}$ m²/s, $G=40$ mol/m³, $K_d=2.3 \times 10^{-6}$ Pa^{-1/2}, $p_0=98$ kPa, $R_0=2$ μm, $T=303$ K, $\alpha_0=10.2\%$, $\chi=1.0$, and $\sigma=25$ mN/m.

4. Discussion

Figures 7(a) and (b) show the calculated values corresponding to the measured values in Fig. 4 and also show the calculated values of volume variations of the released air. In these calculations, the value of K_d for deaerated oil is estimated from the measured value of saturated oil by assuming K_d to be proportional to the percentage content of the air dissolved in the oil. It can be seen from a comparison of Fig. 7 and Fig. 4 that the calculated values not only describe the characteristics of the waveform in the low-pressure

(a) Saturated oil ($K_d=2.3 \times 10^{-6}$ Pa^{-1/2})

(b) Deaerated oil ($K_d=5.2 \times 10^{-7}$ Pa^{-1/2})

Fig. 7 Calculated values of variations of pressure and released air volume

region of the measured pressure variation at the valve end, such as the rounded pressure waveform upon the collapse of the first separation cavity, but also agree well with the measured values of the time at which the first separation cavity collapses, T_{col} , and the surge pressure at this time, p_{max} , and thus that the proposed bubble-diffusion model can accurately simulate the fluid transients generated in the present system. In addition, it can be seen that, as far as the estimation of T_{col} and p_{max} are concerned, the first separation cavity may be almost filled with vapor from the oil in the case of deaerated oil, and that the marked differences in T_{col} and p_{max} between saturated oil and deaerated oil are dependent on the amount of air dissolved in the oil (that is, the amount of diffusion). Moreover, since the difference between the calculated values of $D=1 \times 10^{-10}$ and $D=3 \times 10^{-10}$ shown in Fig. 7(a) is almost the same as that between the measured values of Figs. 4(a) and (a)', it may be conjectured that the differences in the observed pressure waveforms of each experiment using saturated oil under the same operating conditions, are caused by variation of the parameters of the released air bubbles. In addition, the effects of the other parameters of the released air bubbles on the fluid transients were examined by calculation with various K_d in the range of 1.5×10^{-6} to 3×10^{-6} and R_0 of 1 to 2 μm. As a result, the differences in pressure waveform were in the range of that shown in Fig. 7(a). From these results, it may be concluded that the measured values of the parameters of the released air bubbles in section 2 are sufficient for rating the fluid transient phenomena for practical use.

Figure 8 shows the effect of the initial pressure in the pressure vessel, p_c , on p_{max} and T_{col} , in which the measured values in the case of saturated oil and deaerated oil and the values calculated from the bubble-diffusion model and the vapor model are indicated for examination of the effects of diffusion. It can be seen from the figure that the differences in p_{max} and T_{col} between saturated oil and deaerated oil increase as T_{col} (in other words, cavitation duration) increases, and that the proposed bubble-diffusion model can predict the phenomena over a wide range of operating conditions with sufficient accuracy.

Figures 9(a) and (b) show a comparison of the values calculated from various mathematical models corresponding to the measured values shown in Fig. 1, and Fig. 9(c) shows the calculated values of the flow-rate variations at both upstream and downstream ends of the valve for the case shown in Fig. 9(b). In the calculations of the gas model and the bubble model, we assume that half of the air volume released before the collapse of the first cavity, which

Fig. 8 Effect of initial working pressure p_c on $p_{\max}$ and T_{col}

is calculated from the bubble-diffusion model (this is nearly equal to the volume of residual air measured after completion of the phenomena in the previous study⁽²⁾), exists at the valve end of the return line from the beginning ($t=0$). From these, we can describe physically the effects of the diffusion at the separation cavity on $p_{\max}$ and T_{col} as follows. The liquid velocity upstream of the valve, $u_{1,m}$, after column separation occurs (point A) is nominally dependent on the physical model of the separation cavity because the velocity of the liquid column in the high-pressure line is dominated mainly by the pressure in the pressure vessel and the flow resistance of the decompression valve. On the other hand, the velocity of the liquid column in the return line is strongly dependent on the physical model of the separation cavity because it is dominated mainly by the pressure in the separation cavity and the reservoir pressure. That is, when the separation cavity expands, since the volume of air in the cavity of the bubble-diffusion model is relatively small compared to those of the gas model and the bubble model which assume the existence of a constant volume of air in the cavity, the partial pressure of air in the cavity of the former model becomes lower than those of the latter models, and hence the deceleration of the liquid column in the return line becomes more marked. However, when the separation cavity contracts, since the volume of the released air in the bubble-diffusion model is relatively large compared to those of the other models, the partial pressure of air of the former model becomes higher than those of the latter models, and hence the deceleration becomes slower. Therefore, in the case of the bubble-diffusion model, the velocity of the liquid column in the return line when the separation cavity collapses, that is,

(a) Case of relatively short cavitation duration

(b) Case of relatively long cavitation duration

(c) Flow rates at both ends of valve [case of (b)]

Fig. 9 Calculated values of variation of pressure and flow rate

relative velocity (at the time of the collapse of the first cavity) $u_r (=u_{1,m} - u_{2,1})$, is relatively low compared to those of the other models, and thus the surge pressure upon the collapse of the cavity, $p_{\max} (= \rho c u_r)$, becomes lower than those of the others. This can also be explained thermodynamically as follows. In the cases of the gas model and the bubble model, change of state of the air in the separation cavity in expansion and contraction processes is a reversible one, and hence no transportation of energy between the air and the liquid column occurs (area bounded by the closed curve in the P-V diagram is merely equal to zero). On the other hand, in the case of the bubble-diffusion model which takes into account diffusion, change of state of the released air is an irreversible one, and hence the kinetic energy of the liquid column

in the return line decreases due to the work done on the air and the velocity of the liquid column at the time of the collapse of the first cavity becomes lower than those above.

Moreover, it may be qualitatively considered that the effects of the released air on the fluid transients consist of the following three effects, that is, (1) the effect of partial pressure of the air of constant volume, (2) the effect of surface tension of the air bubble of constant volume and (3) the effects of the time-histories of the partial pressure and surface tension of the air bubble due to the diffusion. Although these three effects take place simultaneously in any system, their quantitative correlation depends on the system itself and the operation conditions. For instance, in the case of the fluid transient phenomena associated with column separation generated downstream of the valve in a single-pipeline system^{(1),(7)}, since the volume of released air reaches a maximum in a very short time after valve closure and clusters of bubbles coalesce into one or two large bubbles, the effect of (1) is dominant. In the case of the fluid transients in the return line during the decompression cycle of a hydraulic machine press, since the deceleration of the liquid column in the return line after column separation is nominally affected by the time-history of the partial pressure of the released air in the separation cavity but dominantly by the reservoir pressure because the reservoir pressure is usually maintained at 0.5 to 0.6 MPa (considerably larger than the pressure in the cavity), the effects of (1) and (2) are dominant [that is, the values calculated from the bubble model are nearly equal to those from the bubble-diffusion model, as shown in Fig. 9(a)]. In the decompression operation of any other system in which the reservoir pressure is close to atmospheric pressure, it may be considered that the effects of (1) to (3) are almost of the same degree.

In regard to the effects of released gas on the fluid transient phenomena associated with column separation, it has been pointed out that the discrepancy between the experimental and theoretical (vapor model using steady flow resistance) results in Baltzer's study⁽¹⁵⁾ can be explained by considering the energy loss due to the shock wave propagating in the gas-liquid two-phase flow formed by release of air in the liquid column^{(4),(5)} or by considering the energy loss due to the expansion and contraction processes of the gas bubbles released in the liquid column⁽⁶⁾. In the present system, however, no air release is observed in any part of the pipeline, except for in the separation cavity during the decompression operation, and Baltzer's discrepancy can be explained quantitatively by considering unsteady flow resistance, as pointed

out in the previous study⁽¹⁾. Therefore, we again emphasize that only the diffusion between the air dissolved in the oil and the air bubbles in the separation cavity at the valve end is taken into consideration in our proposed bubble-diffusion model, on the basis of the experimental results.

5. Conclusions

A mathematical model was presented for numerical simulation of the fluid transient phenomena in the return line during the decompression operation.

Particular attention was paid to the clarification of the effect of diffusion of the air dissolved in the oil on the fluid transients because part of the separation cavity was made up of a number of minute gas bubbles. Experiments using oil with an ordinary air content and deaerated oil as test fluids showed that the formation mechanism of the separation cavity and the fluid transients are significantly affected by the diffusion between the air dissolved in the oil and the air bubbles in the separation cavity. Values calculated from the proposed bubble-diffusion model, which takes into consideration the effects of diffusion as well as partial pressure of the air in the separation cavity and surface tension of the air bubbles, by using the measured values of surface tension of the oil, the total volume of air released from the oil flowing out of the valve before column separation occurs and the diameter of released air bubbles estimated from the measured pressure variations, agreed well with the measured values of the time at which the first separation cavity collapses and of the surge pressure at this time, over a wide range of operation conditions.

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