船舶技術研究所報告　第29巻　第4号　研究報告（平成4年7月）

REDUCTION OF THE RESIDUAL AMOUNT OF NOXIOUS LIQUID SUBSTANCES IN THE PIPING SYSTEM OF CHEMICAL TANKERS AFTER UNLOADING PROCEDURE OF CARGO (PART 3: REDUCING EFFECT OF RESIDUE IN THE DISCHARGING OPERATION WITH THE LINE BLOWING-ANALYSIS)*

By

Katsuji YAMAGUCH**, Izuo AYA***, Kenji YAMANE***
and Sadahiro NAMIE****

ABSTRACT

The method to strip residues by the gas flow from the piping system in the chemical tankers, which it is usually refer to as the line blowing, is described. The line blowing was performed with the large scale laboratory experimental apparatuses which are specified in Annex II of MARPOL 73/78 and the Standards of Procedures and Arrangements. Water and air were used as the test fluid. Gas flow was generated by compressed gas supplied to the piping when the manifold valve installed at the exit end of the horizontal pipe is opened quickly.

To evaluate the performance of the line blowing, a simple analytical model for predicting the quantity of the remaining water in the horizontal and vertical pipe during the process of the line blowing was developed, based on the arrangement of the experimental apparatus and the operating procedures as well as the results of flow observations. The line blowing process was modeled according to the location of the front of the flowing single air slug along the pipeline for the piping arrangement provided to maintain the back pressure with the 10 m. long vertical riser pipe (10mp) and the constant pressure valve (CPV) set the tripping point at 1 kgf/cm^2 at the exit end of the horizontal pipe.

The results predicted by the analysis for two experimental apparatuses were compared with wide range of the experimental data for 4-in. and 6-in. diameter pipelines. Good agreement with the experimental data of the remaining water rate in the horizontal and vertical pipe is shown. Predictions of the remaining water rate in the horizontal pipe for two experimental appratuses are in satisfactory agreement.

The experimental and analytical results suggest the excellency of the line blowing method.

---

* Received on May 6, 1992

** Ship Equipment and Marine Environment Division

*** Osaka Branch

**** Power and Energy Engineering Division

1. INTRODUCTION

Release of harmful substances from the ships constitutes a serious source of pollution of the marine environment. To preserve the sea and coastal environment from pollution by harmful substances, there is a need to minimize the remaining cargo in the cargo unloading line after unloading under the normal operation of the cargo pumping system and to reduce the discharging quantity of the remaining cargo or contaminated water by these substances into the sea.

With these points as background, Annex II of MARPOL 73/78 and the Standards for Procedures and Arrangements (P & A Standards) contained requirements for cargo tank stripping have been entered into force. These are that each tank designated for every ship carrying category B (for example, Chloroform, Etheylene dichloride) or C (for example, Creosote, Toluene) substance shall not retain more than a defined quantity of residue in the piping system. The stripping system has to be installed and the test of the stripping capabilities of these tanks must be in accordance with the Standards by using water as the test fluid. During the onboard test, either the 10 m. long vertical riser pipe (10mp) or the constant pressure valve (CPV) set at 1 bar minimum has to be installed to maintain a back pressure at the cargo tank's unloading manifold.

Consequently, the ability to predict the quantity of the residue after the stripping procedures is of importance to prevention of marine pollution. However, a single reference, dealing with the experimental and theoretical aspects of the stripping procedures, has not been found. To obtain the efficient stripping system, the efficient stripping procedures, the reliable expressions for the stripping quantity and quantitiy of residue for the particular ship have been required. Predicting the stripping quantity of some ships which can not be met their specified efficient stripping condition during the real unloading operation is also required for minimizing the stripping time in port.

For these purposes, methods for predicting and reducing the quantity of residue in the horizontal pipe in accordance with the test procedure and the test arrangement set out in P & A Standards have been investigated.

In the previous paper[1], the line blowing method was discussed experimentally, and the conditions to strip water effectively from the large scale pipeline were proposed. A static model which describes the condition of the ideal line blowing (same volume of water in the horizontal pipe as the volume of the air blown into the horizontal pipe is displaced and water is discharged from the pipe outlet) was proposed. The agreement between the analytical results and the experimental results is satisfactory at higher remaining water rate. However, the model does not predict well the lower remaining water rate data. Further investigaiton of a more general expression for the remaining water rate is needed.

In this paper, a simple analytical model for predicting the quantity of the remaining water in the horizontal and vertical pipe during the process of the line blowing, based on the arrangement of the experimental apparatus and the operating procedures as well as the result of flow observations, is described. The analytical results compare favorable well with the data of the wide range of the design and operating conditions. The experimental and analytical results showed that water in the horizontal and vertical pipe is sufficiently removed by the line blowing.

NOMENCLATURE

10 mp: 10 m. long vertical riser pipe
CPV:constant pressure valve
c: coefficient of contraction(−)
d: diameter of the orifice (m)
D: inner diameter of the test section (m)
g: acceleration due to gravity (m/s^2)
h: height of vertical riser pipe (m)
j: volumetric flux density (m/s)
ι: length of horizontal pipe (m)
P: pressure (kgf/cm^2)
Q: volume(m^3)
q: volumetric flow rate (m^3/s)
R: remaining water rate or gas constant (−)
R′: local remaining water rate(−)
T: absolute temperature (K)
t: time(s)
V: gas velocity (m/s)
V_0: velocity of the gas cavity concerning to the gravity (m/s)
W: weight (kg)
y: thickness of liquid film (m)
z: location of bubble front measured from exit (m)
α: void franction (−)
β: refer to eq (7) ($=10.5\times10^{-4}$) (s^2/m)
γ: specific weight (kg/m^3)
ζ: friction coefficient of pipe (−)
η: Q_1 $[(P_{10}+1)/(P_3+1)-1]$ $/Q_H(-)$ non-dimensional available air quantity
κ: adiabatic exponent(−)
μ: viscosity ($kgfs/m^2$)
ξ: loss factor (−)
τ: time required to open/close the manifold valve from zero to full opening or vice versa (s) or wall shear stress (kgf/cm^2)
υ: specific volume (m^3/kg)
ω: angular velocity of valve opening (rad/s)

SUBSCRIPTS

0: atmospheric pressure or initial condition
1: air tank
2: air supply hose
3: back pressure
4: middle point along the horizontal pipe
b: bent
e: entrainment
g: gas
H: horizontal pipe
In: inlet
l: liquid or liquid film
TPG: two phase flow
P: back pressure maintained by a 10m. long vertical riser pipe
V: back pressure maintained by a constant pressure valve, vertical pipe or valve

2. MODEL FOR LINE BLOWING

A simple analytical model for predicting the quantity of the remaining water in the horizontal and vertical pipe during the process of the line blowing was developed, based on the arrangement of the experimental apparatus and the operating procedures as well as the results of flow observations.

2.1 Experimental Apparatus and Operating Procedures

A schematic diagram of the experimental apparatus is presented in Fig. 1. The apparatus consists of the 11.2 m. long transparent plexiglass horizontal pipe to permit visual observation of flow, the manifold valve (V_1) and the 10 m. long vertical riser pipe or the constant pressure valve to maintain a back pressure at the end of the horizontal pipe. The CPV used in this work

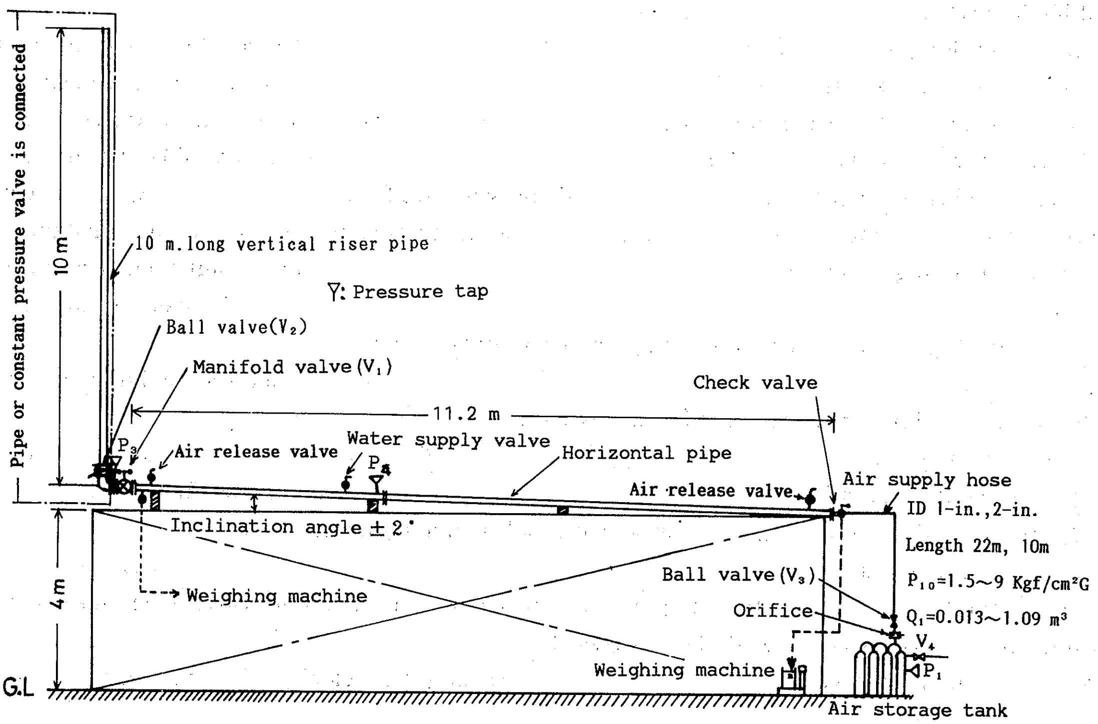


Fig. 1 Schematic diagram of experimental apparatus

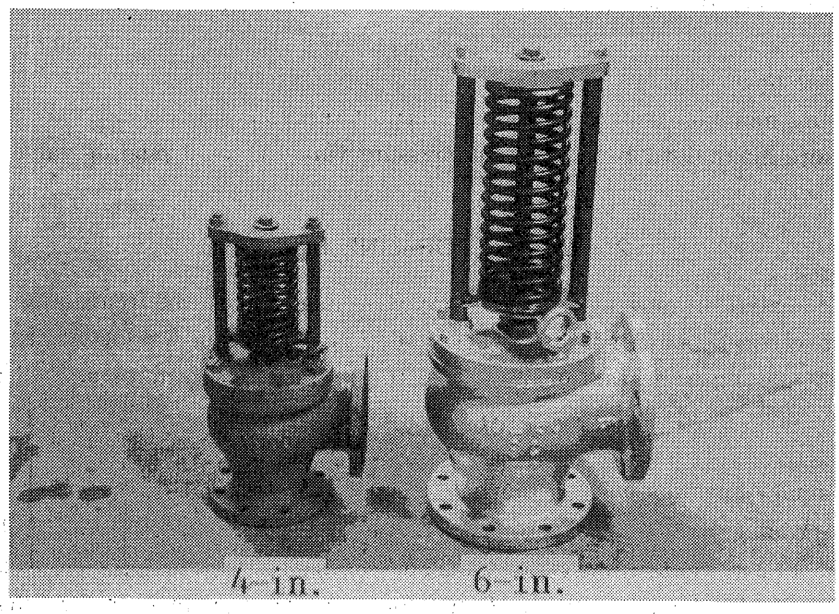
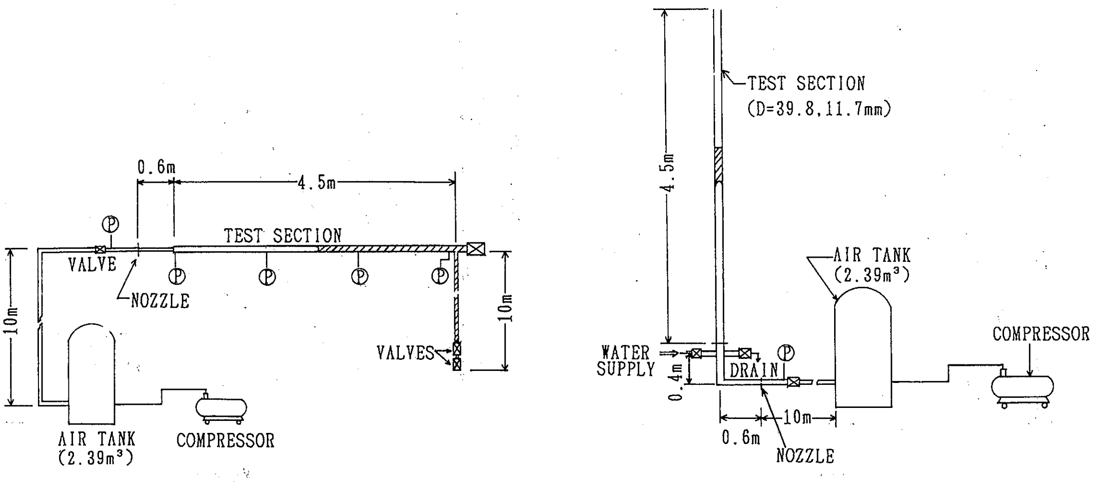


Photo. 1 Constant pressure valve

is shown in Photo. 1. The trippig point of the CPV was set at 1kgf/cm^{2}G by spring force. They are same in bore diameter and connected in series. The internal diameters of the test section were 4-in. and 6-in. The test section is supported by the frame that can be pivoted between angles of $\pm 2°$ from the horizon. The electrically actuated butterfly typed manifold valve can be opened and closed at constant speed. The orifices can be installed in the air supply hose.

To perform an experiment, at first, the valve V_1 was closed and the pipeline was filled with water. Then compressed air (initial air pressure P_{10}: 1.5~9 kgf/cm^{2}G) was supplied from the air storage tank (volume Q_1: 0.013~1.09 m^3) through the air supply hose (i.d 1-in. and lengths of 22 and 10 m.) to the horizontal pipe at pressure P_{10}. The line blowing was started by opening the valve V_1. Air is blown into the horizontal pipe and the single slug bubble is formed. Water in the pipeline will be blown from the outlet of the pipeline to the atmosphere. The line blowing was stopped for different mode, by closing V_1 at constant speed, or by closing the ball valve V_2 or V_3 quickly, depending on the location of the front of the bubble slug. Pressures were measured at the air storage tank (P_1), middle point along the horizonal pipe (P_4), the end of the horizontal pipe, and between the CPV and the manifold valve (P_3). Pressure P_3 denotes the back pressure. Remained water after the line blowing in the horizontal and vertical pipe (10 mP) was measured. The mean bubble slug velocity in the horizontal pipe V_{gH} was determined by measuring the time required for a bubble to move a fixed distance along the horizontal pipe and by closing the ball valve V_2 or V_3 quickly, then the amount of remained water was weighed. In this way, the mean discharge water velocity j_l from the pipe could be obtained. To obtain constant values of V_{gH} and V_{gV}, additional experiments were carried out with large air storage tank (volume Q_1:2.35m^3). Measurements of V_{gH}, V_{gV}, the water surface velocity and j_l were made using pipes of 40 mm and 11.7 mm in diameter, and 4.5 m. in length. A schematic diagram of the experimental apparatus is shown in Fig. 2. Compressed air is supplied to the horizontal pipe which is filled with water or to the vertical pipe which is filled to a preselected water level and



(a) horizontal pipe

(b) vertical pipe

Fig. 2 Experimental apparatus to measure bubble velocity the long bubble slug is generated. Motions of the bubble head and the water surface (vertical pipe experiment) were recorded by the video tape recorder and the quantity of the discharging water (horizontal pipe experiment) during measured time was weighed. V_{gH}, V_{gV} and j_l were

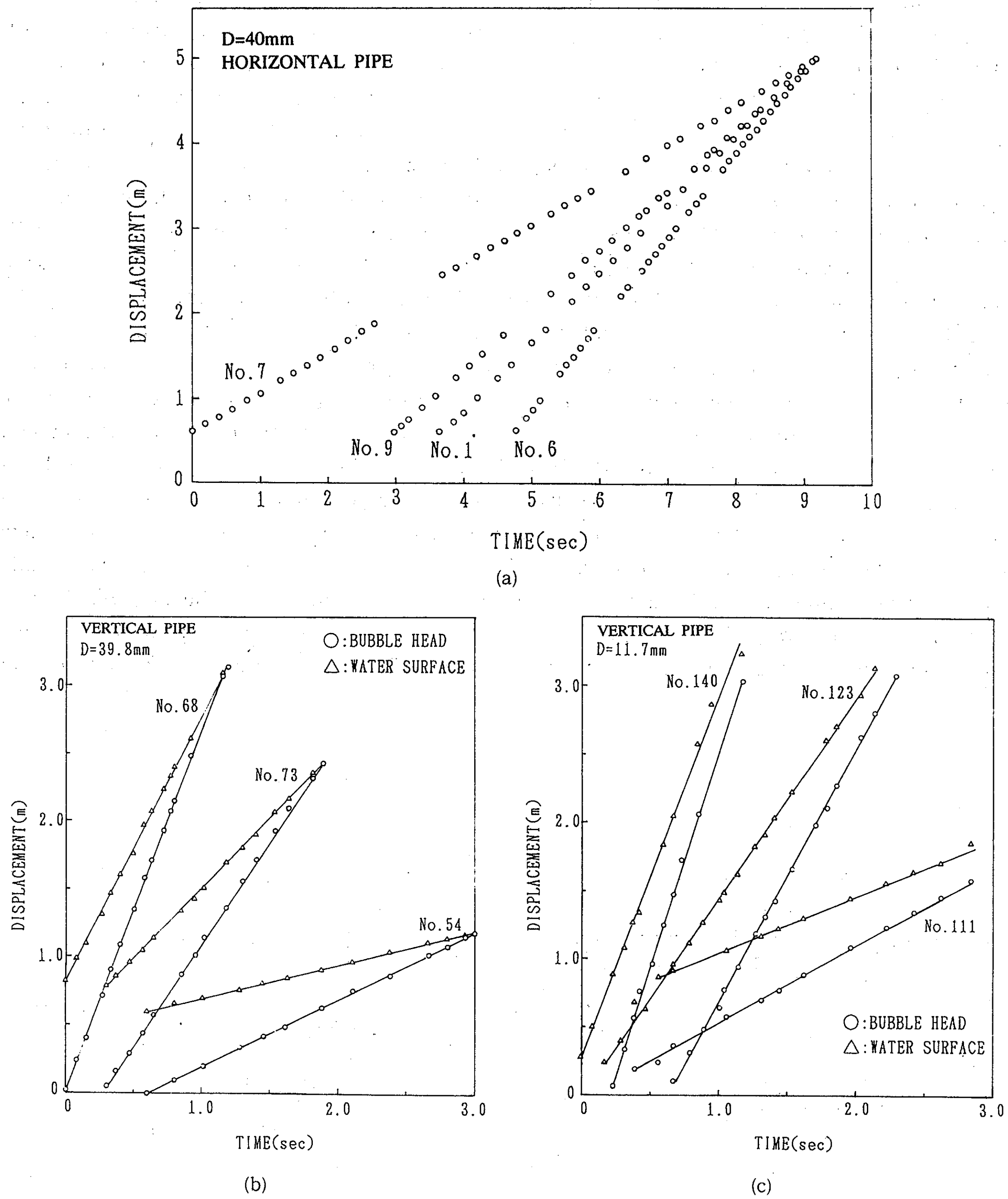


Fig. 3 Motion of bubble

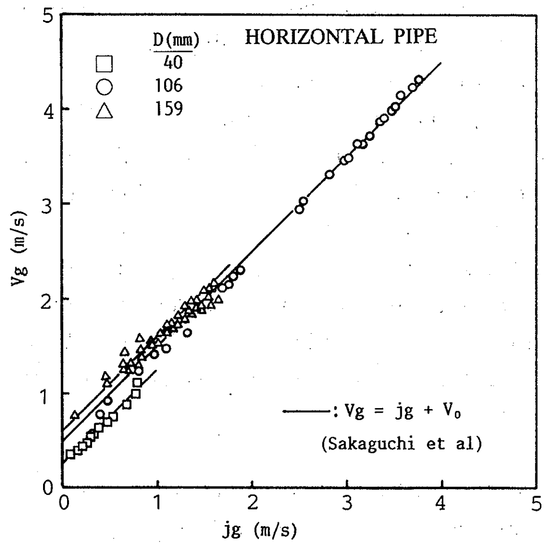
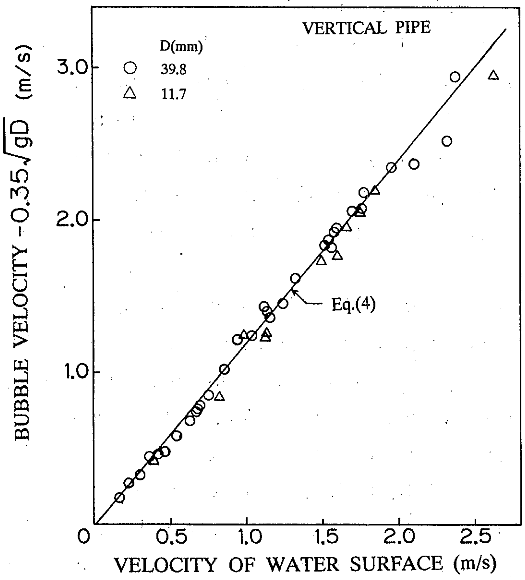


Fig. 4(a) Bubble velocity vs. j_g



4(b) Bubble velocity vs. velocity of water surface

determined from these data. Fig. 3(a) shows motion of the bubble head and the constant bubble velocity. Figs. 3(b) and (c) show motions of the bubble head and the water surface. The bubble velocity is plotted against j_g in Fig. 4(a) assuming $j_l=j_g$ and in Fg. 4(b) assuming the velocity of the water surface equals to j_g. These data were used to obtain the correlation of the local remaing water rate. For analyzing the line blowing process, this correlation is required.

A further description of the experimental apparatus as well as the operating procedures can be found in reference[1].

2.2 Brief Description of Flow Observations

Typical flow phenomena observed in the test section during the line blowing process can be described as follows.

As the mainfold valve begins to open, air is blown into the horizontal pipe and the single bubble slug is formed. The front of the bubble is rounded and leans over to upper side of the pipe. Water remains in the form of the water layer with the gas passing above. After the front of the bubble slug passes through the horizontal pipe, the air front travels downstream of the 10 mp in the form of continuous single bubble slug and decreases the amount of water in the 10 mp. Consequently, the back pressure rapidly decreases and approaches to the atmospheric pressure. For the experimental apparatus provided with the CPV, the CPV maintains the back pressure of 1 kgf/cm^{2}G minimum accompanying pressure fluctuation due to chattering. When the rounded nose of the bubble reaches to the outlet of the pipeline, air-water mixture is violently blown out. Then the air flow with entrained droplets is observed. The air pressure in the storage tank and the air velocity decrease with time and the line blowing will come to an end.

2.3 Model for Line Blowing

Fig. 5 shows the typical flow patterns observed and the flow models in the test section. Following to the arrangement of the experimental apparatus, two cases are illustrated:

1) discharge water from the horizontal pipe through the 10 m long vertical riser pipe
2) discharge water from the horizontal pipe through the constant pressure valve

The process of the line blowing is divided and modeled into three stages according to the location of the front of the bubble slug along the pipeline. Fig. 7 shows the notations for the model.

(i) stage 1: Air blown into the horizontal pipe filled with water forms the single bubble slug and the front of the bubble moves to the outlet of the pipe. Water remains in the form of the water layer with the air passing above. Water is blown from the outlet of the pipeline. Water in the vertical pipe remains full. Axial coordinate of the bubble front z measured from the outlet of the pipeline is $h < z \leqq l + h$.
In case of the CPV test arrangement, $h \to 0$.

In Fig. 4(a), the bubble slug velocity in the horizontal pipe V_{gH} is plotted against j_g assuming $j_l = j_g$ and compares well with the following correlation proposed by Sakaguchi et al[2].

$$V_{gH} = j_g + V_0 \tag{1}$$

where V_0 is the velocity of the gas cavity concerning to the steady gravity current of the stational liquid in the corresponding horizontal pipe. V_0 is a function of the pipe diameter and took the value obtained from the Zukoski's paper[3].

Since $j_l = j_g$, we obtaine the relation of

$$V_{gH} = \frac{j_g}{1 - R'_H} \tag{2}$$

From Eqs. (1) and (2), we have the correlation of local remaining water rate in the bubbling slug

$$R'_H = \frac{V_0}{j_g + V_0} \tag{3}$$

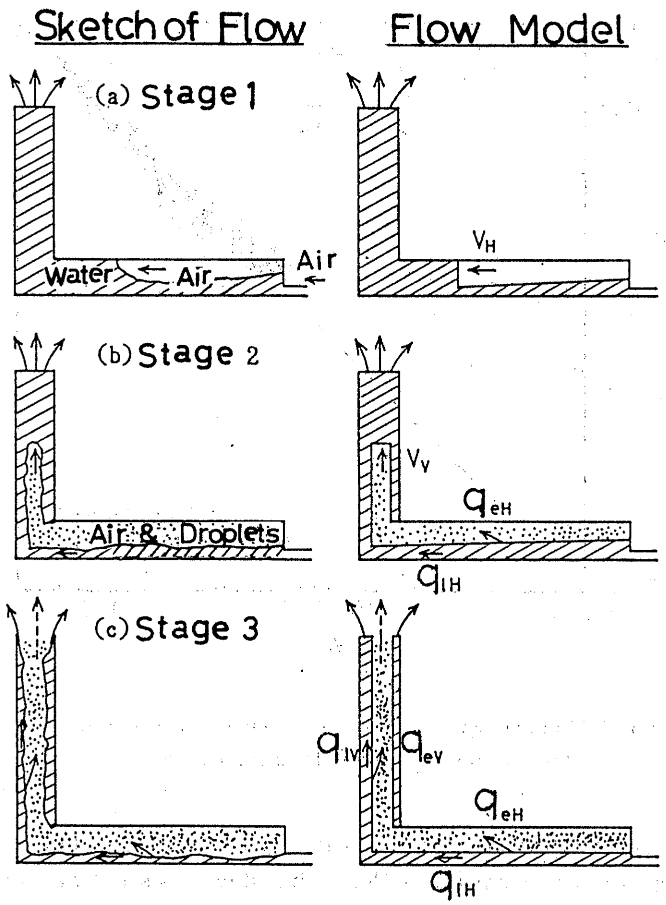
Equation (3) was compared with the experimental data in Fig. 6 and shows good agreement. So, eq. (3) was used in analyzing the line blowing process in the horizontal pipe.

(ii) stage 2: The front of the single bubble slug travels downstream of the vertical pipe ($0 < z \leqq h$). The velocity of the bubble slug in the vertical pipe is given by (Fig. 4(b) and Nicklin et al.[4])

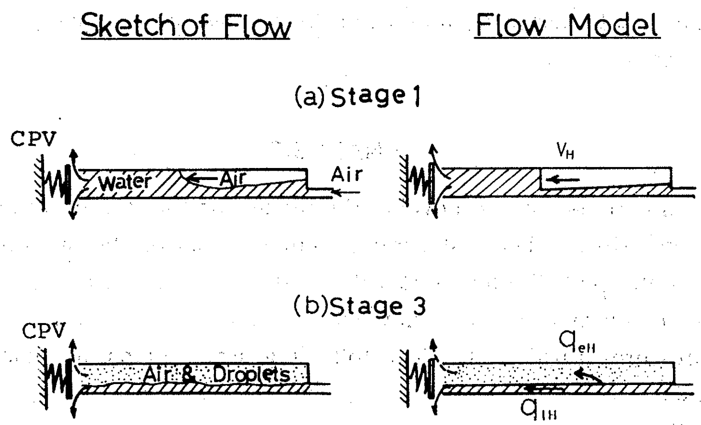
$$V_{gV} = 1.2 j_g + 0.35\sqrt{gD} \tag{4}$$

Similar relation to eq. (2) is obtained for the vertical pipe. Then the local remaining water rate in the vertical riser pipe is

$$R'_V = \frac{0.2 j_g + 0.35\sqrt{gD}}{1.2 j_g + 0.35\sqrt{gD}} \tag{5}$$



(a) experimental apparatus for 10 mp



(b) experimental apparatus for CPV

Fig. 5 Sketch and model of flow

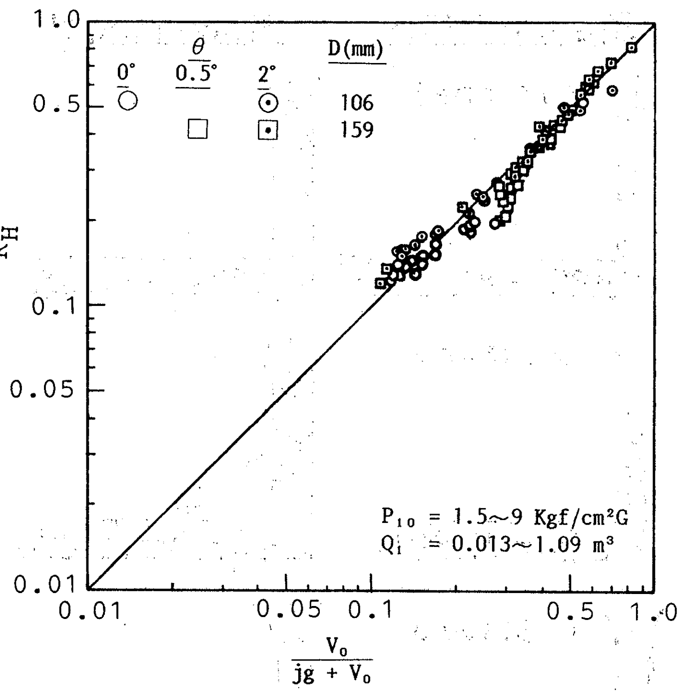


Fig. 6 Comparison of Eq. (3) with remaining water rate in bubble slug length for horizontal pipe

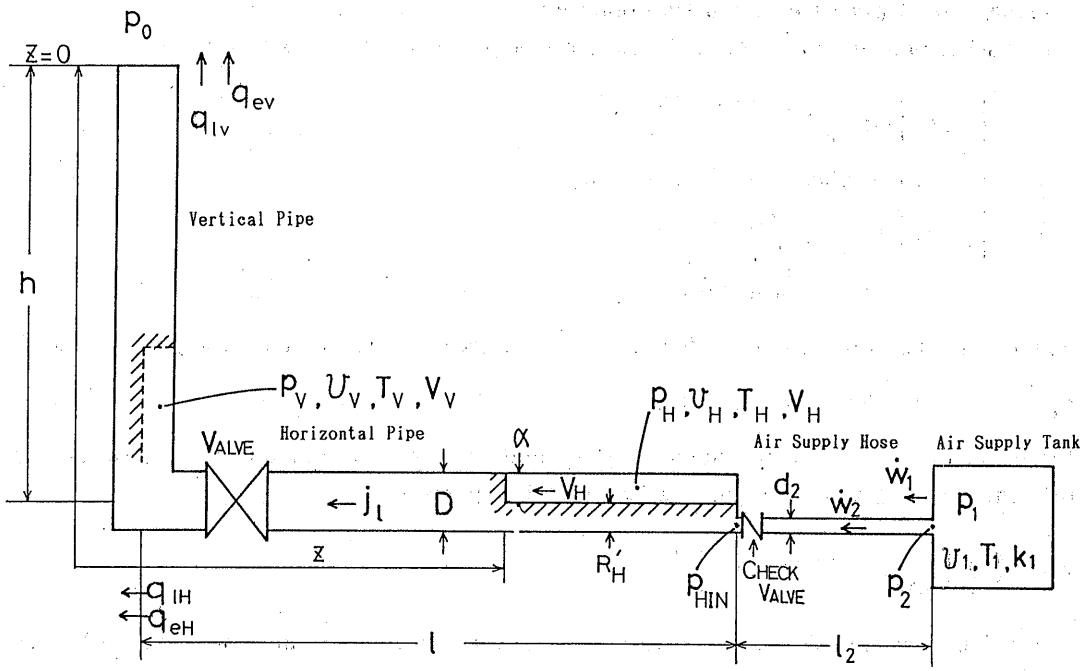
Over full length of the horizontal pipe, water remains as the liquid layer with the gas passing above. Water is blown from the outlet. This stage does not appear in case of the CPV test arrangement.

(iii) stage 3: This stage starts after the front of the bubble slug reaches at the outlet of the pipeline. Water in the liquid film moves downstream of the pipe and is carried away in the form of droplets due to the forces exerted on liquid film by the fast moving gas. Air flow with small droplets is observed ($z \leqq 0$).

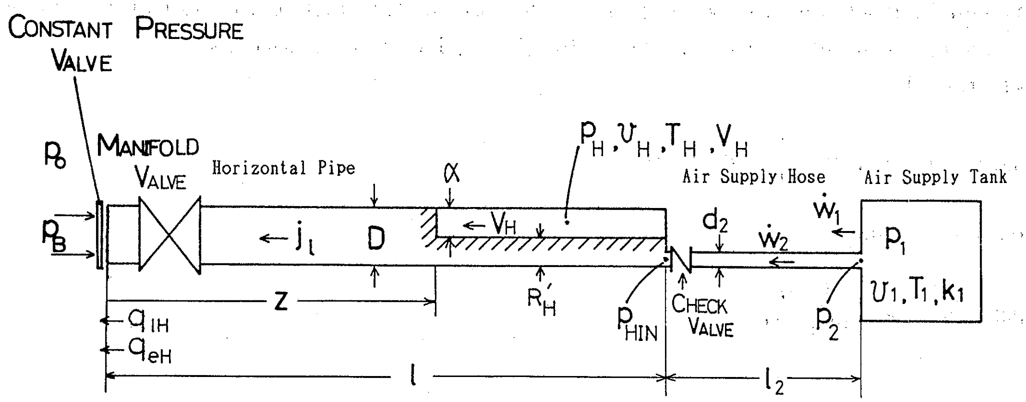
3. ANALYSIS

Fig. 7 shows the notations used to develop the model for the line blowing. The 10 mp test arrangement case is described. The test arrangement consists of the air storage tank, the air supply hose, the horizontal pipe, the manifold valve and the vertical riser pipe. For the CPV test arrangement, same equation as described below can be used, but putting $h \to 0$, and atmostpheric pressure P_0=back pressure=1 kgf/cm^{2}G. The following assumptions are made in the proposed model and its analysis.

1) Flow is one-dimensional.
2) The inclination angle of the horizontal pipe is zero.
3) The volume of the air storage tank includes the volume of the air supply hose.



(a) experimental apparatus for 10 mp



(b) experimental apparatus for CPV

Fig. 7 Notations for the model

4) The control volumes of the air storage tank, the horizontal pipe and the 10 mp are connected with the junction such as the air supply hose and the manifold valve.

5) The pressure and temperature are assumed to be constant within the control volume.

6) The water flow rate and the air flow rate (air velocity) are evaluated at the junctions.

3.1 Supplied Air Flow Rate to the Horizontal Pipe

The discharging air flow rate from the air storage tank can be expressed as [5]

$$-\dot{W}_1=\begin{cases} CA_2\left\{\kappa g\left(\frac{2}{\kappa+1}\right)^{(\kappa+1)/(\kappa-1)}\frac{P_1}{\upsilon_1}\right\}^{1/2} \\ \quad \text{for ciritical flow } \delta=P_2/P_1<\delta_m \\ CA_2\left\{2g\frac{\kappa}{\kappa-1}\frac{P_1}{\upsilon_1}\left(\delta^{2/\kappa}-\delta^{(\kappa+1)/\kappa}\right)\right\}^{1/2} \\ \quad \text{for not critical flow } \delta>\delta_m \end{cases} \qquad (6)$$

where c is the contraction coefficient (=0.6), $A_2=\pi d_2^2/4$ (area of air supply hose) and $\delta_m=\left(\frac{2}{\kappa+1}\right)^{\kappa/(\kappa+1)}$ (=0.5283 for $\kappa=1.4$ (air)).

From eq. (6), $-\dot{W}_1$ is determined from P_1 and the unknown quantity P_2. Air flow rate through the air supply hose (assuming isothermal change) is

$$\dot{W}_2=\frac{\pi}{4}d_2^2\left\{\frac{1}{2\beta RT_2}\frac{d_2}{l_2}(P_2^2-P_{HIN}^2)\right\}^{1/2} \qquad (7)$$

where β is same physical property as $\zeta/2g$. The recommended value of β is $\beta=10.5\times10^{-4}$ (s^2/m)[5].

Air mass balance requires the relation $\dot{W}_1+\dot{W}_2=0$. Therefore, unknown quantities P_2 and W_2 can be calculated by iteration if the pressure at the inlet of the horizontal pipe P_{HIN} is given. Using the annular flow friction factor ζ_{TPG}[6], P_{HIN} is expressed as

For stage 1

$$P_{HIN}=P_H+\zeta_{TPG}\frac{V_H^2}{2g\upsilon_H}\frac{0.5}{D}(h+l-z) \qquad (8\text{-}1)$$

For stage 2 and 3

$$P_{HIN}=P_H+\zeta_{TPG}\frac{V_H^2}{2g\upsilon_H}\frac{0.5l}{D} \qquad (8\text{-}2)$$

but

$$\zeta_{TPG}=\begin{cases}0.02(1+300y/D)(D/(D-2y)) & \text{for } y/D>0.023 \\ 0.16(D/(D-2y)) & \text{for } y/D<0.0233\end{cases} \qquad (9)$$

where y is the mean film thickness.

3.2 Motion of Bubble Front

Refering to figure7, the one-dimensional force (per unit area) equations can be written as follows,

for flow stage 1 (horizontal pipe)

$$P_H-P_O=\zeta_{TPG}\frac{V_H^2}{2g\upsilon_H}\frac{0.5(h+l-z)}{D}+\zeta\frac{\gamma_l}{2g}j_l^2\frac{z(t)}{D}$$

$$+\xi_b\frac{\gamma_l}{2g}j_l^2+\xi_V j_l^2\frac{\gamma_l}{2g}+\frac{\gamma_l}{g}\frac{dj_l}{dt}z(t)+\gamma_l h \qquad (10\text{-}1)$$

The six terms on the right side can be regarded as the two phase frictional, the water column frictional, the bent loss, the valve loss, the accelerational, and the gravitational components of the force, respectively.

For flow stage 2 (vertical pipe)

$$P_V-P_O=\zeta_{TPG}\frac{V_V^2}{2g\upsilon_V}\frac{0.5(h-z)}{D}+\zeta\frac{\gamma_l}{2g}j_l^2\frac{z(t)}{D}+\frac{\gamma_l}{g}\frac{dj_l}{dt}z(t)+\gamma_l z(t) \qquad (10\text{-}2)$$

and for flow stage 2 ((h−z) is replaced by h for stage 3)

$$P_H-P_V=\zeta_{TPG}\frac{V_H^2}{2g\upsilon_H}\frac{0.5l}{D}+\zeta_{TPG}\frac{V_V^2}{2g\upsilon_V}\frac{0.5(h-z)}{D}$$

$$+\xi_b\frac{V_H^2}{2g\upsilon_H}+\xi_V\frac{V_H^2}{2g\upsilon_H}+\frac{1}{2g\upsilon_H}(V_V^2-V_H^2) \qquad (10\text{-}3)$$

where ζ is the single phase friction coefficient, ξ_v is the valve loss factor approximated by $\xi_V=10\,EXP((74.4-\omega t)/23.4)$[7], ξ_b is the elbow loss factor (=1.13)[8], and ω is the angular velocity of the valve opening.

The term dj_l/dt can be calculated from Eqs. (10–1) and (10–2), thus j_l is obtained by an integration of dj_l/dt over the time. The location of the bubble front z(t) is obtained from

$$z(t)=h+l-\int\frac{j_l}{\alpha}dt \qquad (11)$$

where

$$\alpha=1-R'_H \text{ and } j_l=j_g$$

P_H and P_V in Eqs. (10–1), (10–2) and (10–3) are defined as the average air pressure in the horizontal and vertical pipe, V_H it the gas velocity in the horizontal pipe, V_V is the gas velocity in the vertical pipe, respectively. These pressure can be calculated from the relation (assuming isothermal change) $P=RT/\upsilon$. The air volume is obtained from the remaining quantity of water W_l in each volume (for example, the air volume in horizontal pipe: $\pi D^2 l/4-W_{lH}/\gamma_l$).

The quantity of the remaining water can be expressed as,

for flow stage 1

$$W_{lH}=\frac{\pi}{4}D^2\gamma_l(l-\int j_l dt) \qquad (12\text{-}1)$$

for flow stage 2

$$\dot{W}_{lH}=-\gamma_l(q_{lH}+q_{eH}) \qquad (12\text{-}2)$$

$$W_{lV}=\frac{\pi}{4}D^2\gamma_l(h+l-\int j_l dt)-W_{lH} \tag{13-1}$$

for flow stage3

$$\dot{W}_{lH}=-\gamma_l(q_{lH}+q_{eH}) \tag{12-2}$$

$$\dot{W}_{lV}=\gamma_l(q_{lH}+q_{eH}-q_{lV}-q_{eV}) \tag{13-2}$$

where q_l is the volumetric film flow rate and q_e is the volumetric droplet flow rate (entrainment) generated by the air flow.

The velocities of the film and droplets for stage 1 are assumed to be much less than the bubble front velocity j_l/α, thus the quantity of the remainig water in the horizontal pipe is not affected by q_l and q_e. In flow stage 2 and flow stage 3, these effects will be appeared. In flow stage 2, the quantities of q_l and q_e are probably small, because the air velocity is not so high and is same order as j_l/α. However, the air velocity is so high that the effects of q_l and q_e on the remaining water rate can not be neglected in flow stage 3.

The available theory and correlation for q_l and q_e for the present experimental system are not found. Following the theory and correlation are employed for similar conditions as present work.

Levy[9] have made an analysis of the velocity of the liquid film. From the force balance, the wall shear stress, τ, is

$$\tau=\frac{\zeta_{TPG}}{2gv}V_g^2 \tag{14}$$

A dimensionless distance from the wall y^+ is

$$y^+=\frac{y}{\mu_l}\sqrt{\tau\gamma_l/g} \tag{15}$$

A dimensionless volumetric flow rate of the water in the film may be obtained by integrating the universal velocity relationships from the wall to y^+.

$$q_l^+=\begin{cases}0.5y^{+2} & \text{for } y^+\leqq 5\\ 12.5-8.05y^++5y^+\ln y^+ & \text{for } 5<y^+<30\\ -64+3y^++2.5y^+\ln y^+ & \text{for } y^+\geqq 30\end{cases} \tag{16}$$

The volume flow rate of the water film may be expressed in dimensional form as

$$q_l=\frac{\pi}{4}D^2\frac{\mu_l g}{D\gamma_l}q_l^+ \tag{17}$$

The method developed by Collier[10] was used for estimating the liquid flow rate as droplets carried to the gas stream.

$$q_e=7.87\times10^{-6}\gamma_l\frac{q_g}{q_l}\frac{dP}{dz}\frac{\phi}{W_{ec}} \tag{18}$$

where q_g is the volume flow rate of air and W_{ec} is the critical Weber number (recommended value is 13), and

$$\phi=\begin{cases} 949.1X^{2.564} & \text{for } X>0.08 \\ (X/\lambda)^{6.25} & \text{for } X\leqq 0.08 \end{cases} \tag{19}$$

where X is the Martinelli parameter, $\lambda=0.105-0.00125V_g$ and

$$\frac{dP}{dz}=\zeta_{TPG}\frac{V_g^2}{2g}\frac{1}{\upsilon}\frac{1}{D} \tag{20}$$

4. COMPUTATIONAL PROCEDURES

The system of equations (1) to (20) has been numerically integrated with respect to small time step Δt from the start of opening of the manifold valve. Each variable is integrated explicitly. Flow of calculations for the 10mp test arrangement case is shown in Fig. 8.

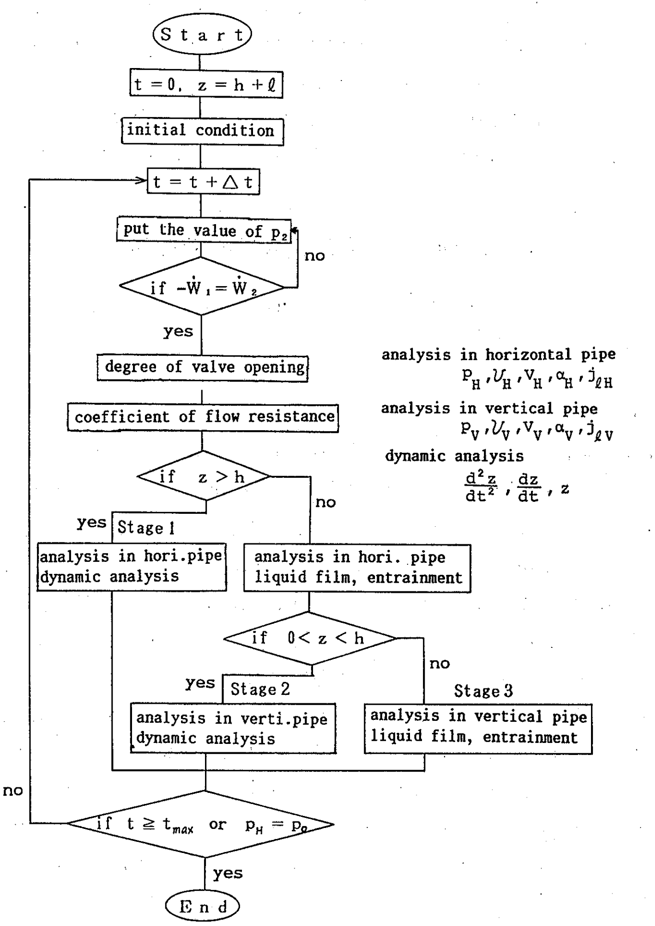


Fig. 8 Flow of calculation

1) Put the values of each variable or carry out preliminary calculation at valve opening $t=0$.
2) Set new time $t=t+\Delta t$
3) Estimate the pressure of the air storage tank at the exit P_2 from the value of one time step before.
4) Calculate P_{HIN} from eq. (8–1) and using it, obtain the unknown quantity P_2 from the relation $W_1+W_2=0$ by iteration.
5) Calculate the flow resistances (resistances of single phase flow, two phase flow, bend and valve).
6) Analyze the flow stage depending on the location of the front of the bubble slug.
i) If $z>h$, carry out the flow analysis in the horizontal pipe (calculations of P_H, υ_H, V_H, α_H and j_{lH}) and the dynamic analysis (dz^2/dt^2, dz/dt and z) for flow stage 1.
ii) If $0<z<h$, carry out the flow analysis in the horizontal and vertical pipe (calculations of P_V, υ_V, V_V, α_V and j_{lV}) and the dynamic analysis for flow stage 2, and calculate q_l and q_e transferred from the horizontal pipe to the vertical pipe.
iii) If $z<0$, carry out the flow analysis in the horizontal and vertical pipe for flow stage 3, and calculate q_l and q_e transferred from the horizontal pipe to the vertical pipe, and from the vertical pipe to the atmosphere, respectively. In this case, the dynamic analysis is not needed because the water column in the vertical pipe does not exist.
7) End the calculation if the pressure at the horizontal pipe fall to the atmospheric pressure or the time attains to the given calculation time. If not, return to step 2.

5. COMPARISONS WITH DATA

The results predicted by the analysis were compared with the experimental data obtained from the two different experimental apparatuses.

5. 1 10 m. Long Vertical Riser Pipe Case

Predictions of the pressure variation with the time are compared with the test results for the typical experimental conditions in Figs. 9 to 11 (Fig. 9 shows the comparison with the data for 4-in. pipeline, $P_{10}=5$ kgf/cm^{2}G, $Q_l=0.083$ m^3, Fig. 10 shows the data for 6-in. pipeline, $P_{10}=5$ kgf /cm^{2}G, $Q_l=1.09$ m^3. Flow stages 1, 2 and 3 are seen in Figs. 9 and 10. Fig. 11 shows the comparison with the test results of stage 1 for 4-in. pipeline, $P_{10}=3$ kgf/cm^{2}G, $Q_l=0.083$ m^3).

Agreement with the experiment for 4-in. pipeline is seen on the whole to be very good and the present analytical model is considered as satisfactorily simulate the pressure variation during the line blowing process. However, after the front of the bubble slug attains to the vertical riser pipe, namely, after the pressure peak in the back pressure appears, large pressure fluctuations are observed in Fig. 10. In 6-in. pipeline, wave appeared on the surface of the liquid layer at the tail of the long bubble slug as the gas moves downstream of the horizontal pipe. Because the thickness of the liquid layer increases and approaches to the upper side of the horizontal pipe, finally bridges the pipe and blocks the gas flow. So, pressure oscillations occur two to three times as a result of the bridging. This phenomenon is not predicted in the analysis.

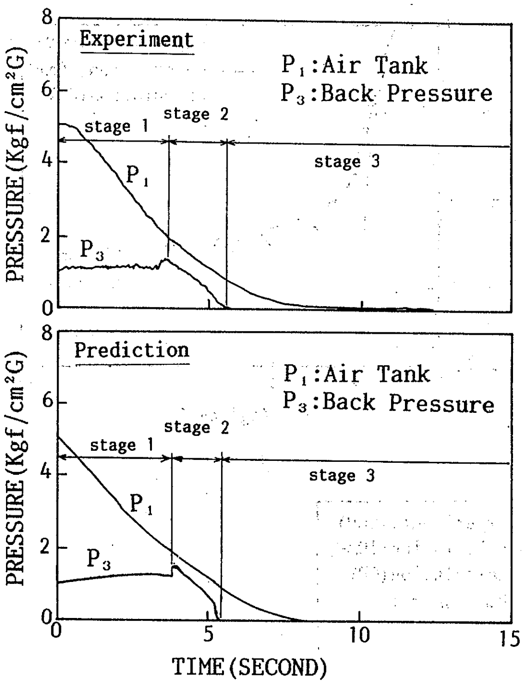


Fig. 9 Pressure variation with time (D=4-in.)

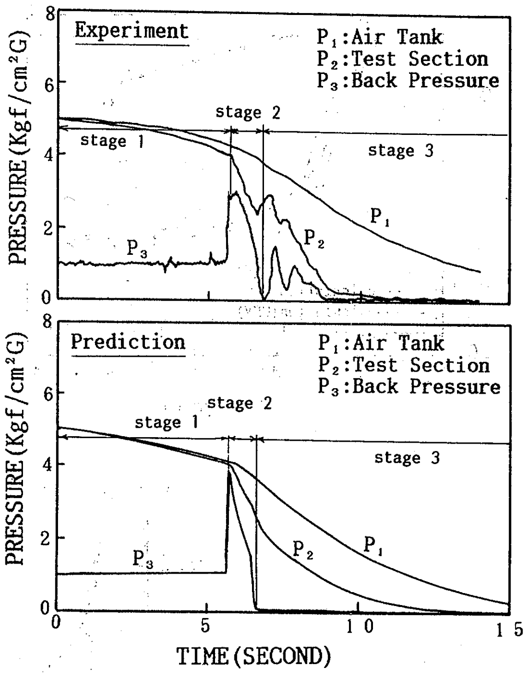


Fig. 10 Pressure variation with time (D=6-in.)

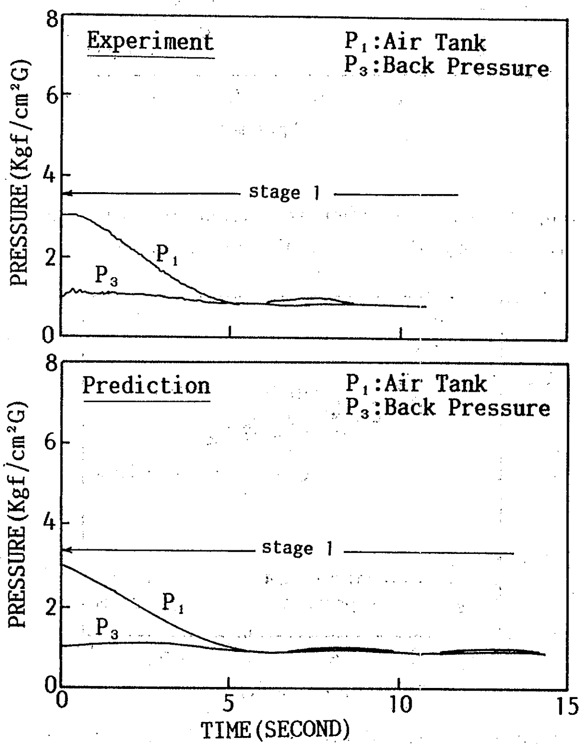


Fig. 11 Pressure variation with time (D=4-in., stage 1)

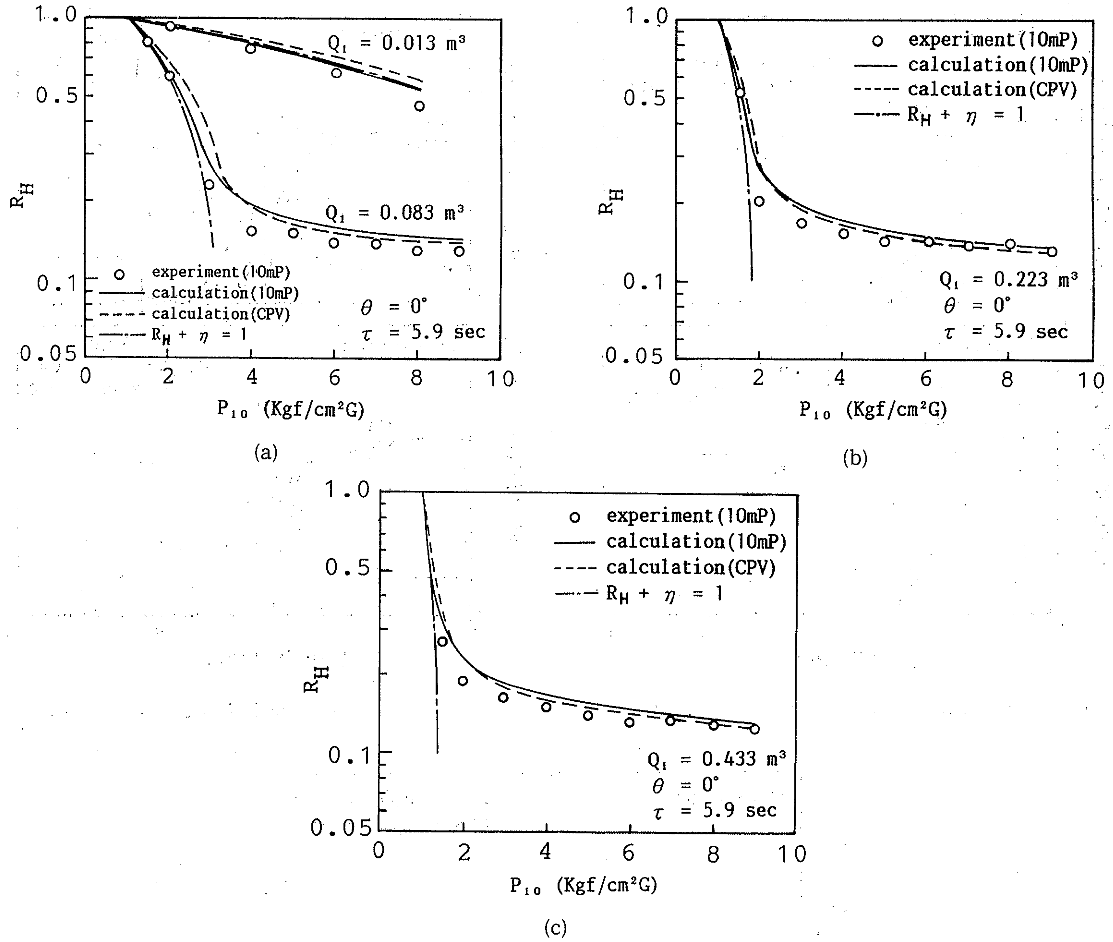


Fig. 12 Comparison of calculation with remaining water rate data for horizontal pipe (D=4-in., at the end of stage 1)

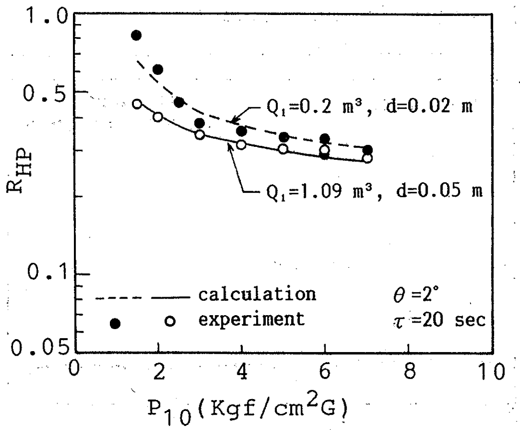


Fig. 13 Comparison of calculation with remaining water rate data for horizontal pipe (D=6-in., at the end of stage 1)

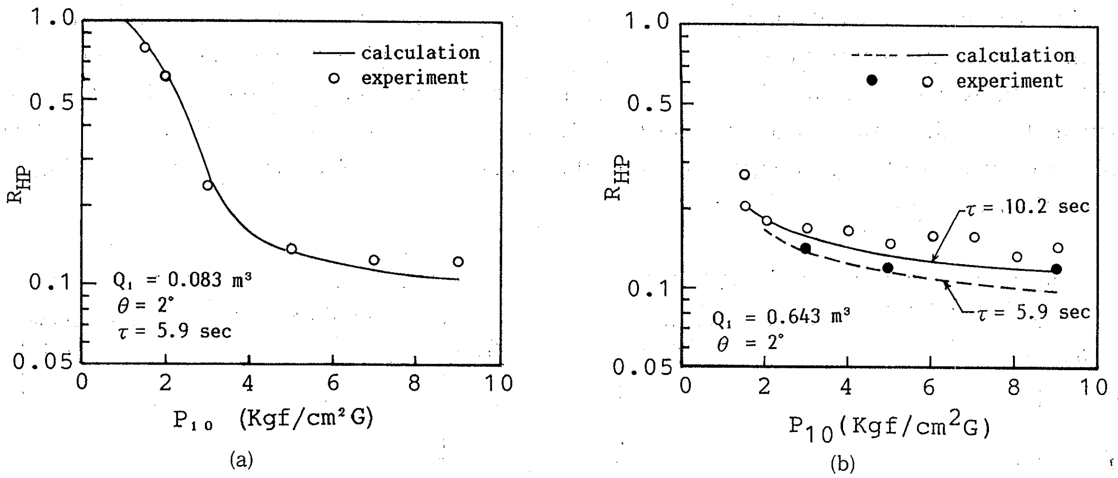


Fig. 14 Comparison of calculation with remaining water rate data for horizontal pipe for 10 mp experimental apparatus (D=4-in., at the end of stage 2)

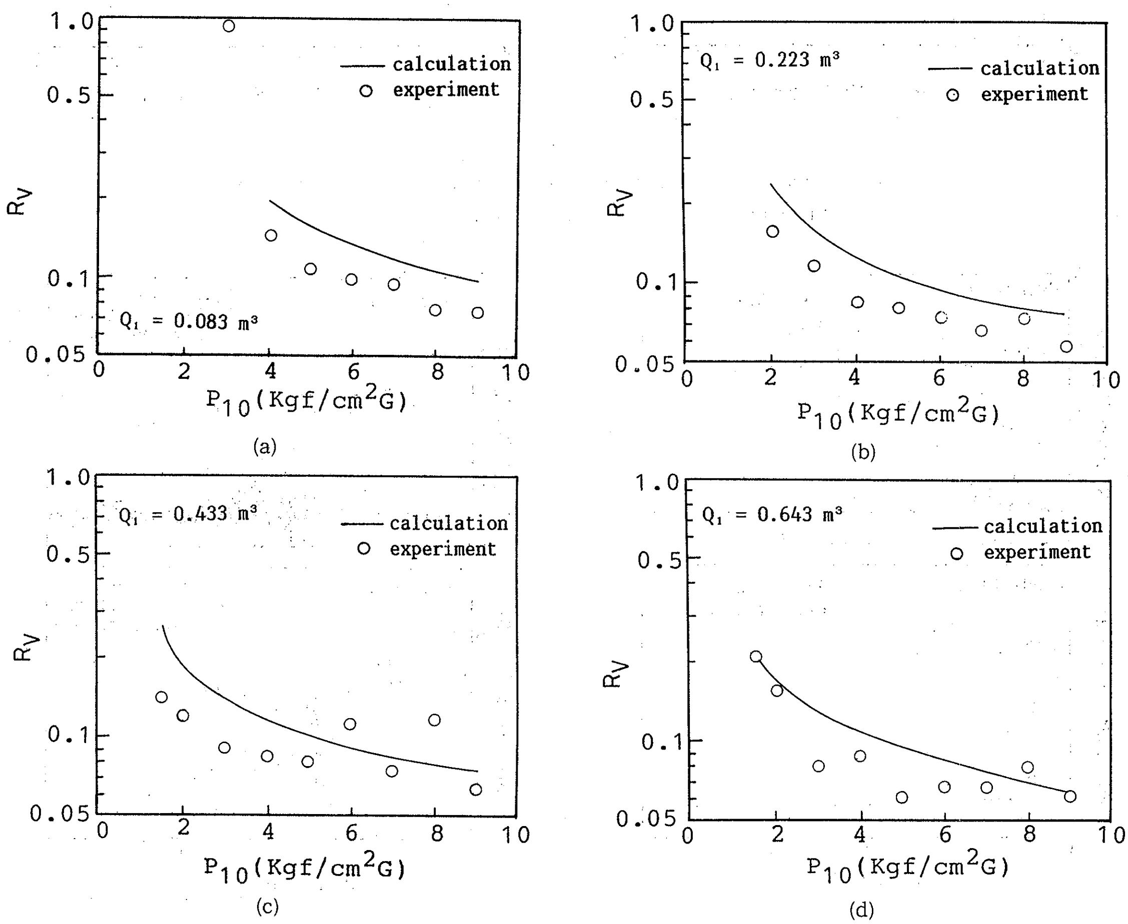
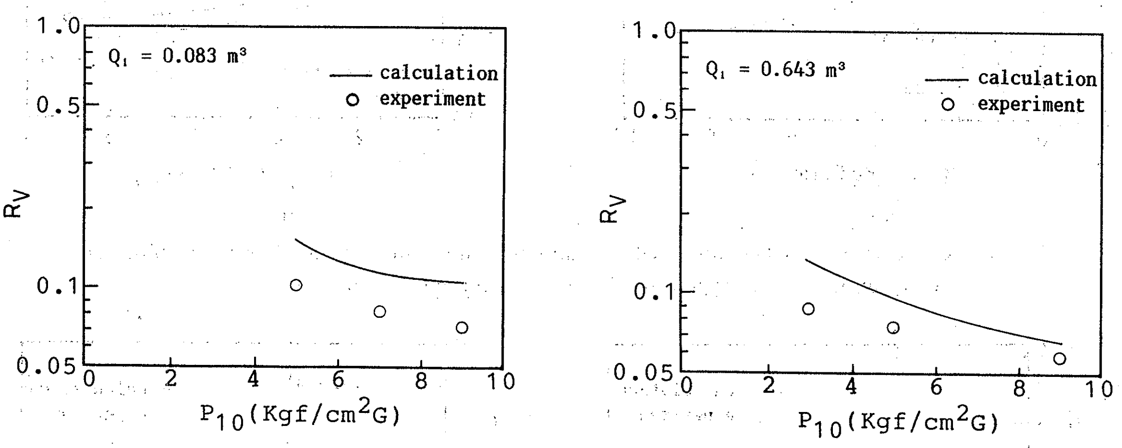


Fig. 15 Comparison of calculation with remaining water rate data for vertical pipe (D=4-in., τ=10.2 sec)

The remaining water data in the horizontal and vertical pipe for various pressure and the volume of the air storage tank, the full open time of the manifold valve, the diameter of the pipeline, the diameter of the air supply hose and the stopping mode of the line blowing were compared with the results of analysis in Figs. 12 to 16. The data for the horizontal pipe show close agreement with the predictions. But the predictions for the vertical pipe are slightly higher than the data.



(a) (b)

Fig. 16 Comparison of calculation with remaining water rate data for vertical pipe (D=4-in., τ=5.9 sec)

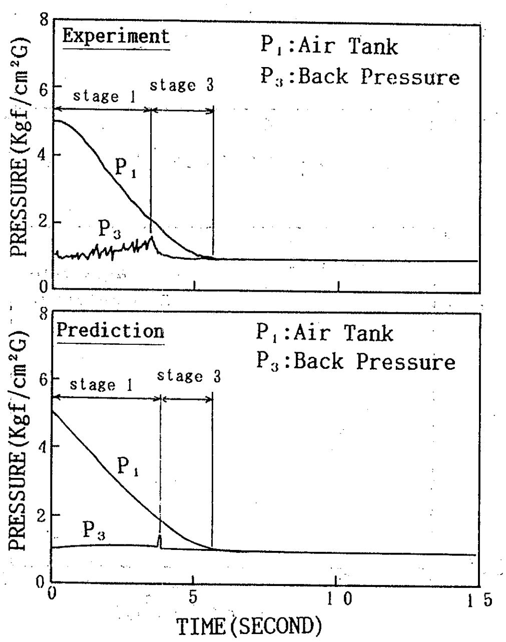


Fig. 17 Pressure variation with time for CPV experimental apparatus (D=4-in.)

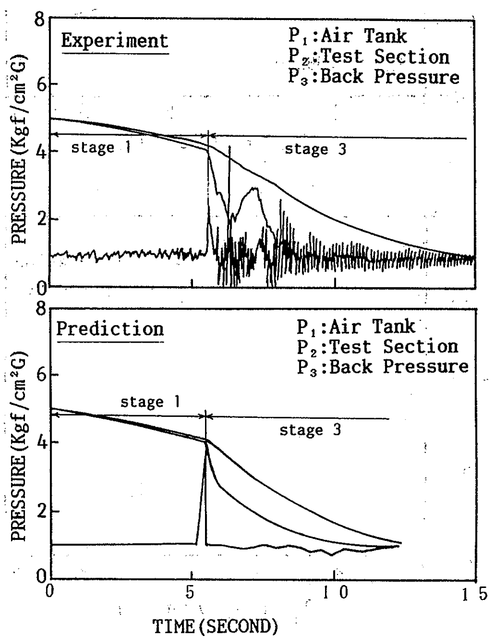


Fig. 18 Pressure variation with time for CPV experimental apparatus (D=6-in.)

5.2 Constant Pressure Valve Case

Predictions of the pressure variation with the time during the line blowing were compared with the data for typical experimental conditions in Figs. 17 and 18 (Fig. 17 shows the comparison with the data for 4-in. pipeline, $P_{10}=5$ kgf/cm^{2}G, $Q_1=0.083$m^3, Fig. 18 shows data for 6-in. pipeline, $P_{10}=5$ kgf/cm^{2}G, $Q_1=1.09$ m^3). Flow stages 1 and 3 are seen in these figures. Pressure fluctuations about 10 Hz due to chattering occur when air and water two-phase flow through the constant pressure valve. Pressure oscillations due to bridging of water are also observed in Fig. 18. Pressure fluctuations and pressure oscillations cannot be accounted for by present analysis. However, it appears that the results predicted by theory are on the whole in agreement with the experimental results. Next, the results predicted by the analysis were compared with the remaining water data. Good agreement with the data over a wide range of the experimental variable is shown in Figs. 19 and 20. The back pressure maintained by the

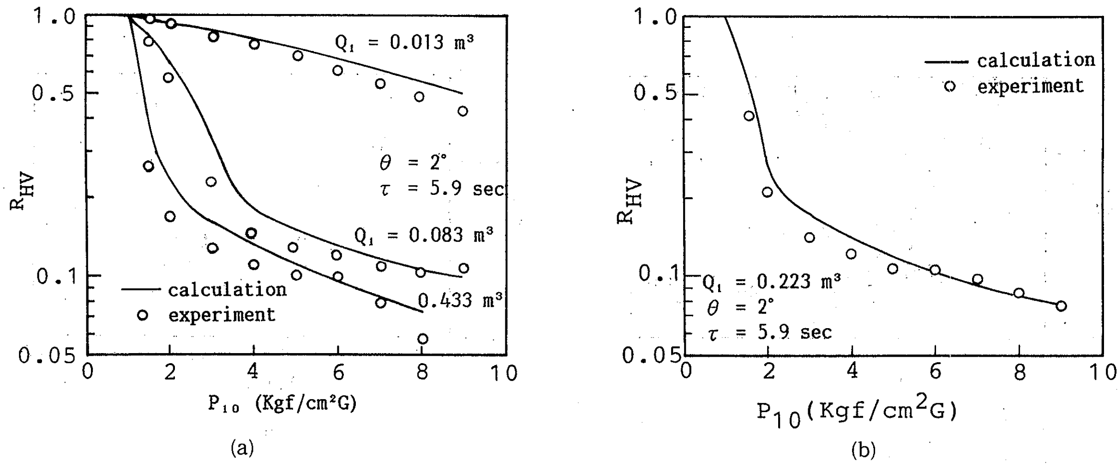


Fig. 19 R_{HV} vs P_{10} (D=4-in., Mode I)

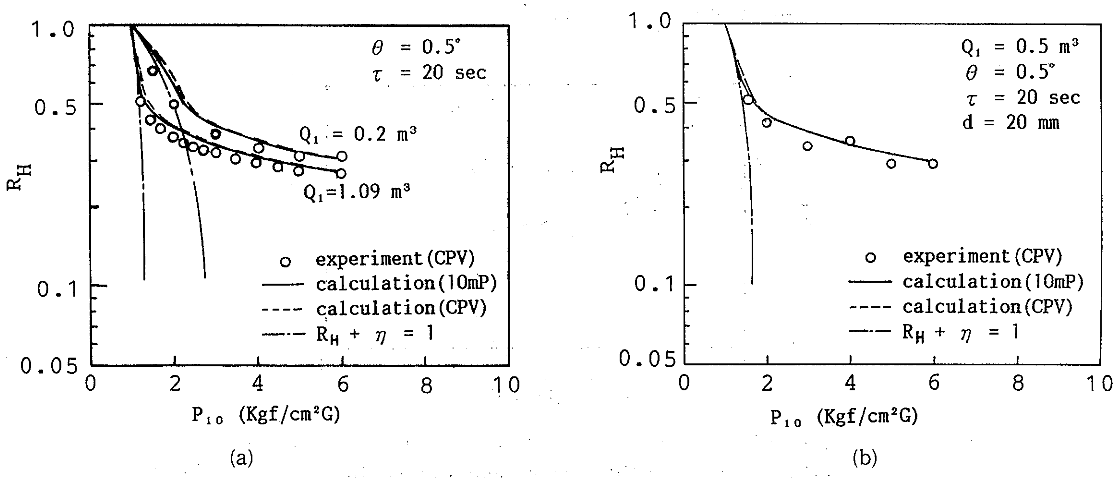
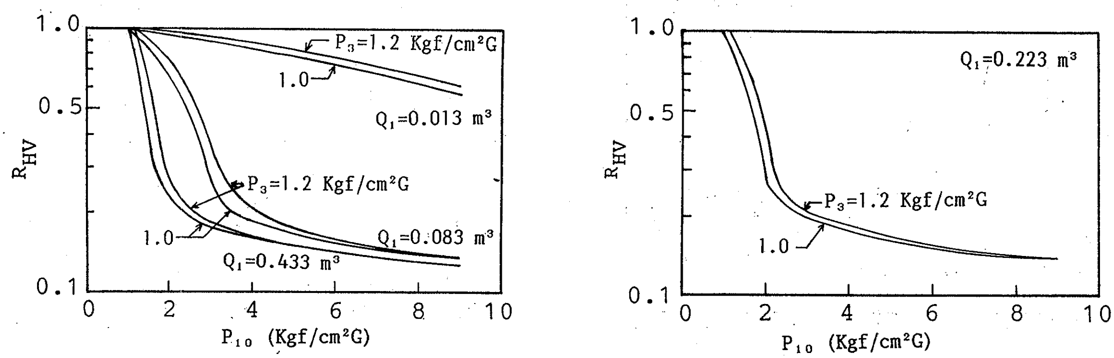


Fig. 20 R_{HV} vs P_{10} (D=6-in., at the end of stage 1) constant pressure valve deviates from the preset value while water is discharged from the pipe. Figs. 21 and 22 show the effect of increasing back pressure by 20% on the remaining water rate. As seen, the effect of increasing back pressure by means of the constant pressure valve on the remaining water rate is considered to be small. Consequently, calculated remaining water rate at the condition of back pressure$=1$kgf/cm^{2}G gives reasonable approximate value.

6. COMPARISON OF CALCULATED R_{HP} WITH CALCULATED R_{HV}

Calculated R_{HP} were compared with calculated R_{HV} at the end of stage 1 in Figs. 12 and 20. The back pressure maintained by the CPV and by the 10 mp is same value in static stage but is not same value in transient state. The small difference between R_{HP} and R_{HV} may be due to the influence of inertial force by the water column in transient state. However, the agreement between calculated R_{HP} and calculated R_{HV} is good. The experimental data of R_{HP} and R_{HV} also



(a) (b)

Fig. 21 Effect of increasing back pressure on remainig water rate in horizontal pipe for CPV experimental apparatus (D=4-in., at the end of stage 1)

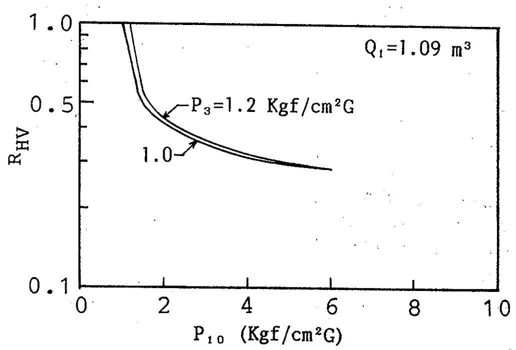


Fig. 22 Effect of increasing back pressure on remainig water rate in horizontal pipe for CPV experimental apparatus (D=6-in., at the end of stage 1)

agree well[1]. This probably means the effect of the method for maintaining back pressure on R_H is small. Representing the ideal limiting case of the line blowing ($R_H+\eta=1$) is also shown in Figs. 12 and 20. The agreements of calculated R_H with the ideal line blowing line are good at higher remaining water rate but calculated R_H deviates from the ideal line at lower remaining water rate. The effectiveness of the line blowing decreases at lower remaining water rate.

7. EFFECT OF PIPELINE LENGTH ON R_H

In unloading the cargo tanks of the chemical tanker, a long horizontal pipeline is equipped on land followed by the cargo piping on ship's side. So the effect of pipeline length on R_H was investigated. Predictions of R_H for the 10 mp test arrangement are shown in Fig. 23. R_H at the end of flow stage 1 decreases with the length for certain length of the pipeline because the velocity of the bubble front increases with length of the pipline.

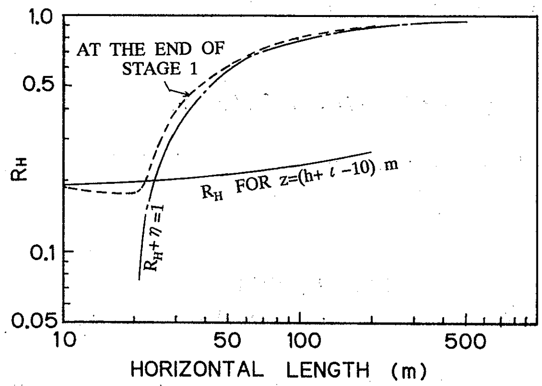


Fig. 23 Effect of horizontal pipe length on R_{HP} for 10 mp experimental apparatus ($D=4$-in., $P_{10}=5$ kgf/cm^{2}G, $Q_1=0.088$ m^3, $\tau=5.9$sec)

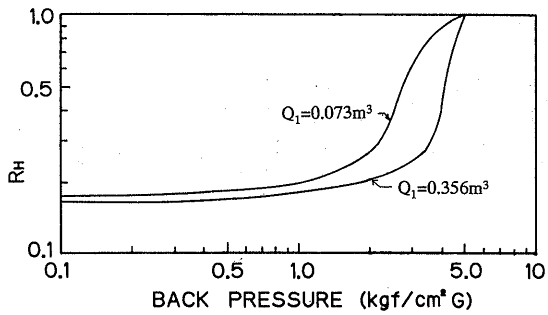


Fig. 24 Effect of vertical pipe length on R_H for 10 m length horizontal pipe ($D=4$-in., at the end of stage 1, $P_{10}=$ 5kgf/cm^{2}G, $\tau=5.9$ sec)

8. EFFECT OF BACK PRESSURE ON R_H

The effect of back pressure on R_H for varying length of the vertical riser pipe is shown in Fig. 24. It can be seen that the remaining water rate increases sharply after gradually increased with increasing the back pressure.

9. CONCLUSIONS

Physicallay based models for the line blowing were used to calculate remaining water rate in the horizontal pipe for the experimental apparatus maintainted the back pressure by the 10 m long vertical riser pipe and the constant pressure valve set at 1kgf/cm^{2}G. The test results have been compared with the analytical results. The model predicts well the line blowing process. Good agreement with the data for the remaining water rate in the horizontal pipe at the end of the flow stage 1 is obtained. Analysis suggests that the effect of increasing back pressure of the constant pressure valve on R_H is small and that the constant pressure valve has equivalent performance to the 10 m. long vertical riser pipe.

ACKNOWLEDGEMENTS

A part of this work was performed as the research program of the Shipbuilding Research Association of Japan.

REFERENCES

[1] K. Yamaguchi, K. Yamane, I. Aya, S. Namie and M. Ono, Papers of Ship Research Institute Vol. 27, No. 2, March 1990.
[2] T. Sakaguchi et al. , 3rd Int. Topical Meeting on Reactor Thermal-hydraulics, Vol. 2-20D. (1985).
[3] Zukoski, E. E. , J. Fluid Mech. **25** [4] , 821 (1966).
[4] D. J. Nicklin, J. O. Wilkes, and J. F. Davidson, Trans. Inst. Chem. Engrs., **40**, 61 (1962).
[5] for example, T. Ihara, "Kogyo Netsurikigaku" , Rikoh Tosho pp. 483-507.
[6] Govier, G. W. and Aziz, K., "The Flow or Complex Mixtures in Pipes" , Van Nostrand Reinhold, p. 428 (1972).
[7] Tomoe valve Co. , Cat. No. Ja 071-3
[8] JSME Mechanical Engineers' Handbook 4th ed. pp. 8-23.
[9] Levy,S., Int. J. Heat Mass Transfer, **9**, 171 (1966).
[10] Collier, J. G., and G. F. Hewitt, Trans. Inst. Chem. Engrs., **39**, 127 (1961)