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DISCHARGING FLOW BEHAVIOR FROM DISK-TYPE FLOW CONTRACTION

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ABSTRACT The disk-type flow contraction can be seen at the opening condition of safety or relief valves. The discharging flow rate is restricted with the minimum flow area between disk and pipe end. The flow rate is usually smaller than the calculation with the minimum flow area due to the vena contraction. The discharging flow rate of liquid was measured at different lifts and seat configurations. The liquid flow rate was affected with the lift and seat due to the different formation of vena contraction. The two-phase discharging flow rate was also measured and compared with the non-equilibrium critical flow model. The two-phase flow rate was affected not only with the vena contraction but also with the critical flow rate. It was suggested that the discharging coefficient of two-phase flow was larger than that of single-phase flow. The single and two-phase discharging behavior was carefully observed by using the transparent disk.

Keywords: Safety valve, Discharging flow, Vena contraction, Seat, Lift, Critical Flow, Non-equilibrium

1. INTRODUCTION

When safety or relief valves are open, fluid is discharged through the disk-type flow contraction. The contraction is the minimum flow area between disk and pipe end, which is called as the curtain area of valve as shown in Fig.1. The curtain area *A* is defined as,

$$A = Ld\pi \qquad (1)$$

where L is the valve lift and d is the valve diameter. The valve seat is defined as the surface of pipe end which contacts to the disk at closing

The flow rate of discharging fluid is restricted with the curtain area. The discharging flow rate is usually smaller than the flow rate calculated with the curtain area due to the vena contraction. The vena contraction is strongly affected with the valve lift and the seat configuration.

The vena contraction also can be seen in the flow through orifice. Generally when a fluid flows through the contraction such as orifice or disk-type contraction, the flow rate is approximately 60% of the calculation using the minimum flow area. So in the actual design of orifice or valves, the discharging coefficient of approximately 0.6 is usually used to calculate the flow rate. However the vena contraction is mitigated in the thick orifice(1) or narrow passage where the discharging coefficient becomes larger than 0.6.

When the subcooled liquid or two-phase flow enters into the contraction, the phenomena become much more complicated due to the phase change. The phase changing flow rate was affected not only with the vena contraction but also with the critical flow rate. Furthermore the critical flow rate is strongly affected with the non-equilibrium as known as the delay of boiling.

The discharging coefficient obtained in single phase flow could be used in the prediction for the flashing flow rate(2)(3) of subcooled liquid from safety valves. The international standard ISO recommends the discharging coefficient of 0.65 both for single and two-phase flow. However, the regulation by ASME gives 0.65 for single phase and 0.8 for two-phase flow. It was suggested that the vena contraction for two-phase was different from that for single-phase flow. It should be noted that the non-equilibrium behavior and the vena contraction in the disk-type contraction is not well understood. For the correct regulation of safety and relief valves, it is very important to investigate the behavior of discharging single and two-phase flow under the clear boundary conditions in this study.

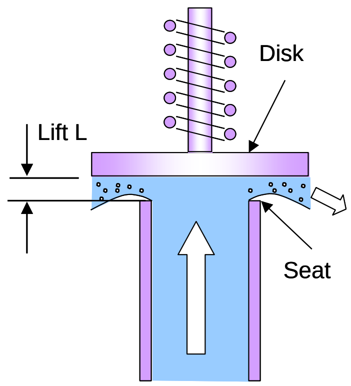

Fig.1 Disk-type flow contraction

2. EXPERIMENTAL APPARATUS AND METHOD

Shown in Fig.2 is the schematic of experimental apparatus. Water is supplied from the water tank to the test section after depressurized through the control valve. When the depressurization exceeds the saturation pressure, flashing takes place and two-phase is supplied to the test section. The water tank is connected with steam boiler and air compressor, and can be pressurized up to 0.6 MPa. The flow rate through the test section is measured with the electromagnetic flow meter of which measurement error is within ±0.5%. The meter without a contraction can prevent the flashing. The pressure is measured with pressure gage of which measurement error is within ±1.25 Pa. T-type sheath thermocouple of 1mm in diameter is used to measure the temperature. The water tank has a water level indicator to confirm the discharging flow rate.

The vena contraction is strongly affected with the valve lift and the seat. The taper and parallel seats were used in the present experiment to study the effect of seat configuration. The test section is the simple disk-type contraction consisted of pipe and disk as shown in Fig.3. The inner and outer diameters of pipe were 10 and 30 mm, respectively. Thermocouple and pressure gage were installed just before the curtain area. The measured pressure and temperature were used to calculate the discharging coefficient and non-equilibrium. The outside of the curtain area was open to atmosphere. The valve lift between the seat and disk was measured with a narrow gage or a laser distance meter. The valve lift was set at between 0.3 and 2.5 mm in the present experiment. So the ratio of lift to diameter was between 0.03 and 0.25. As the material of disk, brass and transparent glass was used to provide the observation and different boiling ability.

The temperature of water was approximately 20°C and the discharging pressure was controlled between 0.1 to 0.6 MPa for liquid discharging experiment. On the other hand, the discharging pressure of 0.14 to 0.45 was maintained and liquid subcooling was adjusted in the flashing experiment. Basically the experiments were conducted with changing the discharging pressure and temperature step by step. .

The discharging behavior was recorded with video camera. The observation of discharging flow was conducted both from the side and the back of transparent disk. The observation from the disk back is expected to find cavitation or flashing two-phase flow just downstream of the curtain area.

The coefficient of discharging liquid flow can be calculated by using volumetric flow rate Q, the pressure difference ΔP between the discharging pressure and atmospheric pressure, and curtain area A as,

$$c_v = \frac{Q}{A}\sqrt{\frac{\rho}{2\Delta P}} \tag{2}$$

where $A = Ld\pi$, ρ is fluid density.

3. EXPERIMENTAL RESULTS

3.1 Liquid discharging behavior

Shown in Fig.4 is the flow through an orifice. The fluid converges to flow through the hole and sometimes results as the too much contraction of flow called as the vena contraction. When the ideal fluid flows through a hole of thin orifice, the area ratio of vena contraction to hole is[1] expressed as,

$$\beta = \frac{\pi}{2+\pi} = 0.61 \tag{3}$$

So the discharging flow rate is usually smaller than the flow rate calculated with the area of hole due to the vena contraction. In thick orifice, the flow after the vena contraction sometimes re-attach to the wall of hole as shown in Fig.4. The re-attachment makes a separation bubble just after the curtain area. It should be noted that the discharging coefficient becomes larger than 0.61 when the separation bubble is formed. The vena contraction is mitigated with the re-attachment of flow to the wall.

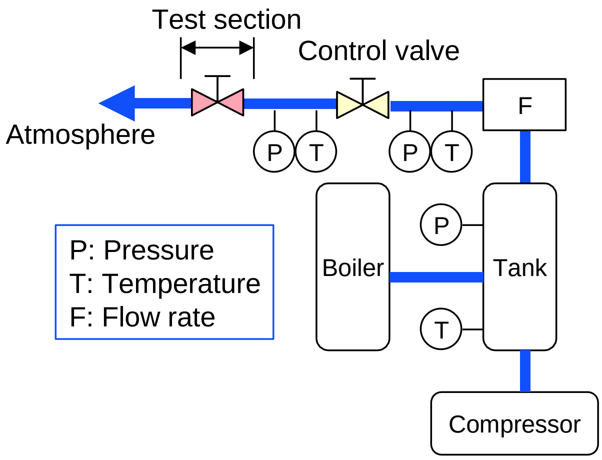

Fig.2 Experimental apparatus

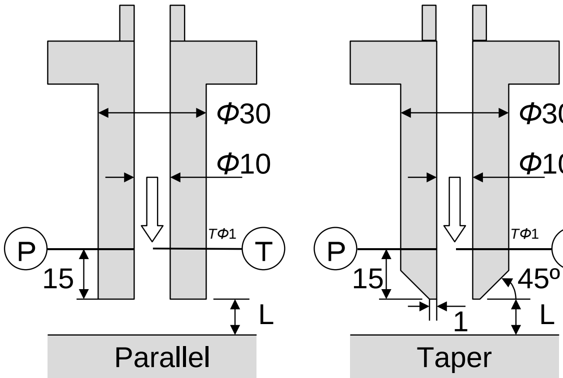

Fig.3 Valve seat configuration

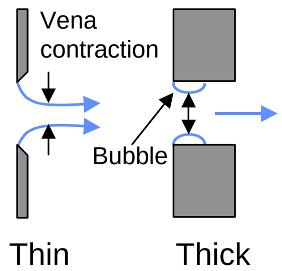

Fig.4 Flow through orifice

Shown in Fig.5 is the relation between liquid discharging coefficient and pressure difference in the disk-type contraction of this study. The dash-dotted line is c_v=0.61 that is same as the ideal fluid flows through a hole of thin orifice. All data at lift of 0.3 to 2.5mm agree well with c_v=0.61 for the taper seat. It is considered that the taper seat can provide the free flow and vena contraction as same as the thin orifice.

On the other hand, the discharge coefficient is larger than 0.61 at lift less than 1mm for the parallel seat when the pressure difference is small. The coefficient gradually decreases as the pressure difference increases. The coefficient larger than 0.61 suggests the free flow like orifice cannot be obtained. It is clear that the discharging flow is affected with the seat configuration. Increasing the pressure difference and discharging velocity, the coefficient suddenly drops to c_v=0.61 as shown in Fig.5. This sudden drop indicates the change of vena contraction.

All the data of discharge coefficient for the parallel seat are approximately 0.61 at lift of 2.5mm. When the lift is enough large compared to the radial length of seat, the vena contraction becomes as same as that for the taper seat.

The pressure difference at which the discharging coefficient becomes c_v=0.61 is larger at the smaller lift. The larger pressure difference and the higher velocity are needed at the smaller lift to make a free flow like the orifice flow. It is considered that the seat configuration can affect the vena contraction at the smaller lift condition. On the other hand, the taper surface always gives a flow like the orifice.

Shown in Fig.6 is the relation between Re and discharging coefficient for all the data. The dash-dotted line is also c_v=0.61 when the ideal fluid flows through a hole of thin orifice. Increasing the pressure difference and Re, the coefficient suddenly drops to c_v=0.61. The Re at which the discharging coefficient becomes c_v=0.61 is smaller at the smaller lift. At the drop, Re once decreases and again increases with increasing pressure difference. The sudden drop of discharging coefficient decreases the flow rate and Re, and increases again with increasing pressure difference.

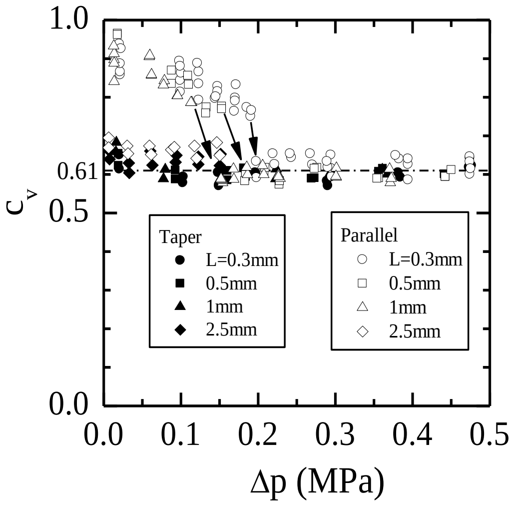

Fig.5 Relation between discharging coefficient and pressure difference

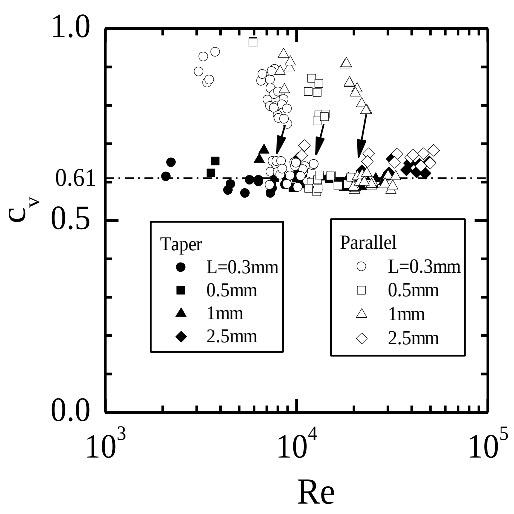

Fig.6 Relation between discharging coefficient and Re

The sudden drop of discharging coefficient can be seen only in the parallel seat. The flow behavior at the drop was observed from the side. The discharging behavior for the lift of 1mm and the parallel seat is shown in Fig.7. Before the sudden drop of coefficient, the discharging flow is contacting to the rim of parallel seat as shown in the left photo of Fig.7. The gap between seat and disk was filled with the discharging flow. After the sudden drop of coefficient, the gap between seat and disk was not filled with the flow. The space between the seat and water film could be observed and the thickness of water film became thinner.

However there was no change of discharging flow in the taper seat even when the lift is less than 1mm as shown in Fig.8. The discharging water film is thin as same as the condition after the sudden drop in the parallel seat. When the lift is 2.5 mm in taper and parallel seats, the space between the seat and water film was always observed and the sudden drop was not observed as shown in Fig.9.

The flow change at the sudden drop of coefficient was observed from side as mentioned above. The clear observation was not obtained when the flow rate was relatively large. So the test section was set upside down and the transparent disk was installed for the observation from disk back. In the observation, the lift was fixed at 1 mm and the flow behavior affected with the seat configuration was investigated. The upside down state was also used in the flashing experiment to provide the smooth upwards flow of two-phase.

c_v>0.61 c_v=0.61

Fig.7 Discharging behavior in parraller seat (L=1mm, ΔP=0.15MPa)

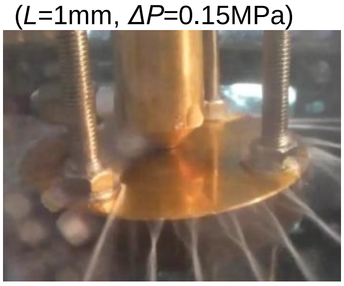

Fig.8 Discharging behavior in taper seat (L=0.3mm, ΔP=0.3MPa)

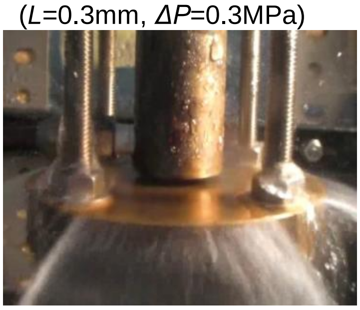

Fig.9 Discharging behavior at lager lift in parraller seat (L=2.5mm, ΔP=0.1MPa)

The white annulus between the parallel seat and disk was observed from the disk back as shown in the left photo of Fig.10 when the pressure difference and discharging velocity is small. When the annulus existed, the noisy sound was recognized. The sound is considered to be due to cavitation of flow. Further increasing the pressure difference, the sudden drop of coefficient took place and the white annulus with the sound disappeared. The seat can be seen clearly as shown in the right photo of Fig.10. This indicates the gap between the seat and disk was not filled with water.

The flow observation in the taper seat does not show the flow change as that in parallel seat. The thin water film is always discharged as shown in Fig.11.

The discharging flow rate is usually smaller than the flow rate calculated with the curtain area due to the vena contraction. The vena contraction is strongly affected with the valve lift and the seat that is the surface of pipe end which contacts to the disk at closing. When the pressure difference and flow rate are small in the parallel seat, the flow after the vena contraction re-attach to the seat as shown in the left of Fig.12. The re-attachment makes a separation bubble just after the curtain area. So at the separation bubble region, the pressure decreases below the outlet pressure of atmosphere and the cavitations occurs. The cavitation is recognized as the white annulus in the left photo of Fig.10. It should be noted that the discharging coefficient becomes larger than 0.61 when the separation bubble region is formed. The vena contraction is mitigated with the re-attachment of flow to the seat as same as the thick orifice.

On the other hand, the larger lift prevents the re-attachment and formation of separation bubble. The gap between seat and disk was not filled with the flow as shown in the right of Fig.12. The larger pressure difference and the higher discharging velocity also prevent the re-attachment even at the smaller lift. In this case, the pressure smoothly decreases to atmosphere and the cavitations do not appear.

c_V>0.61 c_V=0.61

Fig.10 Discharging behavior in parralle seat (L=1mm, ΔP=0.15MPa)

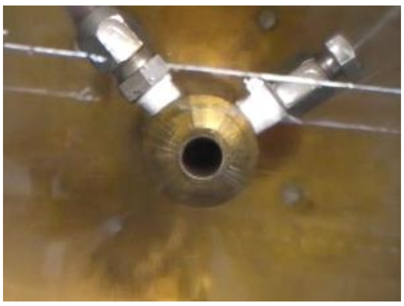

Fig.11 Discharging behavior in taper seat

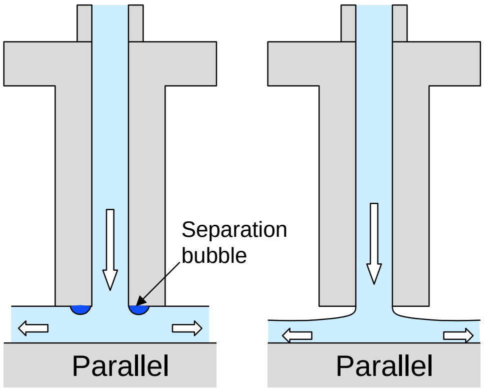

Fig.12 Vena contraction in parallel seat

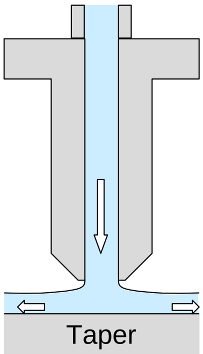

Fig.13 Vena contraction in taper seat

Also the taper seat prevents the re-attachment and formation of separation bubble as shown in Fig.13. In this case, the pressure also decreases to atmosphere smoothly and the cavitations do not appear.

3.2 Two-phase discharging behavior

Energy balance gives the following equation of discharging mass flux assuming the isentropic change.

$$G = \frac{u_1}{v_1} = \frac{1}{v_1}\sqrt{2\Delta h} \tag{4}$$

Considering the phase change does not take place until the saturation pressure p_S, the enthalpy drop in Eq.(4) can be described as,

$$\frac{(Gv_1)^2}{2} = -v_0(\,p_s - p_0\,) - \int_{p_S}^{p_1} v dp \tag{5}$$

Below the saturation pressure, the phase change takes place. When the actual specific volume v' is expressed as

$$v' - v_S = N(\,v - v_S\,) \tag{6}$$

where N: non-equilibrium parameter, v: specific volume at equilibrium, v_S: specific volume at saturation pressure. The non-equilibrium parameter N is between 0 and 1. When N is 0, the phase change is completely depressed. In the previous study, N of 0.035 is recommended to describe the flashing flow through the valves. Equations (5) and (6) give

$$\begin{aligned}\frac{(Gv_1')^2}{2} &= -v_0(\,p_s - p_0\,)\\ &\quad + N(\,h_S - h_1\,) + (1-N\,)v_S(\,p_S - p_1\,)\end{aligned} \tag{7}$$

When the valve inlet is already two-phase flow, the depressurized volume is described as,

$$v' - v_0 = N\left(v \ - v_0\right) \tag{8}$$

So the mass flux can be expressed as

$$\frac{\left(Gv_1'\right)^2}{2} = N\left(h_0 - h_1\right) + \left(1 - N\right)v_0\left(p_0 - p_1\right) \tag{9}$$

When the phase change does not take place, the mass flux can be expressed with the Bernoulli equation as,

$$\frac{\left(Gv_1\right)^2}{2} = v_0\left(p_0 - p_1 \right) \tag{10}$$

The mass flux defined at the curtain area of valve can be obtained by multiplying the discharging coefficient c_v. In this paper, the non-dimensional mass flux was defined as,

$$G^* = \frac{G}{\sqrt{p_0 / v_0}} \tag{11}$$

Shown in Fig.14 is the relation between non-dimensional mass flux and the inlet subcooling. The experimental data was obtained at the inlet pressure of 0.14-0.45 MPa by using the transparent glass and brass disks. To eliminate the effect of lift and seat, the lift was fixed at 1 mm and the taper seat was used in the two-phase experiments. The data gradually decreases as the subcooling decreases. The lines in the figure is the prediction with Eq.(7) at the pressure of 0.35 and 0.2 MPa. The effect of pressure on the calculation is considered to be relatively small. The non-equilibrium coefficient of 0.035 and the discharging coefficient of 0.61 were used in the calculation. Generally the experimental mass flux is larger than the prediction and some data near the zero subcooling condition agree well with the prediction.

Shown in Fig.15 is the photo from the back of transparent disk at subcooling of 3.3 and 1.2K. The small bubbles radiated in all directions just after the curtain area at the subcooling of 3.3 K in the left photo. The radial streams of small bubbles like the spokes of a wheel could be recognized. When the subcooling decreased to 1.2 K in the right photo, the vigorous flashing after the curtain area can be observed. This low subcooling data can be well predicted with the non-equilibrium critical flow model.

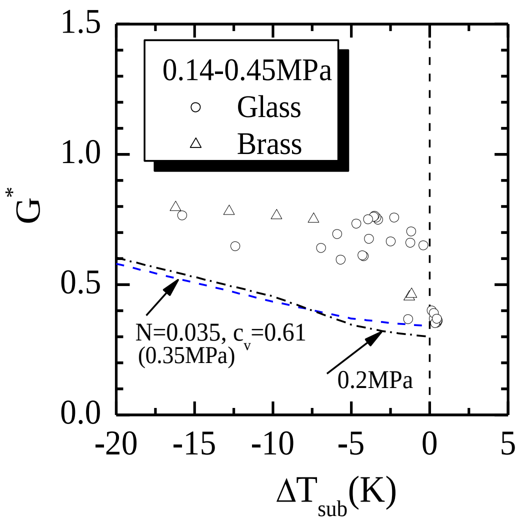

Fig.14 Mass flux of subcooled liquid

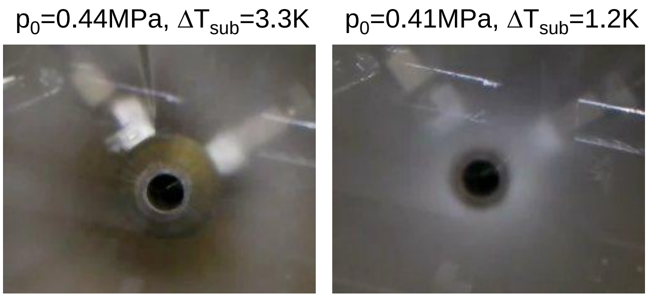

Fig.15 Flashing behavior of subcooled liquid

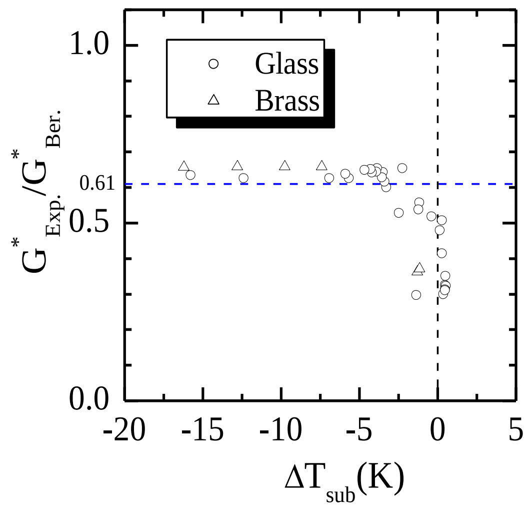

Fig.16 Ratio of experimental mass flux to Bernoulli prediction of subcooled liquid

The experimental mass flux was divided with the Bernoulli mass flux by Eq.(10). Shown in Fig.16 is the relation between the divided ratio and the inlet subcooling. The data of high subcooling agree well with the single phase discharging coefficient of 0.61. This suggests the no phase change before the vena contraction. The decreasing ratio near the saturated temperature suggests the phase change. It is considered that the boiling was depressed significantly as the boiling ability of glass and fresh brass surfaces are relatively low compared to the common metal for industrial usage.

Shown in Fig.17 is the relation between discharging two-phase mass flux and the inlet quality. The experimental non-dimensional mass flux gradually increases as the quality increases. The line shows the calculation result by Eq.(9) assuming N of 0.035. As the ASME standard adopted the larger discharging coefficient than that for the single phase, c_v of 1 is tentatively used in the calculation. The increasing behavior of Eq.(9) is similar to the experimental data. On the other hand, the closed symbols show the calculation result by the Bernoulli equation (10) for each data. The discharging coefficient c_v of 1 is tentatively used also in this calculation. The Bernoulli results indicate the no phase change and the non-equilibrium parameter N of 0. At the high quality region, the experimental data approximately agree with the Bernoulli result. This suggests the higher c_v than the single phase flow and no phase change at the region. The experimental data locate between the Bernoulli and non-equilibrium critical calculation assuming N of 0.035.

4. CONCLUSION

The single-phase liquid discharging flow rate for the taper and parallel seats was measured at the different lift and inlet pressure. The flashing two-phase flow rate for the taper seat with lift of 1 mm was also measured at the different inlet pressure and subcooling. The followings are major results.

(1) The liquid discharging mass flux at lift of 0.3 to 2.5mm for the taper seat and lift of 2.5mm for the parallel seat agreed well with the discharging coefficient c_v=0.61. It is considered that the taper seat or the enough large lift can provide the free flow and vena contraction as same as a thin orifice.

(2) The discharging coefficient of liquid was larger than 0.61 at the lift less than 1mm for the parallel seat when the pressure difference was small. The observation of flow suggested the flow after the vena contraction re-attached to the seat. The re-attachment made a separation bubble just after the curtain area. At the separation bubble region, the pressure of flow decreased below the outlet pressure of atmosphere and the cavitation occurred. Increasing the inlet pressure, re-attachment suddenly disappeared and the coefficient became 0.61.

(3) The pressure difference to obtain the liquid discharging coefficient of 0.61 was larger at the smaller lift. The larger pressure different and the higher velocity were needed at the smaller lift to make a free flow like an orifice flow.

(4) The non-equilibrium coefficient of 0.035 and the discharging coefficient of 0.61 were used in the calculation for the flashing of subcooled liquid. Generally the experimental mass flux was larger than the prediction and some data near the zero subcooling condition agreed well with the prediction.

(5) The experimental mass flux for the flashing of subcooled liquid at the high subcooling agreed well with the Bernoulli mass flux with the discharging coefficient of 0.61. This suggests the no phase change before the vena contraction. It is considered that the boiling was depressed significantly as the boiling ability of glass and fresh brass surfaces are relatively low compared to the common metal for industrial usage.

(6) At the high quality region, the experimental data approximately agreed with the Bernoulli result with c_v=1. This suggests the higher c_v than the single phase flow and no phase change at the region. The experimental data located between the Bernoulli and non-equilibrium critical calculation assuming N of 0.035.

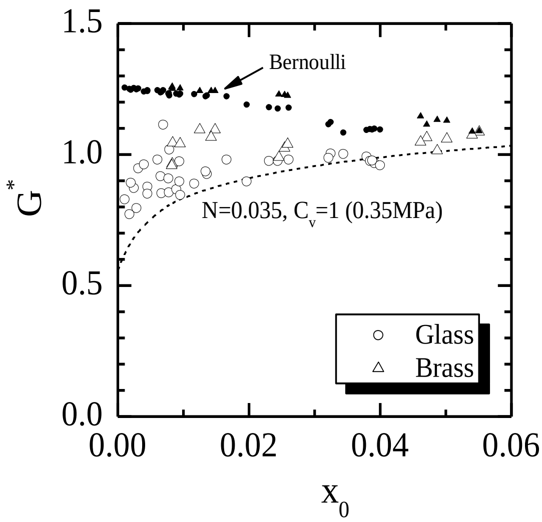

Fig.17 Mass flux of two-phase flow

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NOMENCLATURE

A : Curtain area [m^2]
c_v : Discharging coefficient [-]
d : Pipe diameter [m]
G : Mass flux [kg/m^2]
h : Enthalpy[kJ/kg]
L : Lift [m]
N : Non-equilibrium parameter [-]
p : Pressure [Pa]
Q : volumetric flow rate [m^3/s]
T : Temperature [K]
v : Specific volume [m^3/kg]
β : Vena contraction ratio[-]
ρ : Density [kg/m^3]

subscript

s : Saturated
sub : Subcooled
0 : Inlet
1 : Outlet