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EXPERIMENTAL INVESTIGATION AND A SIMPLIFIED THEORETICAL MODEL ON THE BISTABLE SWITCHING OF A WALL ATTACHMENT FLUID DEVICE

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ABSTRACT

In this paper, the switching transient of the attached jet in a bistable fluid device is experimentally investigated, and a more practical model for splitter switching is proposed, based on the results of foregoing experiment. The behaviour of jet was observed to examine the effect of loads and control flow rate. Above all, in the small control flow region, a remarkable feature of the bubble volume was recognized through the switching transient. Consequently, it was shown that the bistable switch, considerably affected by splitter, might be described by means of the two-phases model, since the switching process could be divided into two parts which were distinguished each other.

1. Introduction

Since a study on the dynamic features of wall attachment fluid devices was attempted by Muller (1964), a considerable amount of result has been reported on the attached jet. However, it is still remained under difficult condition to set up the competent theoretical model which represents the bistable switching of jet with reasonable correctness, because of not only geometrical complexity of devices, but also properties of working fluid. It is wellknown that there are three types of switching which are termed (a) end-wall switching, (b) splitter switching and (c) opposite-wall switching. Properly, in the practical devices, it is rare case that the jet is switched in terms of only one mode, the actual switching is caused by the combination of some modes as to be mentioned above. Generally speaking, the end-wall switching yields, when the device has relatively short attachment walls and large offset with small control to supply flow ratio. And the opposite-wall switching yields, when the device has small offset with large control to supply flow ratio. As for end-wall switching, it seems that the first attempt to analyze this type of switching was done by Lush (1968). This technique was developed in terms of combined jet formed by supply and control jets and accomplished as Epstein's model (1971) which consisted of three phases of switching transient. A theoretical analysis on the case of opposit-wall switching was attempted by Ogzu and Stenning (1972), and some important results were obtained.

On the other hand, the analytical technique given by Goto and Drzewiecki (1973) was based on the complete model in which the effect of vents, splitter and opposite wall were taken into account, and the effect of input and output impedances was also included. However, this method was very lengthy and required the solution of extremely many simultaneous equations, although the results agreed well with experiment. On the contrary, a simpler model had been submitted by authors (1975), and how to determine the actual value of jet spread parameter throughout the switching transient was proposed. This paper presents a more simplified two-phases model for splitter switching, which is developed from previous method and based on the result of additional experiment.

2. Nomenclature

A =sectional area
J =jet momentum/unit depth
P =static pressure
Q =volume flow rate/unit depth
R =radius of curvature of the jet
S =distance along the jet center line
U=velocity of the jet
V=bubble volume/unit depth
b =nozzle width
d =wall offset
l =splitter distance
t =time
x =reattaching distance
y =distance normal to the jet center line
α =inclined angle of the wall
β =angle between the vector of reattaching streamline and the line tangential to the reattaching streamline
γ =reattaching angle
ζ =pressure loss coefficient
ν =kinematic viscosity
ρ =density of fluid
σ =jet spread parameter
τ $=\left(t\dfrac{Us}{bs}\right)$=nondimensional time
ϕ =deflection angle of the jet

subscripts
L =left hand side towards downstream of the main jet
R =right hand side towards downstream of the main jet
c =control
l =load or output
o =initial or free state
r =reattaching point
s =supply

3. Outline of Experimental Setup

In such a case that the dynamic behaviour of jet passing through the device is not predicted, the dimensions of experimental device cannot been help deciding by analogy based on the past experimental results or experiences. The bistable wall attachment device, applied to the experiments, was made of clear acrylic resin boards with 5 mm of supply and control nozzle widths, 10.5 mm of offset, 100 mm of splitter distance, 15° of wall angle and 2.8 of aspect ratio, as shown in Fig. 1. Fresh water was used for working fluid, and fine particles of polystylene resin was mixed into the fluid as tracer in order to visualize the stream. Mean diameter of the particles was 0.75 mm, and their density was almost 1.04 kg/m^3. The outline of experimental setup is illustrated in Fig. 2. Working fluid was once pumped up to the head-tank of nearly 4.8 m high, and supplied to the main nozzle through a flowmeter and a throttle valve. Control flow is also supplied from the same head-tank, but a solenoid valve and a pressure accumulator, as shown in Fig. 3, were installed between the throttle valve and the control port of the device. This accumulator was utilized to eliminate violent fluctuation of control pressure at the beginning of the valve opening. In order to apply static pressure to the control port, an overflow-tank, as shown in Fig. 4, was prepared. The outlets of device were connected with reservoir through the valves by which the output resistances of the device could be regulated. The pressure transducers were used for measurement of unsteady pressure at the control and output ports, and pressure difference between symmetrically located ports could be electrically obtained by

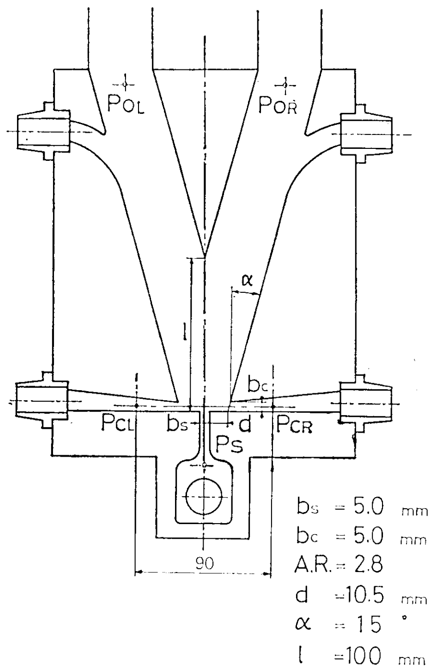


Fig. 1. Geometry of experimental device

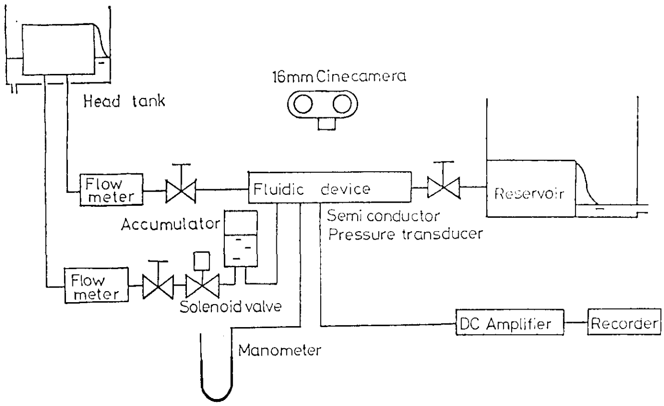


Fig. 2. Outline of experimental setup

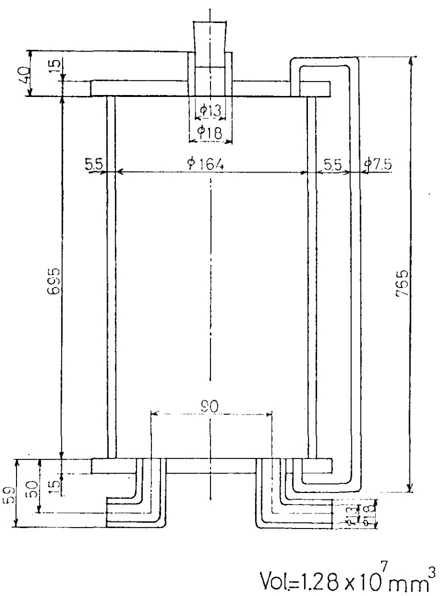


Fig. 3. Sectional view of the pressure accumulator

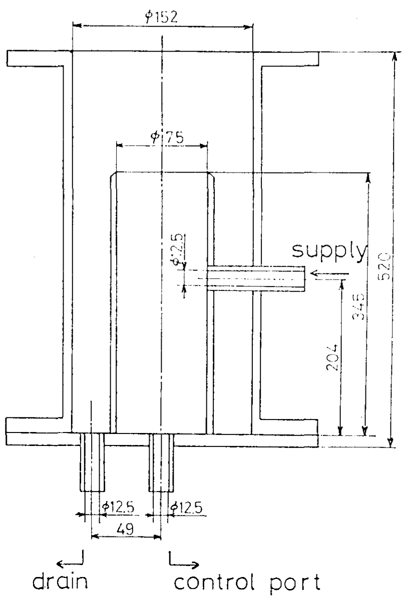


Fig. 4. Sectional view of the overflow tank

mixing amplifires, while static pressure in steady state was measured by water or mercury manometers. Behaviour of the jet in switching transient was recorded by a 16 mm cinecamera and a 35 mm motor drive camera. Geometrical symmetry of the experimental device can be inferred from static characteristics of the device, as shown in Figs. 5 and 6.

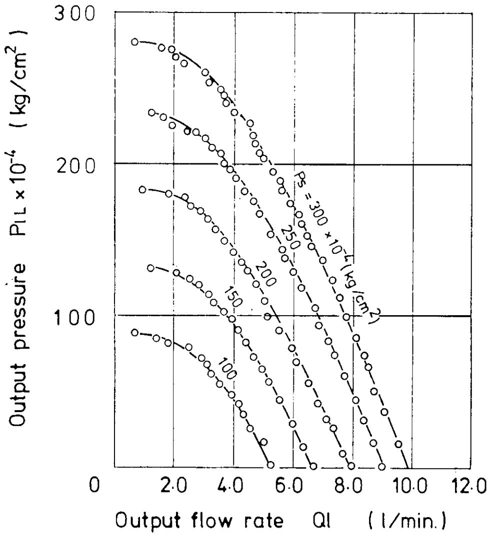


Fig. 5. Load characteristics of the experimental device for left hand side of the output port

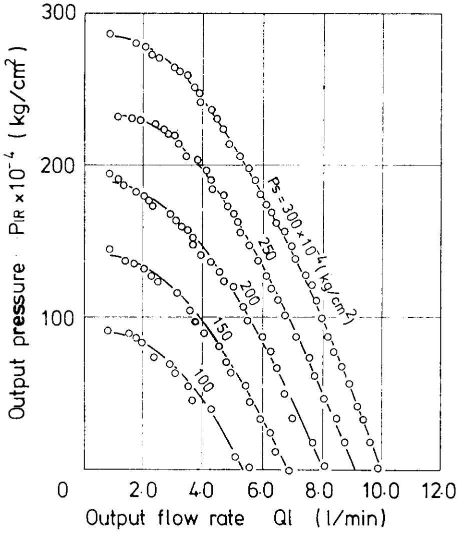


Fig. 6. Load characteristics of the experimental device for right hand side of the output port

4. Switching Transient of Attached jet

The causes by which the jet is switched in a bistable device will be classified into such cases as the jet is switched by making the attached jet strip away from the attachment wall by a proper amount of output resistances, the jet is switched by alternating pressure propagating through the connected line between left and right hand side of the control ports, the control input is derived from the output of itself, and the switching by means of external input. Although the former two cases can be regarded as a kind of self-exciting processes, the latter ones are considered that the switching processes are principally similar, since the attachment bubble is broken by the inflow of control. In such a case, the control flow rate and the output resistances must be taken into consideration as the factors concerning with the jet switching. If the geometry of channel is not vary, a well designed device will cause the load switching in the region of sufficiently high resistances, and the device will cause opposite-wall switching in the region of sufficiently large control flow rate. In the case of gradual increase of control flow under constant output resistances, the attachment bubble begins to increase at the moment when the control flow rate has been above the critical value, and the attaching point moves downstream along the attachment wall. Thus, if the attaching point arrives first at the vent edge and the bubble is broken by the inflow through the vent, so-called the end-wall switching will be caused. If the jet has been put into interaction with the splitter before the attaching point reaches the vent edge, it is considered that the splitter switching would arise. Under this condition, however, if the output resistances are low enough, the switching mode will be directly fall into the opposite-wall region, even if the control flow is in relatively small rate, since the downstream of the jet is still remained on the original side of output channel. Fig. 7 is a expression of these matters conceptively.

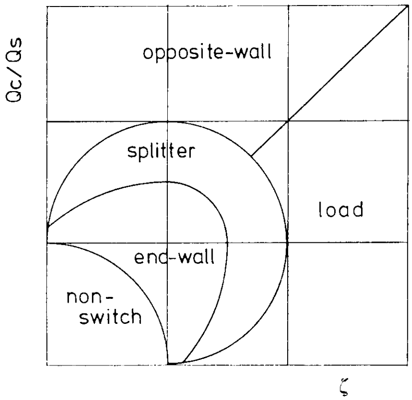


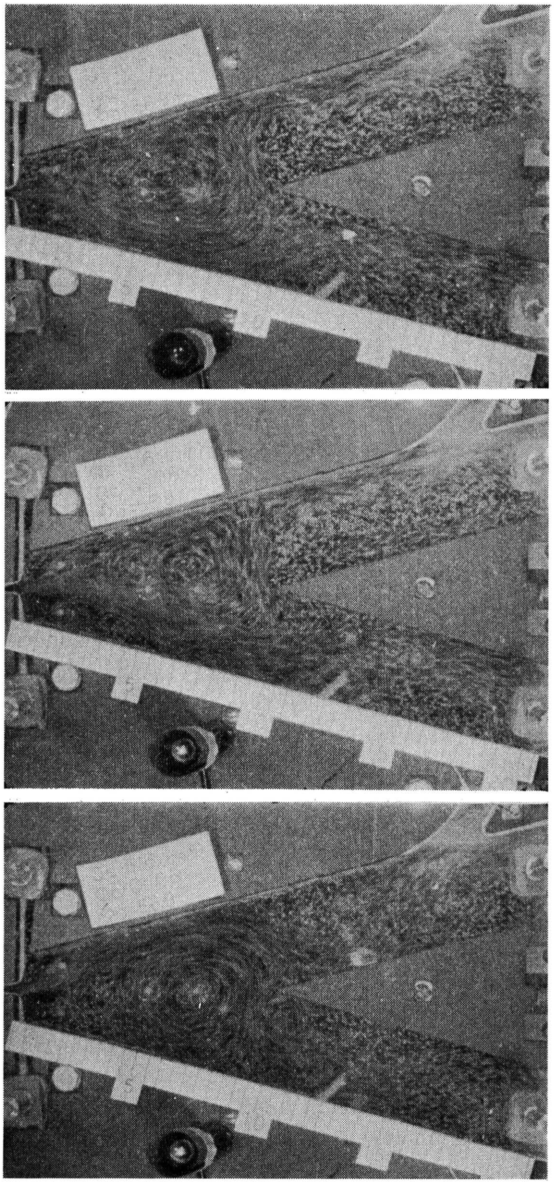
Fig. 7. Explanation of switching modes

4.1 Region of Large Control Flow Rate

As previously stated, in the region where the control to supply flow ratio is sufficiently large, it is expected that the attached jet will be almost switched by the type of opposite-wall. Fig. 8 shows the process of the jet switching observed under conditions of $Qc/Qs=0.6$ and $\zeta=56.9$. (a) is a state before the control flow is not injected. Because of output resistances, a remarkable vortex can be seen at the leading edge of the splitter, however, the existence of the bubble attached to the adjacent wall is also clearly recognized, the attached jet is stable on the wall. The attaching point is placed at the most upstream, and the bubble volume is minimum through the switching transient. (b) is a photograph just after the control flow has been applied to the device. It can be observed that the main jet is deflected at the vicinity of the interacting point with the control jet, and towards the opposite wall in a way. The attachment bubble begins to increase and the attaching point moves a little downstream. After the attachment bubble has grown and the jet reattached on the opposite wall, the vortex travels towards the original side of output channel. (c) shows the state that the attachment bubble is grown up, and the new closed region is formed at the side of opposite wall. In the mean while, a part of the jet is flowing out of the new side of channel, but the vortex moves downstream of the original side of channel. When this vortex has left through the output port, the attachment bubble is broken away, and the switching is completed. This process is evidently the opposite-wall switching, and it is characterized by such behaviour that the reattachment yields at the upstream of the splitter vortex, moreover, the vortex leaves for the original side of the output channel, as shown by Kats (1975).

4.2 Critical Control Flow Rate

It is wellknown that the control flow at which the main jet could be switched is varied with the geometry of device (Harada & Ozaki, 1971). One of the reason



(a) a state before the control flow is not injected

(b) just after the control flow has been injected

(c) the new closed region is formed

Fig. 8. Switching process for $Qc/Qs=0.6$, $\zeta=56.9$

will be concerned with the mass conservation with respect to the working fluid occupied the attachment bubble, and the other reason will be related to the interaction of momenta by the main and control jets. Hence, the critical flow rate when the static pressure is applied to the control port, is generally different from the case when the control pressure is suddenly changed. The author had shown that the critical control flow rate of this experimental device was nearly 0.238 of

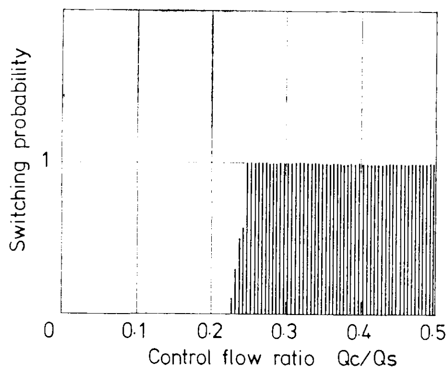


Fig. 9. Switching probability under condition of stepwise control input

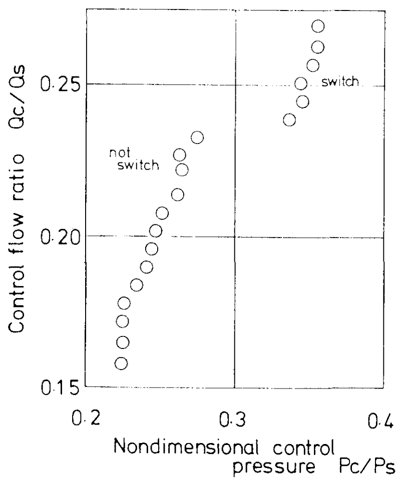
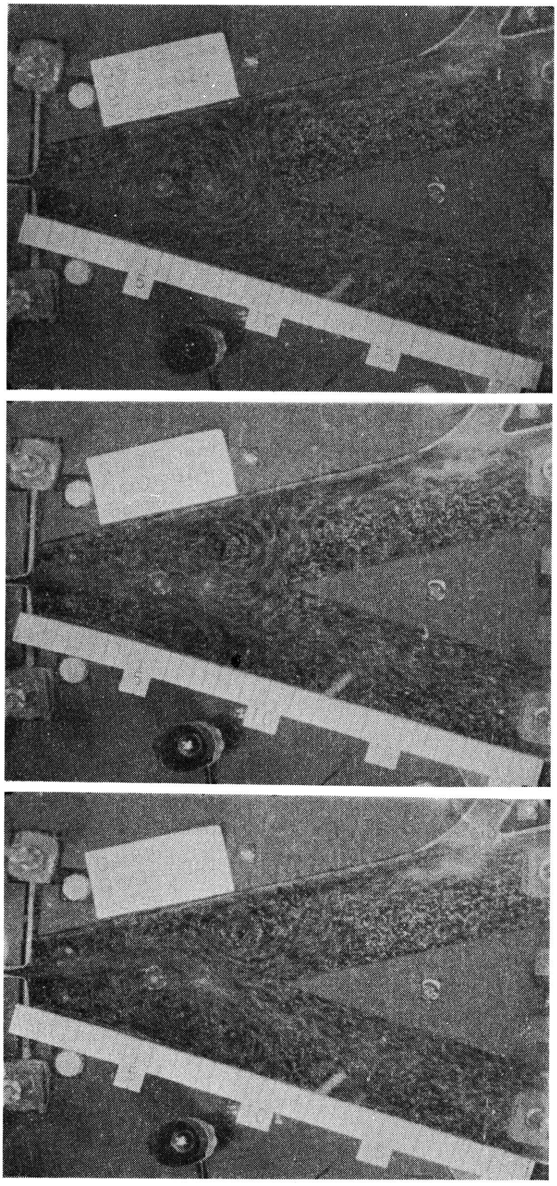


Fig. 10. Switching characteristics of the experimental device

Qc/*Qs* (1974). Fig. 9 shows the switching probability obtained from the experiment when the control flow was suddenly changed like stepwise, so that the jet is not switched at $Qc/Qs=0.225$, but at $Qc/Qs=0.250$. On the other hand, when the control flow was gradually increased, as recognized from Fig. 10, the boundary between switched and unswitched cases was not so clear, but it was estimated as $Qc/Qs=0.234\sim0.239$. The experiments showed, there were so different results between the two cases that it became evident the momentum interaction of the jets could not help being considered.

4.3 Region of Small Control Flow Rate

The switching transienł in the vicinity of the critical flow rate is shown in Fig. 11. The pressure loss factor at the output ducts was 56.9, and the control to supply flow ratio was 0.24. (a) is a state before injecting the control jet. Similarly with the case of large control flow rate, the attachment bubble exists between the jet and the wall, and the attachment on the wall is extremely stable. When the control jet begins to flow into the attachment bubble, the bubble volume is gradually increased, and the attaching point moves downstream along the wall. According as the convex side of jet boundary is approached to the leading edge of the splitter, the radius of jet curvature decreases in a part of the downstream, because of interaction with the splitter face. At the attaching point, the jet becomes to collide against the wall with larger angle than before, however, the bubble volume is further increasing. Consequently, the splitter vortex moves aside for the opposite wall from the original position, and the jet makes itself into the unstable equilibrium condition, as shown in (b). In time, as shown in (c), the vortex flows down to the opposite side of output channel, i.e. not original side, and the switching is over. This process clearly represents the splitter type of switching transient with output resistances. Since the jet is divided into both sides of the channel by the splitter, if the control flow was stopped under this condition, the process might



(a) a state before the control flow is not injected

(b) the splitter vortex moves aside for the opposite wall

(c) the vortex flows down to the opposite side of output channel

Fig. 11. Switching process for $Qc/Qs=0.24$, $\zeta=56.9$

be either the jet returned to the original side of wall, or the jet continued to switch and reattached on the new side of wall.

4.4 Effects of control Flow Rate and output Resistances

In the previous experiments, when the control to supply flow ratio was less than 0.4, the switching transient behaved as splitter switching. However, it seems that this value of control flow ratio is almost full extent of this type of switching.

If the control flow ratio exceeds this value, the switching process will become no longer to show a clear mode of splitter switching. On the other hand, under the constant control flow ratio, the splitter vortex shows a tendency to be vanished at any control flow rate, as the output resistances are decreased. As for $Qc/Qs=0.4$, the switching mode which had shown the behaviour of splitter type at first was varied to opposite-wall switching, when the vortex was completely vanished. Observing this process for $Qc/Qs=0.6$ under the small output resistances, the main jet without control flow was hardly affected by the splitter, and flowed out through the attached side of the output duct, since the initial attachment is stable and extremely strong. But once the control jet is injected, the main jet is considerably deflected at the outlet of supply nozzle, and the convex side of main jet approaches rapidly to the opposite wall. In time, because of increment of the attachment bubble, the main jet makes contact with the splitter face, and is divided into both sides of the splitter, however, the closed region has been already formed at the upstream of the jet. Such situations are symbolized in Fig. 7, as, in the control flow ratio less than 0.4, the switching either splitter or opposite-wall type is realized according to the output resistances, but in the control flow ratio more than 0.6, the splitter switching is no longer realized at any output condition for this device.

4.5 Transition of Bubble Volume

The transition of attachment bubble in switching transient makes distinctive features by various kind of factors. However, as for this device, the remarkable difference according to the supply flow rate was not recognized. On the contrary, the variation of output resistances affects the switching transient as before, and the transition of attachment bubble showed the distinct characteristics. Namely, as shown in Fig. 12, when the output resistances are either sufficiently small or large enough, the bubble volume is increased monotonically in both cases, however, if the proper amount of resistances is prepared at the output ducts, the growth of attachment bubble is halted for a while, and makes again rapid increment of the bubble volume at the end of the process. Fig. 13 describes the above mentioned

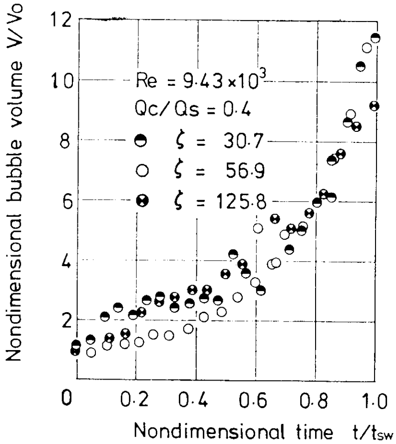


Fig. 12. Transition of bubble volume with respect to loads

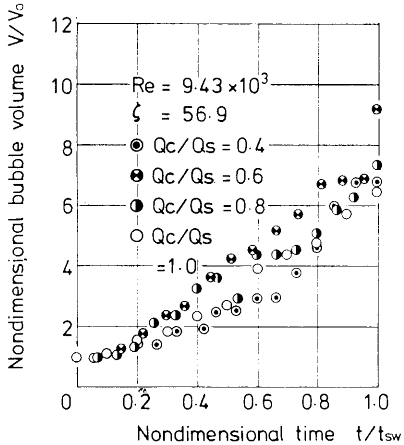


Fig. 13. Transition of bubble volume with respect to control flow

process with respect to the control flow ratio. The clear distinction may be regarded between the case of $Qc/Qs=0.4$ and the others. Figs. 12 and 13 well explain the concept as the switching process is not so affected by supply flow rate, but control flow rate and output resistances. This tendency concerning with the transition of bubble volume becomes more remarkable as the control flow rate decreases, and the region of constant bubble volume is, as shown in Fig. 14, almost from 20% to 80% of the switching time in the vicinity of the critical control flow rate.

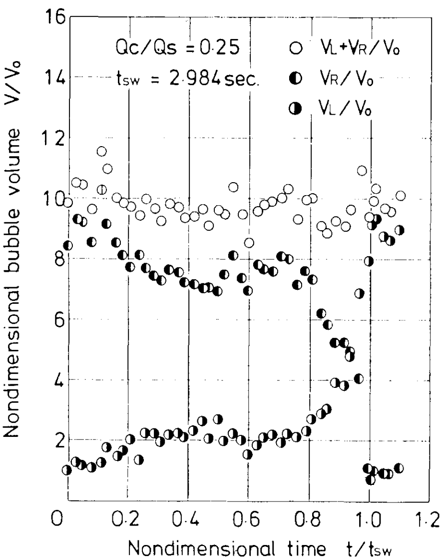


Fig. 14. Transition of attachment and reattachment bubbles for small control flow region

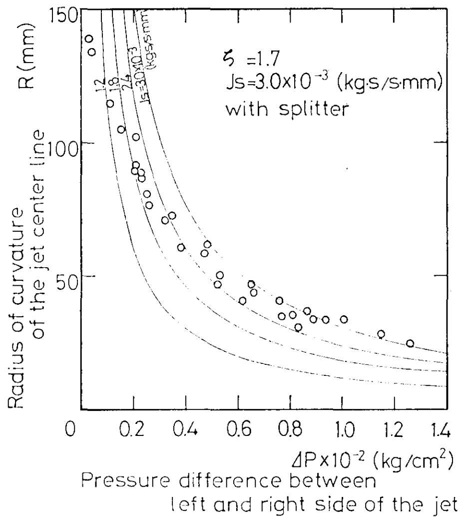


Fig. 15. Radius of curvature of the jet center line

4.6 Critical Radius of Curvature

On the effect of splitter in switching transient, a definitive conclusion could not be obtained up to the present, though a large number of approaches has been attempted by many research workers. For this reason, how to take the splitter effect into the theoretical model is extremely troublesome even at present. In this work, three types of splitter were prepared in advance, however, the device with 100 mm of splitter distance, as to be already mentioned, was applied to the final experiment. Under this condition, the attached jet is not affected by the splitter at the beginning of the switching, because of about 1.8 times of critical splitter distance, moreover, the process of switching is finally subjected to the splitter effect. The solid lines in Fig. 15 show the theoretical relation between the radius of curvature of the jet center line and the pressure difference between in- and outside of the attachment bubble. If the static pressure was applied to the control port under the condition without splitter, the relation between them would agree well with the theoretical result. But, when the similar experiment was attempted using the device with splitter, the experimental data left from the original line and towards the line of smaller momentum condition, as the control pressure became higher and the bubble volune increased. This fact well explaines that the jet is hardly affected by the splitter in the region where the experimental values exist on the original line, however, the jet is put under influence of the splitter through the vicinity of the point getting out of the original line. Accordingly, letting this point be the point where the jet begins to be interfered by the splitter in modeling, and defining the radius of curvature of this moment as the critical radius of curvature for the attached jet, the description of the switching transient of the jet which is finally switched by means of splitter effect will be more simplified.

5. Two-phases Theoretical Model

5.1 Preliminary Discussion for Modeling

In the modeling of bistable switch, there are several factors which must be previously considered. Essentially, the jet spread parameter is the value which should be determined through the caraful experiment. However, it is almost impossible to take the every information of the jet into the theoretical model, since the velocity profile of the attached jet with control flow is not symmetry to the jet center line, and the value of jet spread parameter for attaching side varies with the distance along the jet center line, as explained by Kinoshita, et al. (1974). Also in this case, the jet spread parameter cannot help being similarly treated with any other models as a kind of free parameter in order to make the analytical result agree with the experiment. The relation among the bubble volume, the control flow rate and the jet spread parameter is shown in Fig. 16, which was obtained from the experiment and the foregoing three-phases model by Komatsubara, et al. (1975). It is easily recognized tha: the jet spread parameter without

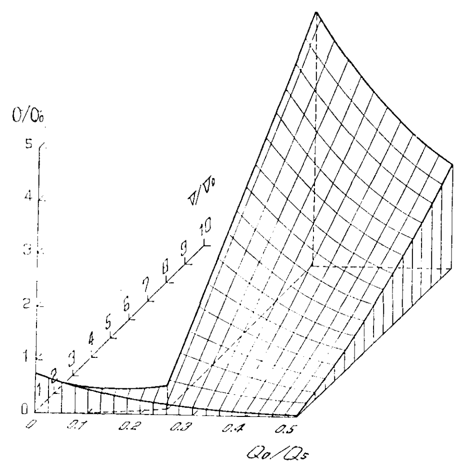


Fig. 16. Distribution of jet spread parameter

control flow shows the value slightly less than the case of free jet, and the value of this parameter, which is required to maintain the bubble volume constant, decreases as the control flow rate increases. Further, the volume of attachment bubble does not develop into infinity, because of gradual increment of the parameter under the constant control flow rate. Interference of jet by the splitter is decided by means of applying the concept of critical radius of curvature, but in order to put this method into practice, the equivalent radius of curvature, which is determined from the geometry of device and the behaviour of jet, must be calculated at any moment through the process of switching transient. As regards the shapes of attached jet, Lush (1968) approximated the jet center line by the only circular arc, while Bourque (1960) proposed to express the most inside path of attached jet as the dividing streamline, and provided a simple vector equation. In general, since the inside pressure of the attachment bubble is not uniform, and the leading edge of the splitter is located far from the critical distance of splitter, it is preferable to represent the shape of attached jet with the dividing streamline, before the control flow is not injected into the bubble. Contrarily, after the control flow was injected, if a circular arc approximation was locally applied to the downstream of the splitter leading edge, the shape of the attached jet would not so differ in a global sense. Fig. 17 expresses the rate of time which is required for the jet deflection in switching transient. It is evidently predicted that if the jet spread parameter was more than the value of free jet, and the control to supply flow ratio was less than 0.4, the elapsed time during the jet deflection could be neglected through the switching process. Based on the above discussed conditions and experimental results, a two-phases theoretical model could be composed as follows.

i) Switching process I starts at the moment when the control flow begins to inject into the device. The main jet is instantaneously deflected up to the angle determined by the momentum ratio between the main and control jets. The attaching point simultaneously moves downstream along the wall, however, the radius of curvature of the jet center line increases with increment of the bubble

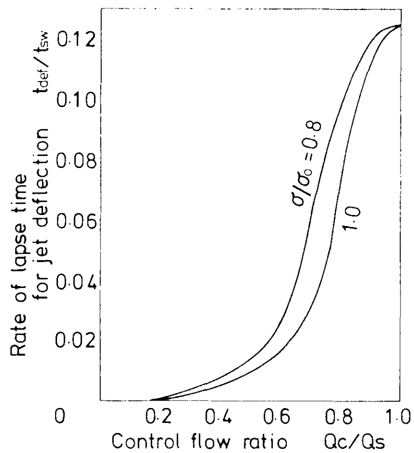


Fig. 17. Lapse time required for jet deflection

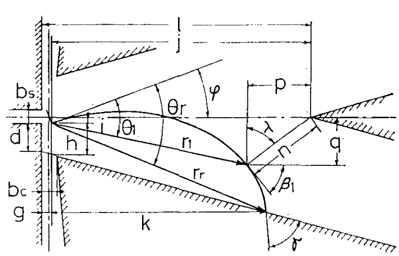
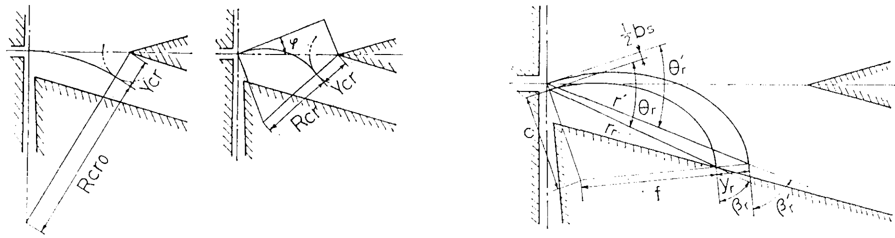


Fig. 18. Geometric relation for switching process I



(a) critical radius of curvature　　(b) correlation between jet center line and reattaching stream line

Fig. 19. Definition of critiɔal radius of jet center line

volume. The critical radius of curvature is reached, and the process I is over.

ii) The jet is divided into both sides of splitter. A part of the jet flows downstream along the counter face of the splitter and towards the opposite side of the output port, however, the other part of jet is treated as the secondary jet injected through a hypothetical nozzle defined by the dividing streamline and the location of splitter leading edge. The rate of bubble volume for jet switching is reached, and the switching process is completed, where the transition between phases is characterized by an instantaneous shift.

In addition to the above mentioned facts, following assumptions were introduced.

1. Flow is two-dimensional and incompressible.
2. The velocity profile of jet is the same with Goertler's free jet profile.
3. The value of jet spread parameter on both sides of the jet is the same.
4. The process is nondissipative.
5. Distance measured along the reattaching streamline is the same as the distance measured along the jet center line.
6. The switching process whenever is treated as to be quasi-steady.

5.2 Switching Process I

In order to describe the velocity profile of the attached jet, the Goertler's expression which had been corrected for a case of finite nozzle width was applied as follows.

$$U=\sqrt{\frac{3\sigma J}{4\rho(S+Ss)}}\,\mathrm{sech}^2\left(\frac{\sigma y}{S+Ss}\right) \tag{5.1}$$

where Ss is the distance along the jet center line from the hypothetical origin of the jet to the supply nozzle exit. The correlation between the jet momentum and the angle of jet deflection is given by

$$J_{s+c}=J_s\sqrt{1+\tan^2\phi} \tag{5.2}$$

and

$$\phi=\tan^{-1}\frac{Jc}{Js} \tag{5.3}$$

where

$$Js=\frac{\rho Qs^2}{bs} \tag{5.4}$$

$$Jc=\frac{\rho Qc^2}{bc}. \tag{5.5}$$

Considering about the equilibrium of momenta with respect to the angle between the vector r, mentioned below, and the initial direction of the jet,

$$J_{s+c}\cos\theta=J_1-J_2 \tag{5.6}$$

$$J_1=\left(\int_{\infty}^{y_r}\rho U^2\,dy\right)_{S=Sr}=\frac{3}{4}J_{s+c}\left(\frac{2}{3}+tr-\frac{1}{3}tr^3\right) \tag{5.7}$$

$$J_2=\left(\int_{y_r}^{\infty}\rho U^2\,dy\right)_{S=Sr}=\frac{3}{4}J_{s+c}\left(\frac{2}{3}-tr+\frac{1}{3}tr^3\right) \tag{5.8}$$

where

$$tr=\tanh\left(\frac{\sigma y_r}{S_r+S_s}\right). \tag{5.9}$$

Hence, t_r can be rewritten as

$$tr=2\cos\frac{\theta+\pi}{3}. \tag{5.10}$$

Since the reattaching streamline is given by Bourque (1960) as

$$r=a\sin\frac{\pi}{2}\frac{\theta}{\theta_{max}}, \tag{5.11}$$

the angle between the vector of reattaching streamline r and the line tangential to the reattaching point becomes

$$\beta_r=\tan^{-1}\left[\frac{2\theta_{max}}{\pi}\tan\frac{\pi}{2}\frac{\theta_r}{\theta_{max}}\right] \tag{5.12}$$

and

$$\gamma=\theta_r-\phi+\beta_r-\alpha. \tag{5.13}$$

Further, the volume of attachment bubble is varied with the rate of

$$\frac{dV}{dt}=Q_r-Q_e+Q_c. \tag{5.14}$$

5.3 Determination of Splitter Effect

As stated before, interference by the splitter begins at the moment when the equivalent radius of curvature of the jet center line has achieved the critical radius. Hence, letting the critical radius of curvature without deflection be R_{cro}, the radius of curvature deflecting at angle ϕ can be written as

$$R_{cr}=\frac{\left(1-\frac{1}{2}b_c\right)^2+y_{cr}^2}{2\left[y_{cr}+\left(1-\frac{1}{2}b_c\right)\sin\phi\right]} \tag{5.15}$$

where

$$y_{cr}=\sqrt{\left(1-\frac{1}{2}b_c\right)^2+R_{cro}^2}-R_{cro}. \tag{5.16}$$

Simultaneously, equivalent radius of curvature of the jet center line is

$$R=\frac{r'}{2\sin\left[\frac{(\theta r+\beta r)}{2}\right]} \tag{5.17}$$

and

$$r'=\sqrt{\left(c+\frac{1}{2}b_s\right)^2+(f+y_r)^2-2\left(c+\frac{1}{2}b_c\right)(f+y_r)\cos(\theta_r+\beta_r)} \tag{5.18}$$

where c and f are the solutions of following simultaneous equations, as

$$\left.\begin{aligned} c\sin\theta_r+f\sin\beta_r&=r_r \\ c\cos\theta_r&=f\cos\beta_r \end{aligned}\right\} \tag{5.19}$$

5.4 Switching Process II

After achieving the splitting condition, the jet is divided into both sides of the splitter, so that the center line of jet in downstream of the splitter leading edge can be represented by a circular arc. If the pressure difference between in- and outside of attachment bubble was equal to Δp, as explained in Fig. 20, the following relation should be satisfied in this region.

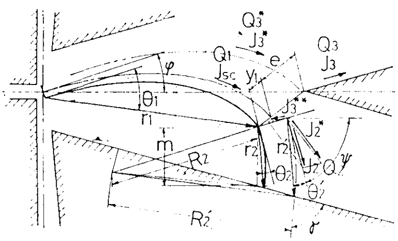


Fig. 20. Geometric relation for switching pracess II

$$R'=\frac{J_1}{\Delta p}. \tag{5.20}$$

Similarly as before, the rate of change of the bubble volume is expressed by

$$\frac{dV}{dt}=Q_r'+Q_c-Q_e'-Q_e'' \tag{5.21}$$

where Q_e' and Q_e'' are the jet entrainments in up- and downstream interfered by the splitter respectively.

6. Results and Discussions

It was already mentioned that a considerable overshoot or violent fluctuations of control pressure would be arised at the beginning of the solenoid valve openning. This fact means to make a comparison between theoretical result and experiment too difficult. The accumulator adopted by the author produced convenient dumping

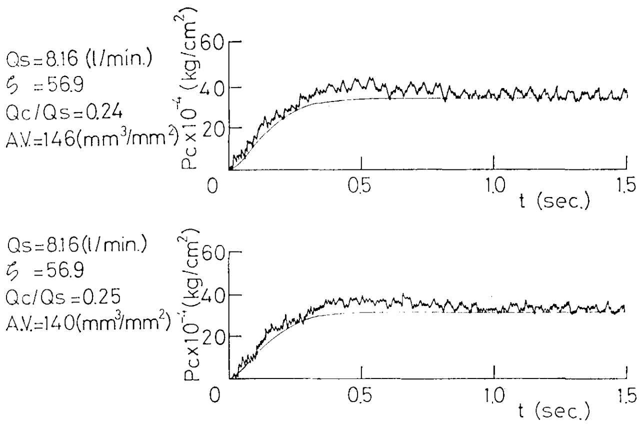


Fig. 21. Exponential control input

effect to the control system of the device through adjusting the amount of accumulated air. Since if a time constant was taken sufficiently small compared with the switching time of attached jet, the control pressure with exponential transition could be easily obtained, thereafter this signal has been applied to the control input as pseud-stepwise signals. Fig. 21 illustrates some examples of this signal. As to be evident from this expression, a following empirical equation could be obtained.

$$Pc(t)=Pc[1-(1+\omega_n t)e^{-\omega_n t}] \tag{6.1}$$

This signal, as stated above, was used to excite the system of the theoretical model instead of a strictly defined step-function. A computational result under a constant value of jet spread parameter showed such a volume change with time of the attachment bubble as represented in Fig. 22. It seems to express that the bubble volume increases as the switching process I proceeds, however, this behaviour attains in time a equilibrium state and the attachment bubble is held for a moment under constant volume, further the volume shows again a tendency of

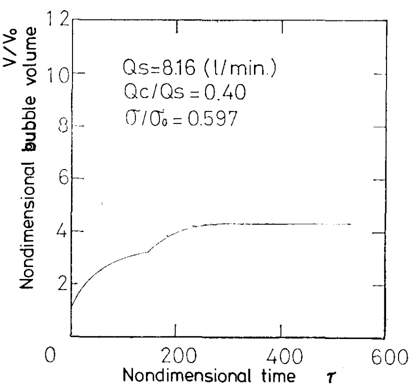


Fig. 22. Computational volume change in switching transient

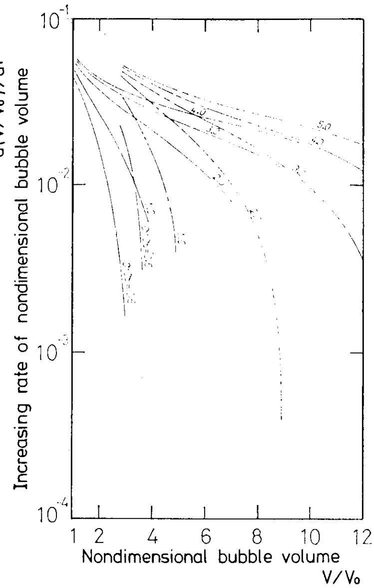


Fig. 23. Increasing rate of bubble volume

rapid increment in the process II. Fig. 23 is also a computational result between the bubble volume and the rate of volume change, where the solid and dotted lines correspond to the switching process I and II respectively. In either case, the rate of volume change becomes more rapid as the value of jet spread parameter is larger, and it becomes more gradual as the volume of attachment bubble is grown. Moreover, it is also recognized that if the value of jet spread parameter is taken sufficiently large, the rate of volume change will be scarcely affected by the volume change of attachment bubble in the switching process II. Fig. 24 illustrates an experimental result of the bubble volume transition with time. In the region corresponding to the process I, the bubble volume is converging to

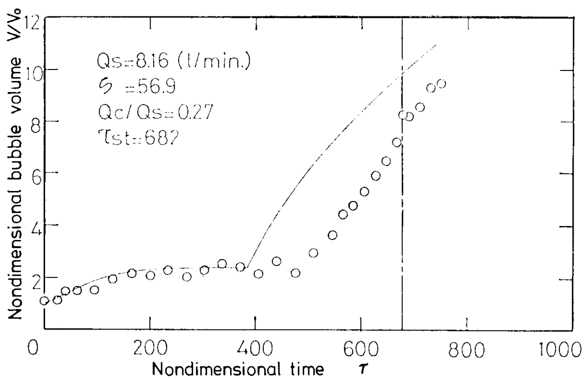


Fig. 24. Transition of bubble volume for small control flow rate

nearly 2.4 of V/V_0. As apparent from Fig. 16, the variation of jet spread parameter is not remarkable in this region that the value of this parameter can be represented as nearly constant. On the other hand, since the volume of the attachment bubble rapidly increases in the process II, it is necessary for this parameter to take sufficiently large value. For instance, if the converged value of the bubble volume is 2.4 of V/V_0 in the process I, the variation of jet spread parameter becomes as shown in Fig. 25, and a following empirical equation will be derived.

$$\frac{\sigma}{\sigma_0}=10.4099\left(0.6-\frac{Qc}{Qs}\right)^{2.7}+3.5 \tag{6.2}$$

Consequently, if the value of jet spread parameter at $Qc/Qs=0.27$ was adopted as representation of this parameter in this region, the computational transient behaviour of jet switching would not be extremely deformed in a global sense. On the contrary, since, in the switching process II, a sufficiently large value must be taken for the spread parameter, and further the curve corresponding to this process must intersect with the curve for the process I at the beginning point of interference by the splitter, the equivalent radius of curvature was experimentally investigated on both cases with and without splitter. As shown in Fig. 26, the splitter effect for this device is conspicuous at 70 or 90 mm of the radious of curvature. Hence, considering that the switching time computed with the process I becomes infinity at $R=85$ mm and $Qc/Qs=0.24$, it seems that the previous experiment gives a reasonable result in order to specify the beginning point of the splitter interference.

Consequently, the transient behaviour of attached jet which is switched under the effect of splitter could be represented by a two-phases model, and the modeling of bistable switch might be extremely simplified than before.

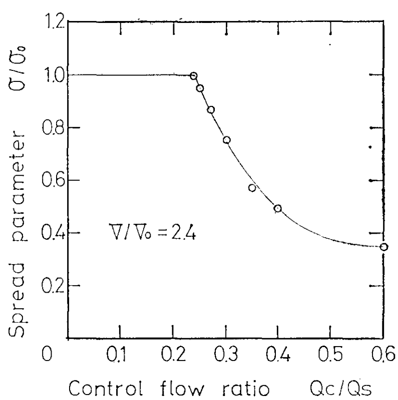


Fig. 26. Effect of the splitter

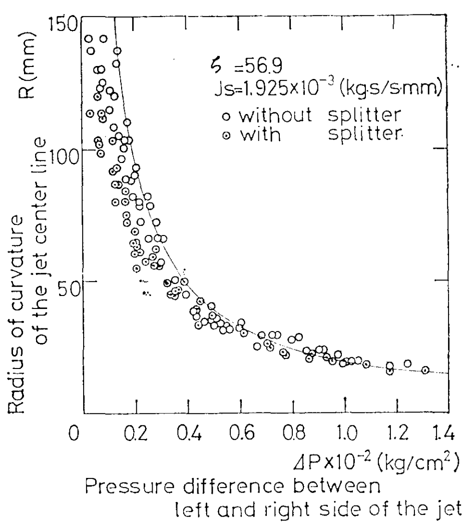


Fig. 25. Variation of jet spread parameter

7. Conclusion

A main purpose of this work was to simplify the modeling of bistable switch in a wall attachment device, i. e. to facilitate the computation of switching transient. A simpler two-phases model could be derived through the discussions for the elapsed time in each phase and the experiments about the time transition of the attachment bubble. Comparison of the previously stated computation with the experiment showed that the jet spread parameter should be given only one value for each phase. Further, in order to determine the interference by the splitter in the theoretical model, a critical radius of curvature was defined, and the computation of the model based on the above definition proved to express properly the increasing process of the attachment bubble. For this experimental device, the critical radius of curvature was about 85 mm. The correlation between the two values of jet spread parameter was remained as an important problem which should be investigated in the near future not only theoretically but experimentally.

Finally, the transient behaviour of jet in bistable switch is also subjected to the splitter distance. In this experiment, three types of splitter with the distance of 60 mm, 80 mm and 100 mm were prepared, and the switching transient was examined respectively. In a case as the splitter distance was extreamely short, the main jet impinged directly against the leading edge of the splitter, and the stream was divided into both sides of the splitter face. In the second case with 80 mm of splitter distance, the jet was initially under influence of the splitter, the attaching point without control flow had been placed fairly upstream on the wall.

A distinctive feature of switching behaviour as discussed in this paper was emphasized around 100 mm of splitter distance. Generally speaking, since the splitter effect through the switching transient may hardly become decisive as the splitter distance is too far from the nozzle exit, if the geometry of device except splitter condition is not varied, it seems that this theoretical model could be available to predict the switching transient for a device with 18 or 24 of splitter distance normalized with respect to the supply nozzle width.

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