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Cavitation Phenomena and Performance of Oil Hydraulic Poppet Valve*
(1st Report, Mechanism of Generation of Cavitation and Flow Performance)

By Shigeru OSHIMA** and Tsuneo ICHIKAWA***

By using an unique half cut model of an oil hydraulic poppet valve, the cavitation phenomena were directly observed and the pressure distribution was measured in the metering restriction between the valve seat and the poppet surface. As a result of this research, the occurrence process of cavitation in a poppet valve and the effects of it on the flow performance were made clear. Also, the differences in a performance of cavitation between the diverging flow and converging flow were understood.

Key Words : Cavitation, Fluid Power Systems, Poppet Valve, Half Cut Model, Flow Performance, Pressure Distribution, Experimental Study

1. Introduction

It is required for the recent hydraulic systems to be used in high pressure and high speed with low noise. In such systems, the cavitation phenomenon occurs easily at the restricted parts like valves. Hence, it is coming to be very important to understand how the cavitation has an effect on the performance of the systems. There are many problems caused by cavitation, for example the effects on the flow rate [1] and the thrust force performance [2], vibration [3], noise [4], erosion [5][6], etc. For the solution of these problems, it is necessary to understand exactly the oil flow condition and the occurrence process of cavitation within the valves.

Concerning the cavitation in a spool valve [7], orifice [8] or cylindrical chokes [9]~[12], there have been many works, in which the boundary for the occurrence of cavitation and others have been investigated. Using a two-dimensional model of a choke [13][14], the cavitating condition or pressure distributions have been investigated, too. However, there have been few works about cavitation of poppet valves, except for works by Aoyama [1]~[3]. Shapes of the metering restrictions in poppet valves, especially in case of the valve seats having chamfer, are generally more complex than that in chokes and spool valves. Therefore, the two dimentional model test is difficult for a poppet valve, and there have been no works studying the condition of cavitating flow within the poppet valve in detail. So, there are many problems still remain unknown which are required to be made clear rapidly.

In this paper, a special half cut model of a poppet valve was produced, of which cut surface was covered with a transparent perspex plate on which a small hole of 0.07 mm diameter was made for measuring of pressure distributions. Using this model, direct observations of cavitation and detailed measurements of pressure distributions in the narrow metering restriction between the valve seat and the poppet surface were well done, without changes in original performance of the valve. The results of experiments made clear the occurrence process of cavitation and its effects on the flow rate performance. In addition, the difference in the performance of cavitation between the diverging flow and the converging flow valve was understood.

2. Test Apparatus and Method

Figure 1 shows the half cut model of a poppet valve used in the experiment, and Fig.2 the important dimensions of it.

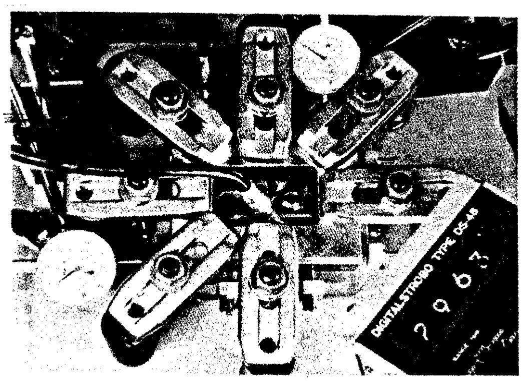


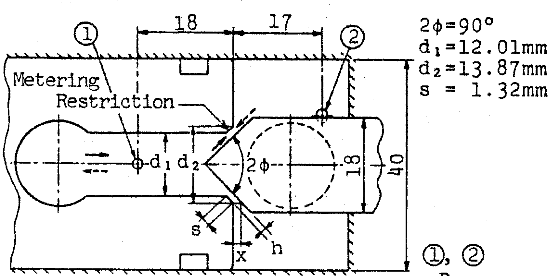
Fig.1 Half cut model of a poppet valve

* Received 12th October, 1983.
** Lecturer, Numazu College of Technology, (3600 Ooka, Numazu, Shizuoka, Japan)
*** Professor, Toyohashi University of Technology, (1-1 Hibarigaoka, Tenpakucho, Toyohashi, Aichi, Japan)

In order to observe the occurrence process of cavitation within the metering restriction of the valve, the cut surface of the half cut model is covered with a perspex plate of 20 mm thickness. A steel plate with a square window is piled up, and it is tighten with bolts and nuts. The observation of cavitation was carried out by naked eyes or using a microscope with repeated illumination by stroboscopic-flashes, and also by photographic means with a short duration of the stroboscopic-flash. Sound noise was measured by a sound level meter (JIS C 1502), setting the microphone at 10 cm away from the test valve.

In Fig.2, it is called "Diverging flow" when oil flows from left to right (→ direction), and it is called "Converging flow" in case of reverse (← direction). Inlet pressure and outlet pressure were regulated respectively with relief valves and measured at the pressure taps ①, ② with precision Bourdon pressure gauges. Flow rate was measured by weighing the discharge flow. Oil was supplied to the test valve through the 10 μm filter. Although the oil was circulated in the test circuit, there was no difference in the performance of cavitation between at the start and the end of the experiments.

Whether cavitation occurred or not was distinguished by eyes and ears, it was defined as "Inception" of cavitation when weak cavitation noise was heard and small cavities were detected for the first time.



x mm	0.4	0.6	0.8
h mm	0.283	0.424	0.566

Fig.2 Important dimensions of the half cut model

The pressure distributions within the very narrow restriction were measured by a pressure tap of 0.07 mm diameter made in a small brass tip which was put into the underside of the perspex plate. The pressure was transformed into a voltage signal and displayed with a digital voltage meter. The perspex plate is able to be transferred with screw bolts, and its displacements of X- and Y- axis directions are indicated with two dial displacement gauges. Thus the position of the pressure tap was varied and set.

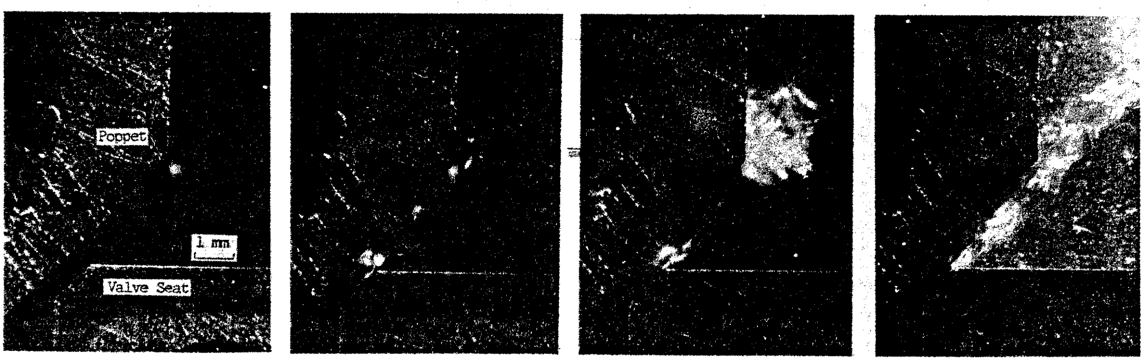
Oil temperature was measured with a thermister thermometer in the inlet pipe line and hold at 40±1°C during tests. The oil was Daphne Hydraulic Fluid 56, and its density ρ and viscosity μ at 40°C were 851 Kg/m^3 and 4.6×10^{-2} Pa·s.

For the purpose of confirmation of identification of the results by the half cut model, the tests with a full shaped model which was produced in the same size as the half cut model (in Fig.2) were carried out. Flow performance and the occurrence limit of cavitation were measured and compared with the results of the half cut model. In case of the full shaped model, whether cavitation occurred or not was distinguished only by ears.

3. Case of diverging flow

Figure 3 and 4 show the occurrence process of cavitation when P_2 was gradually reduced with an inlet pressure P_1 fixed at 5 MPa(abs.). Cavitation number K was defined as $K=P_2/(P_1-P_2)$, here P_1 and P_2 were absolute pressures. The effective exposure time of the photographs was approximately 3 microsec. Figure 5 shows the pressure distributions measured along the chamfer of the valve seat under several pressure conditions. The dashed lines in Fig.5 are based on mere supposition. The ratio of height and length of the expanded drawing of the restricted part is shown in the same as the actual object. And the chain line in the drawing indicates the spreading degree of the flow path area if the poppet valve is replaced with a 2-dimensional model with a constant depth.

The occurrence process of cavitation



(a) ΔP=2.94 MPa(K=0.7) (b) ΔP=3.43 MPa(K=0.46) (c) ΔP=3.92 MPa(K=0.28) (d) ΔP=4.8 MPa(K=0.04)

Fig.3 Occurrence process of cavitation (P_1=5 MPa(abs.), x=0.8 mm, exposure time 3×10^{-6} s) will be explained by Fig.3, 4 and 5 in following.

As P_2 was reduced and the pressure difference ΔP crossed the limit for the inception of cavitation (ΔP=2.65 MPa), intermittent weak sound noise was heard irregularly and small cavities appeared for a moment at long time intervals in the down-stream region located between 2 and 3 millimeter distance from the outlet of the metering restriction. As P_2 was reduced further, the occurrence of noise and cavities became more frequently, and the cavities appeared also in nearer part to the restriction. Figure 3(a) shows this condition. Most cavities appeared near the boundary between the jet surface and the stationary oil in the down stream chamber, and the pressure in the region was still considerably higher as shown in Fig.5. Considering from this fact, the cavitation in this stage is thought to be a same kind of "Vortex cavitation", which has been known to occur around the jet surface into the stationary liquid [15].

With further reduction of P_2, the noise became gradually continuous and cavities became to be observed also at just behind of the restriction and in it. When ΔP exceeded 3.04 MPa, suddenly the noise turned into a different kind of continuous sound as "shee". In this condition, the cavities appeared also at the entrance corner of the restriction, and flew as covering the surface of the valve seat as shown in Fig.3(b). In this stage, as shown in Fig.5, pressure falls below the atmospheric pressure at just behind of the entrance corner of the restriction and it begins to go up after a small distance. It becomes approximately equal to P_2 near the outlet of the restriction. This pressure distribution is similar to that of a sharp edged choke [14]. The cavitation occurred at the entrance corner is considered to be caused by pressure reduction by the separation and turning of the flow. In this condition, the flow rate did not more increase even if P_2 was further reduced, i.e. so-called "choking" happened.

With further reduction of P_2, the occurrence of cavitation became more violent. The discontinuous groups of cavities like clouds were observed within the down-stream region as in Fig.3(c). The groups of cavities turned at the corner on the edge of the cone surface and disappeared immediately after flow for a short distance along the poppet shank surface.

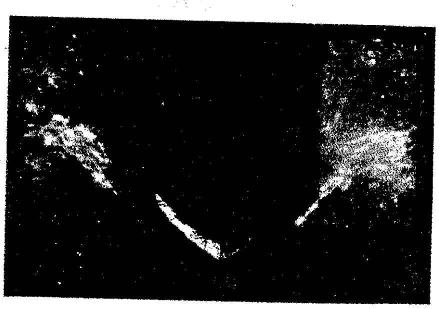


Fig.4 Occurrence process of cavitation (x=0.8 mm)

As P_2 was reduced further, the noise became rapidly larger, and the flow direction of the jet became unstable. When ΔP crossed over 4.6 MPa, the jet suddenly detached from the shank surface at the corner and flew straight ahead as shown in Fig.3(d). In this condition, as in Fig.4, a transparent wedge-shaped potential core was clearly observed and the cavities appeared along the both side surfaces of it in the down-stream chamber. Two large vorticies were observed, too. As P_2 was considerably low in this state, the cavities did not completely collapse in the down stream chamber and flew out to the outlet pipeline. So, the noise level rapidly dropped.

Figure 7 shows the incepient stage (a) and choking condition (b), when the valve lift was 0.4 mm. The occurrence process of cavitation was different from in case of x=0.8 mm. That is, cavitation occurred at the entrance of the restriction before the vortex cavitation appeared remarkably in the down stream region. And, it can be seen from Fig.6 that the pressure regains and becomes approximately equal to P_2 near the middle of the restriction. Hence, it may be supposed that

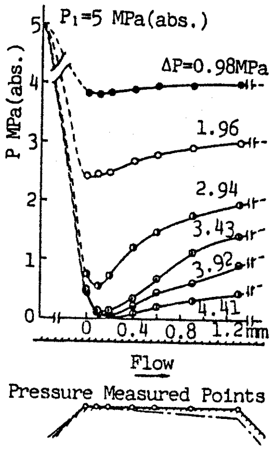


Fig.5 Pressure distribution on the valve seat (x=0.8 mm)

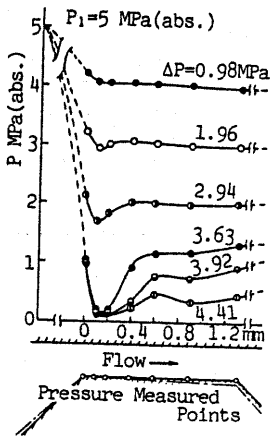
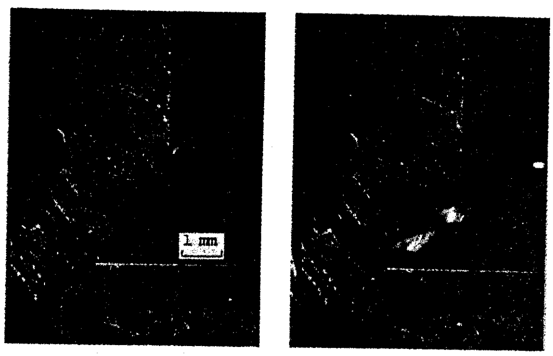


Fig.6 Pressure distribution on the valve seat (x=0.4 mm)



(a) ΔP=3.63 MPa (K=0.38)

(b) ΔP=3.92 MPa (K=0.28)

Fig.7 Occurrence process of cavitation (P_1=5 MPa(abs.), x=0.4 mm) the flow is decelerated and re-attached to the surface of the valve seat within the restriction. Since the boundary layer developes and the gradient of flow velocity within the shearing layer between the jet and stationary oil becomes gentle, the vorticies become not to appear. Hence, the vortex cavitation becomes not to occur easily in this case. It is noticeable that there was a difference in the occurrence process of cavitation with change of the valve lift.

Figure 8 shows the flow rate performance when ΔP was increased with P_1 fixed at 5MPa(abs.). In cases of x=0.4 mm and 0.6 mm, also the data of flow rate and noise level of the full shaped model are indicated together. Since there are not remarkable differences between the both data of half cut model and full shaped model, it is confirmed that the accurate results can be obtained by the half cut model.

In Fig.8, $P_{0.2}$ means the pressure measured at 0.2 mm inward from the entrance corner of the restriction along the surface of the valve seat. It shows the typical change of pressure within the restriction. The mark of ➦ shows the inception of cavitation and ⇨ shows the occurrence of it at the entrance corner of the restriction.

Figure 8 shows the results as follows. The inception of cavitation and the occurrence of cavitation at the entrance, both appeared at smaller ΔP as x was larger. The pressure within the restriction ($P_{0.2}$) begins to fall sharply after inception of cavitation, and immediately after the occurrence of cavitation at the entrance, it falls below the atmospheric pressure and becomes constant. In this condition, the flow rate did not more rise even if ΔP was increased; the saturation of flow rate appeared. When the valve lift is small, the saturation of flow rate appears immediately after the inception of cavitation. Because the cavitation at the entrance occurs shortly after the inception.

Noise level fairly rises with the occurrence of cavitation, but it is not so remarkable. However, when ΔP is between 4 MPa and 4.9 MPa, the noise level becomes very high. The maximum noise level is higher as the valve lift is larger. When ΔP becomes nearly equal to 4.9 MPa; namely P_2 becomes approximately 0 MPa(gauge), the noise level sharply drops because the cavities become not to collapse easily in the chamber.

Figure 9 shows the pressure distributions throughout the inner part of the restriction in cases of x=0.8 mm and ΔP=2.94 MPa. It shows both cases of cavitating condition and non-cavitating condition. The mesh of thin lines indicates the value of P_2.

It is understood that the shape of the pressure distribution under the non-cavitating condition is approximately same as that of the cavitating condition if ΔP is same. So, it is supposed that the curves of streamline of both cases are similar to each other, and also in case of non-cavitation, the flow detaches from the valve seat at the entrance corner of the restriction. However there is a little difference between them; that is, in the cavitating condition the pressure tends to fall more deeply near the entrance corner and the low pressure region extends to the down stream direction.

There is a large difference between the pressure distributions near the valve seat and near the poppet surface. The difference is largest near the entrance of the restriction, the pressure on the poppet surface is 1.47 MPa higher than that on the valve seat at the maximum. It is due to the centrifugal force by the sharp turning of flow at the entrance corner. The difference of them becomes

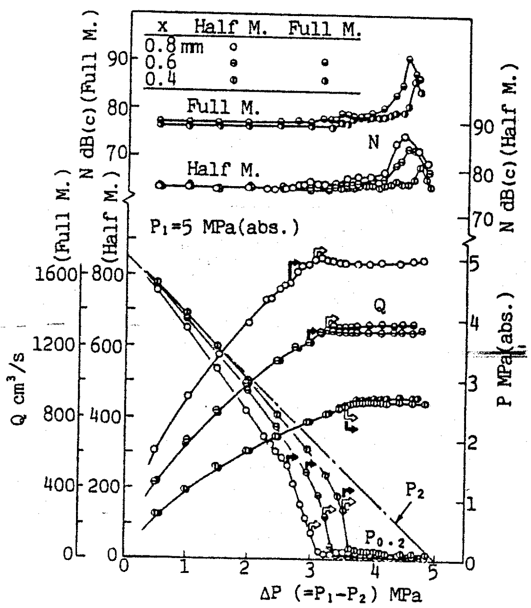


Fig.8 Flow performance (diverging flow)

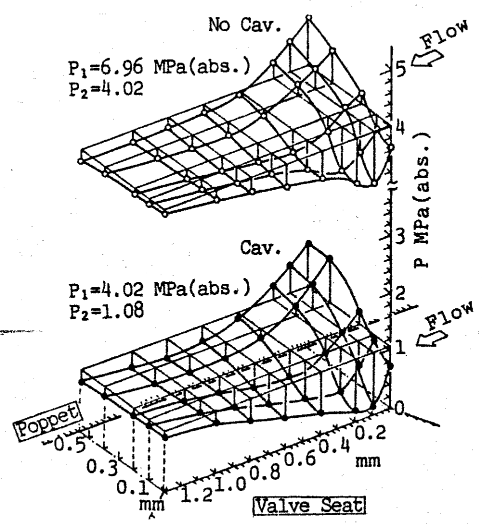


Fig.9 Pressure distribution throughout the inner part of the restriction (diverging flow)

less as coming to the down stream side, and the pressure distribution becomes approximately flat after the middle of the restriction. This fact will be important when the thrust force on the poppet is investigated.

4. Case of converging flow

Figure 10 and 11 show the occurrence process of the cavitation in the case of converging flow. The conditions were same as that in the case of diverging flow in Fig.3. Figure 12 shows the pressure distributions along the valve seat. The dashed lines and the chain line in Fig.12 have the same meaning as that in Fig.5.

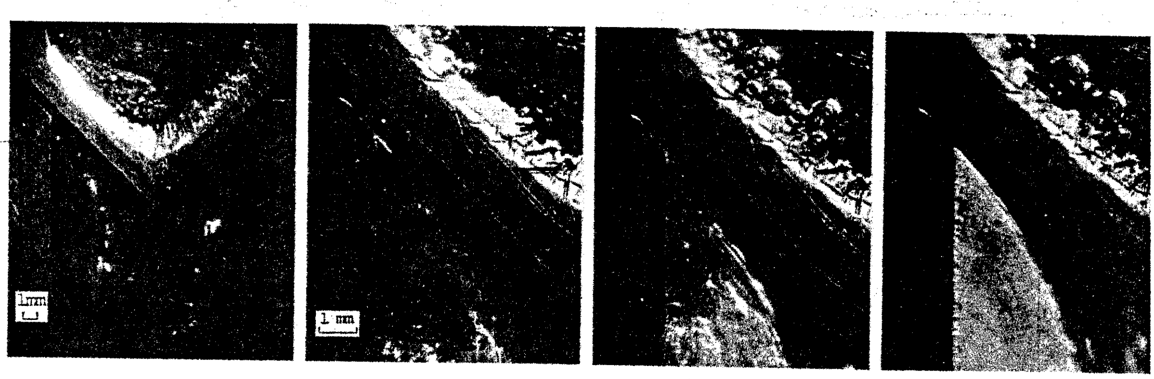
The process of occurrence of cavitation will be explained by Fig.10, 11 and 12 as follows.

When P_2 was reduced gradually and the pressure difference reached to the limit for the inception (ΔP=3.33 MPa), the noise as "puchi, puchi" was heard irregularly at long intervals. Cavities, in size relatively larger than in case of diverging flow, appeared for a moment intermittently within the region between 10 and 20 mm down from the restriction. With further reduction of P_2, the occurrence of cavities and noise became frequently, and the cavities became to appear also in the nearer parts to the restriction. Most cavities appeared along the surface of the jet as shown in Fig.10(a). It is understood from the pressure distributions in Fig.12 that the pressure falls sharply near the entrance of the restriction, because of the separation and the contraction of the streamline. But, the pressure is generally higher than P_2 throughout the restriction and it tends to fall continuously from the entrance to the outlet of the restriction. The pressure became approximately equal to P_2 near the outlet. The value of P_2 in Fig.10(a) was 1.08 MPa(abs.), and it was still higher than the critical pressure for the separation of air bubbles from stationary oil. Considering from this fact, the cavitation in this stage is thought to be "Vortex cavitation" [15]. The same kind of cavitation has been reported with a bell-mouth choke [11] and a round edged 2-dimentional choke [13].

As P_2 was reduced further, noise turned gradually to continuous sound and cavities became to appear also at just behind of restriction. When the pressure difference exceeded 4.2 MPa, the other kind of noise was suddenly heard and cavities appeared also at the entrance corner of the restriction as shown in Fig.10(b). In this stage, the flow rate did not more increase even if P_2 was further reduced; the saturation of flow rate happened. The cavity at the entrance corner was very thin and it disappeared at the point shortly distant from the entrance. This fact is explained as follows by the pressure distributions in Fig.12. As the flow detaches from the valve seat at the entrance corner and the pressure drops deeply, the cavitation occurs there. But, soon the flow re-attaches to the surface of the valve seat, therefore the flow path is widened and the flow is decelerated, the pressure regains, and the cavitation disappears there. After passing there, the flow is accelerated again. Since the pressure falls below P_2 at the end of the restriction, cavitation occurs violently there and in the down stream chamber as shown in Fig.11(a). These cavities generate very loud noise when they collapse near the outlet port. It is very interesting that there is a difference in the occurrence condition of cavitation between the diverging flow and the converging flow.

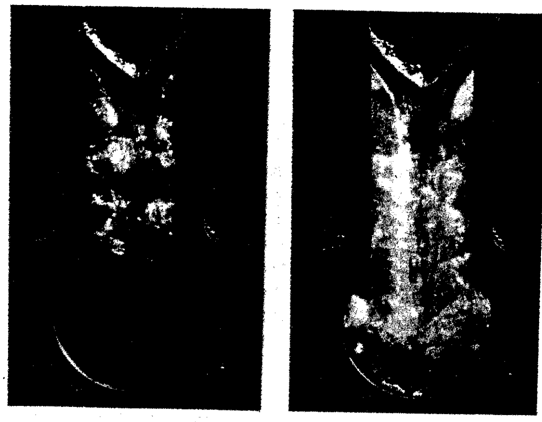
As P_2 was reduced further, the number of cavities increased and large vortices were observed as shown in Fig.10(c). In this stage the noise level became maximum and the value was more 7 dB(c) higher than that of diverging flow. In case of the converging flow, the jet is not decelerated easily in the down stream, because it flows along the poppet surface and tends to concentrate. Hence, the pressure does not readily regain, the cavities collapse not so easily. As a large number of cavities collapse after growing in size, the noise level becomes rapidly higher.

With further reduction of P_2, cavities did not completely collapse in the valve chamber and flew out to the outlet



(a) ΔP=3.92 MPa(K=0.28) (b) ΔP=4.41 MPa(K=0.13) (c) ΔP=4.61 MPa(K=0.085) (d) ΔP=4.88 MPa(K=0.024)

Fig.10 Occurrence process of cavitation
(P_1=5 MPa(abs.), x=0.8 mm, exposure time 3×10^{-6} s)



(a) ΔP=4.41 MPa (K=0.13) (b) ΔP=4.88 MPa (K=0.024)

Fig.11 Occurrence process of cavitation (P_1=5 MPa(abs.), x=0.8 mm)

pipeline, as shown in Fig.10(d) or Fig.11(b). So, the noise level sharply drops. The transparent cross section of the jet surrounded by cavities is able to be observed clearly in Fig.11(b).

Figure 13 shows the pressure distribution along the valve seat when x=0.4 mm. Comparing with Fig.12, it is understood that the pressure distribution becomes more simple drop as x becomes smaller. This fact suggests that the flow scarcely separates from the valve seat at the entrance corner. Even with a microscope, the cavitation was not found out at the entrance region even when the violent cavitation occurred within the down stream region. And the saturation of flow rate also did not occur. It is noticeable that, in case of diverging flow, the vortex cavitation within the down stream region became not to occur easily as the valve lift became smaller, on the other hand, in case of converging flow, the cavitation at the entrance had the same tendency.

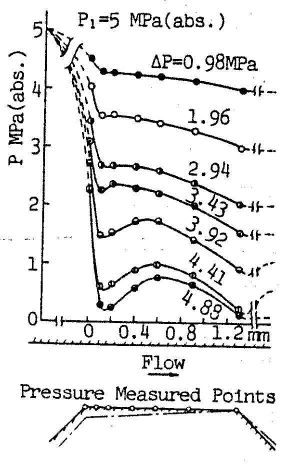


Fig.12 Pressure distribution on the valve seat (x=0.8 mm)

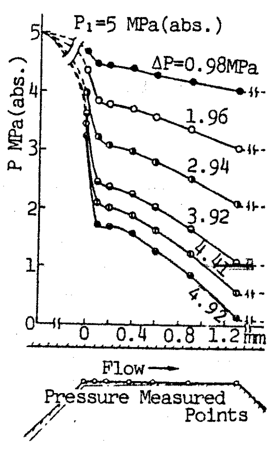


Fig.13 Pressure distribution on the valve seat (x=0.4 mm)

Figure 14 shows the flow performance when ΔP was increased with P_1 fixed at 5 MPa(abs.). In cases of x=0.4 mm and 0.6 mm, also the data of the full shaped model are indicated together for the flow rate and noise level. There are not remarkable differences between the both data of the half cut model and the full shaped model.

The mark of ↱ shows the inception of cavitation and ↱ shows the occurrence of cavitation at the entrance corner. It is understood that the inception happens at almost the same ΔP in the three cases with different valve lift. However, there are differences in the limit for the occurrence of the cavitation at the entrance corner, i.e. there is a tendency to occur at smaller ΔP as x is larger as well as the saturation of flow rate. Comparing with the diverging flow, it is understood that the cavitation occurs not easily rather in case of the converging flow.

Even after the cavitation occurred at the entrance of the restriction and the flow saturation happened, $P_{0.2}$ did not fall below the atmospheric pressure, and neither became constant. So it is supposed that the saturation of the flow rate in this case was not caused by choking of the flow path at the entrance. The pressure at the outlet of the restriction ($P_{1.32}$) also is shown in Fig.14. It dropped sharply and became nearly equal to the atmospheric pressure and became constant as soon as the cavitation occurred at the entrance. Hence, it is supposed that the flow saturation in this case is caused by that the pressure becomes constant at the outlet of the restriction where the flow path area is geometrically smallest.

Figure 15 shows the pressure distributions throughout the inner part of the restriction in case of x=0.8 mm and ΔP=2.94 MPa.

Comparing with the result of Fig.9,

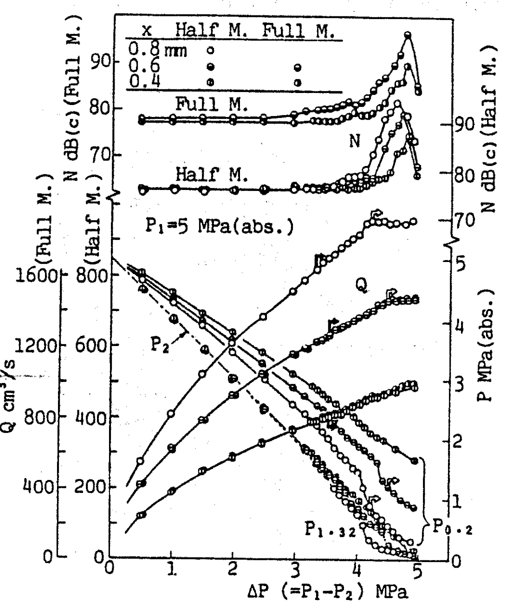


Fig.14 Flow performance (converging flow)

it is understood that the area in which the pressure falls deeply is limited in a very narrow part in this case. The result makes it known why the cavity at the entrance was very thin. The difference of the pressures between on the poppet surface and the valve seat is not so large as in case of diverging flow. Near the outlet of the restriction, the pressure on the valve seat side falls more deeply than that on the poppet surface. The difference of the pressures between on the both side becomes large again there. It is also a different point from the diverging flow.

5. Boundary for the occurrence of cavitation

The critical cavitation numbers for the inception and the occurrence of the flow saturation are indicated for the diverging flow in Fig.16, and for the converging flow in Fig.17. The critical cavitation number was defined as $K_c=P_2/(P_1-P_2)$. And R_e^* of horizontal axis is equivalent to Reynolds' number, in which h is the height of the restriction, ν is kinetic viscosity and ρ is density of the oil. Within this experiment, K_c had a tendency to gather on a single curve in spite of difference of valve lift. A similar result has been reported concerning a spool valve [7].

In case of diverging flow, the both critical numbers; for the inception and for the flow saturation, become larger as R_e^* increases. Also the difference between them has the same tendency, and the difference disappears when R_e^* becomes less than 300 or 400. That is, the saturation of the flow occurs simultaneously with the inception of the cavitation when R_e^* is small.

In case of converging flow, the both critical cavitation numbers considerably less than in case of diverging flow. Within the range of large R_e^*, the critical cavitation number of inception has a tendency to become a constant value.

Figure 18 shows the pressure distributions which were calculated by Eq.(1) for the diverging flow and by Eq.(2) for the converging flow. The equation (1) and (2) were obtained by modification of the equation which had been applied to the laminar radial flow between the parallel plates [17]. They were applied to the oil flow within the restriction of the poppet valve, approximating the flow path of the restriction to a clearance between the parallel fan-shaped plates [16] like a part of nozzle and flapper valve. Besides, Fig.19 shows the experimental results measured under the same conditions as Fig.18. Both results agree with each other in tendency. A little difference of them was caused by neglecting the effect of contraction of flow line near the entrance.

As the poppet angle is 90°, the flow bending angles at the entrance of the restriction are 45° for the both case of diverging and converging flow. On the other hand, the cross sectional area of the flow path becomes larger for the diverging flow and becomes smaller for the coverging flow as coming to the down stream side; namely, the ratio of the outlet area of the restriction to the inlet area is 1:1.16 for the diverging flow, and 1:0.87 for the converging flow. Hence, the flow is decelerated and the pressure regains within the restriction in

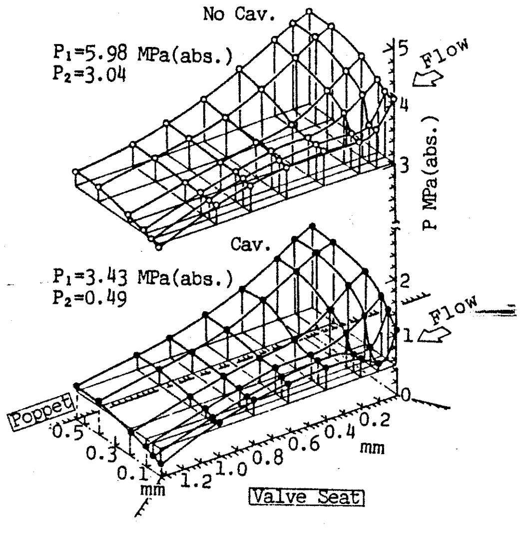


Fig.15 Pressure distribution throughout the inner part of the restriction (converging flow)

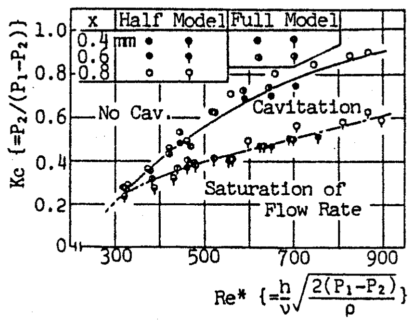


Fig.16 Boundary for the occurrence of cavitation (diverging flow)

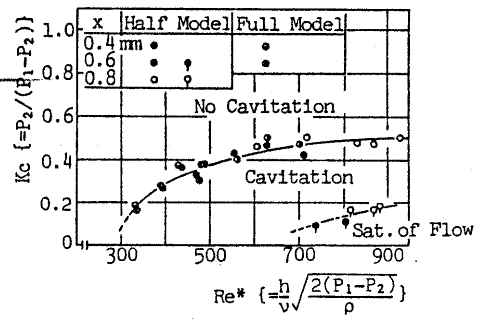


Fig.17 Boundary for the occurrence of cavitation (converging flow)

case of the diverging flow, and the flow is accelerated and the pressure falls as coming to the down stream side in case of the other. Figure 18 and 19 show clearly the difference between the pressure distributions of diverging flow and converging flow.

It is supposed that the differences in the occurrence process of cavitation, flow performance and noise characteristics, between the diverging flow and the converging flow, are almost due to this difference of the pressure distributions.

$$\frac{P-P_2}{P_1-P_2}=\frac{1}{P_1-P_2}\left[\frac{6\mu\tilde{Q}}{\pi h^3}\ln\frac{r_2}{r}+\frac{\rho}{2}\left(\frac{54}{35}\right)\times\left(\frac{\tilde{Q}}{2\pi h}\right)^2\left(\frac{1}{r_2^2}-\frac{1}{r^2}\right)\right] \quad \cdots\cdots\cdots\cdots (1)$$

$$\frac{P-P_2}{P_1-P_2}=\frac{1}{P_1-P_2}\left[\frac{6\mu\tilde{Q}}{\pi h^3}\ln\frac{r}{r_1}+\frac{\rho}{2}\left(\frac{54}{35}\right)\times\left(\frac{\tilde{Q}}{2\pi h}\right)^2\left(\frac{1}{r_1^2}-\frac{1}{r^2}\right)\right] \quad \cdots\cdots\cdots\cdots (2)$$

where, $\tilde{Q}=Q\operatorname{cosec}\phi$, $r_1=(d_1/2)\operatorname{cosec}\phi$, $r_2=(d_2/2)\operatorname{cosec}\phi$, $h=x\sin\phi$, $r=r_1+\Delta r$ (for diverging flow) and $r=r_2-\Delta r$ (for converging flow), and μ is viscosity of the oil.

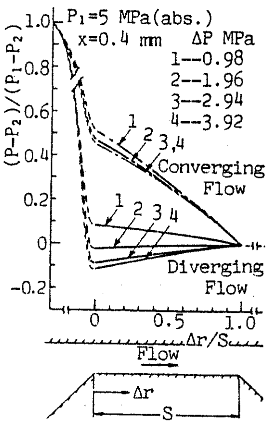


Fig.18 Calculated pressure distribution

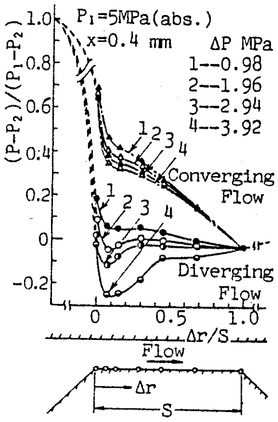


Fig.19 Measured pressure distribution

6. Conclusion

The half cut model of a poppet valve made it possible to observe directly the cavitating condition within the narrow restriction of the poppet valve and to measure the detailed pressure distributions. As a result of experiment with the half cut model, the occurrence process of the cavitation and the effects of cavitation on the flow performance and the noise characteristics were made clear.

It was a noticeable result that there were remarkable differences in occurrence condition of the cavitation, flow performance and noise characteristics, between the diverging flow and converging flow. The differences were almost due to the difference of the pressure distributions in the restriction, caused by the difference of the flow path form; whether the cross sectional area of the flow path became larger or smaller as coming to the down stream side. And, it was also understood that the occurrence process of cavitation changed with the difference of the valve lift.

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