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Cavitation in an Axial Piston Pump*

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In an axial piston pump made of acrylic resin, cavitation is observed by the naked eye with a strobo-scope and by high speed photography, and the pressure changes in the cylinder are measured. The cavitation is classified into the following two groups; one, related to the trapping phenomenon, can be prevented by a suitable design of valve plates, while the other, not related to the trapping phenomenon, is mainly observed in shear layers after the contraction and/or the enlargement of flow passages. In this case, the minimum measurable cylinder pressure corresponding to the appearance of a shock pressure is less than 10 kPa. The cavitation is also studied in a water-glycol hydraulic fluid.

Fluid Power Systems, Piston Pump, Cavitation, Occurrence Mechanism, Occurrence Limit, Minimum Cylinder Pressure, Petroleum Base Hydraulic Fluid, Water-Glycol Hydraulic Fluid.

1. Introduction

Cavitation is one of the important factors limiting the operational range of oil hydraulic pumps. Therefore, it is desirable to evaluate the cavitation inception clearly. Especially, though they are widely used owing to such characteristics as high efficiency, availability for variable displacement types, axial piston pumps have their cavitation characteristics not so good as those of other hydraulic pumps.

Much work on the cavitation of hydraulic pumps has been done, that is, some workers (1), (2) proposed a treatment based on the air separation pressure and others (3)-(5) developed a treatment for axial piston pumps. The physical meaning of the air separation pressure, however, is not always made clear by them, and they did not observe directly the cavitation appearance. The cavitation appearance was observed during a trapping period of an axial piston pump made of a transparent resin (6). However, since the tested range is narrow, there remain plenty of unknown and unclarified matters.

The present study aims to observe the cavitation appearance and to discuss the cavitation mechanism as well as the inception in an axial piston pump whose main parts are made of acrylic resin. Moreover, the cavitation appearance is also observed in water-glycol to clarify the effect of fluid difference.

2. Test apparatus and method

For the convenience of observation, we used an axial piston pump of cylinder block-rotating swash plate type. In this type, non-return valves are usually used to switch the flow, but in the test pump, a rotary valve plate was used as shown in Fig. 1. So the switching of flow from the inlet port to the outlet one is not possible, thus the hydraulic fluid goes and returns through the pipe line as well as the cylinder merely. It is suspected that small bubbles grow gradually due to the reciprocating fluid motion. But this does not necessarily mean that the present study deals with a special cavitation state unlike the actual one, because there are plenty of small bubbles in an oil tank in actual hydraulic systems. To observe the cavitation appearance clearly the parts between the suction port and the cylinder bore, that is, the bottom cover, the valve plate and the cylinder block were made of acrylic resin. And hydrostatic bearings are installed around the valve plate to prevent the cylinder block,

Fig. 1 Test pump

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the valve plate and the bottom cover from touching each other. The piston is 19 mm in diameter, 2 in number and the volumetric displacement per piston is 8.14 cm³ per revolution.

Each cylinder of the pump is connected to the suction tank through straight and horizontal nylon hoses, 20 mm in diameter, 535 mm in total length. The suction tank pressure is kept at a set value by a bladder receiving air from a compressor. To circulate the fluid between the main tank and the suction tank a vane pump was used. The fluids used in the test were a petroleum base fluid and a water-glycol hydraulic fluid, whose properties are shown in Table 1. The temperature is 40±1 °C or the room temperature in some cases for the former fluid, and the room temperature for the latter fluid.

The cavitation is observed by both the naked eye with a stroboscope (input to a discharge tube 60 W, duration of spark 12–22 μs) and by a high speed photography. The cavitation inception is mainly judged by the appearance of a shock pressure on the trace of a semiconductor type pressure transducer (natural frequency more than 60 kHz) to measure the cylinder pressure. Since the transducer tends to produce a drift under a cavitating condition, special care has to be taken in measurements. And the cylinder pressure is measured in the bore shown on the right side in Fig. 1, because the bore pressure was a little lower than the cylinder passage pressure on the suction stroke. The bottom dead center is detected by a non-contact type gap sensor, the pump rotational speed by a photo-electronic transducer and the fluid temperature by a thermister thermometer.

The test was carried out in such a way that the pump was accelerated by means of a stepless transmission at a constant rate under a given suction tank pressure.

3. Test results and discussions

3.1 Cavitation during trapping period

The valve plate tested is of symmetric underlap type as shown in Fig. 2. In the non-cavitating condition, the cylinder pressure has the lowest value when the cylinder port and the valve plate port are connected through a passage 2 mm in depth on the latter half suction stroke, and the second lowest value when both ports are connected through a passage 1 or 2 mm in depth on the former half suction stroke.

Fig. 2 Valve plate dimensions

Fig. 3 Cylinder pressure p_c
(incipience of shock pressure,
700 rpm, suction tank pressure
 $p_s=0.376$ MPa, 0.245 MPa/div.)

Fig. 4 Cavitation state
(650 rpm, $p_s=0.302$ MPa)

Table 1 Properties of the tested fluids

	petroleum base	water-glycol
density kg/m ³	0.85x10 ³ (40°C)	1.08x10 ³ (18°C)
kinematic viscosity mm ² /s	30 (40°C)	120 (18°C)
vapor pressure Pa	10 ⁻² ~ 10 ⁻³	1.3x10 ³ (18°C)
air content* vol %	9.4	2.2

* converted to 101.3 kPa, 0°C

During these periods the cylinder pressure decrease sufficiently in the narrow passage, so that since the cylinder pressure P_c almost reaches an absolute 0 kPa even at a low rotational speed, a shock pressure takes place at the moment when the pressure increases, that is, when the cylinder is connected by a through path on the valve plate and when the delivery stroke begins (Fig. 3).

On the high speed photographs, bubbles appeared in a jet shape out of the passage composed of the valve plate port and the cylinder port, and entered the cylinder shown in Fig. 4. Then the bubbles disappeared suddenly at the beginning of pressure recovery.

The minimum rotational speed where the incipient shock pressures are detected increases with a high suction tank pressure, as shown in Fig. 5. Where P_s is the suction tank pressure, n is the rotational speed. Clearly no shock pressure is detected immediately after bubble initiation. We can predict the cavitation occurrence by estimating the discharge coefficient as well as the flow area between the valve plate port and the cylinder port and by assuming a fluid vapor pressure as the critical cavitating pressure.

Since the cavitation appearance is similar to that in restrictors (7), we can say as follows. The cavitation may occur even when the cylinder pressure or the pressure at the valve plate port is higher than the vapor pressure, if the pressure differential across the flow passage is large.

Judging from the results, it is effective for the cavitation suppression during the trapping period to select a suitable valve port angle. In fact, it was possible to make the cylinder pressure minimum in the middle suction stroke for the case of a valve plate whose through path was 120° in center angle and whose passage 2 mm in depth was 156° , and one which was designed not to cause a trapping on the suction stroke.

During the trapping period in the pump delivery, the effect of the cavitation on erosion and so on is summarized as follows. The effect is usually small on the pump volumetric efficiency, because the change of the cylinder volume is small enough during the trapping period compared to the volumetric displacement. However, the effect on erosion, vibration and noise is large, because the cavitation is vaporous. Especially, care should be taken when a jet is easily formed out of a high pressure region into a low pressure one.

3.2 Cavitation independent of trapping

The test pump has hydrostatic bearings to support the valve plate. Thus, a considerable amount of oil flows from these bearings into the cylinders and seems to affect the cavitation occurrence when there is no such a definite cause as trapping.

Considering both the period of the cavitation appearance and easiness of mea-

surement, the following modification to the valve plate was adopted with no use of the bearings:

(1) The case without a valve plate: the fluid flows into the cylinder through both the suction pipe and the space for the valve plate.

(2) The case with a fixed valve plate: O-rings are used to seal the outer portion of the clearance between the bottom cover, the valve plate and the cylinderblock.

(3) The case where O-rings sealing the inner portion are added in the case 2.

Fig. 5 Inception of cavitation during trapping period

Fig. 6 Cylinder pressure where no shock pressure is detected

These cases are called seal 1, seal 2 and seal 3 respectively. The cylinder pressures for seals 1 and 2 are shown in Fig. 6, when no shock pressure is detected.

Let us clarify the effect of a changing rate of the pump speed. We start from $n=500$ rpm, and select an increment of 100 rpm for each time step Δt . Then the effect is examined by changing the time step Δt from 10 s to 120 s for the case of seal 2.

Fig. 7 shows the results. For $\Delta t = 120$ s the rotational speed corresponding to the shock pressure inception decreases and the minimum cylinder pressure P_{cm} increases slightly.

For the cases of $\Delta t = 10$ s to 40 s, the difference is scarcely detected, so that $\Delta t = 40$ s is chosen for the convenience of observation.

The minimum cylinder pressure corresponding to the shock pressure inception is less than 10 kPa and nearly 5 kPa on an average. Depending on the operational conditions, the cavitation state is classified as follows:

(a) The state where small bubbles appear within the whole cylinder: Though it is difficult to decide the incipient condition of the bubbles clearly, a detectable amount of bubbles can be observed under a strobo-light even when the cylinder pressure is higher than the air saturation pressure, that is, the atmospheric pressure. In our test, there are so many nuclei that bubbles can grow up easily under the low pressure induced by the clearance fluctuation in the sliding parts and/or the bearings.

(b) The state corresponding to a shock pressure appearing at a higher speed than that of the type a: The bubbles go continuously into the cylinder in a group through the inner clearance (nearer part to the shaft) between the piston and the cylinder wall. Before the shock pressure initiates, small amplitude and high frequency fluctuations are observed in the cylinder pressure as the type a. However, the bubbles appearing on the suction stroke disappear with the following pressure increase, so that the type b clearly differs from the type a. The type a may be recognized as a gaseous cavitation while the type b as a vaporous one.

(c) The state corresponding to a higher speed than the type b. The cavitation is observed in the separation layer formed out of the edge of the cylinder port and/or an abrupt enlargement to the cylinder. Accompanying the piston motion, the bubbles go into the cylinder, and disappear near the piston head. In the developed state, cavities are formed in the cylinder port region. Figure 8 shows such a developed state. When the cylinder pressure begins to increase after passing the point of the maximum piston speed, the bubbles collapse suddenly into smaller ones. In the cases where the remaining bubbles are small and few, a single shock pressure is detected. In the case of relatively large and many bubbles, a reflection of the shock pressure is observed.

The cavitation state is related to the seal conditions as follows: The state

corresponding to the shock pressure inception is the type c for seal 1, the type c (or b) for seal 2 and the type a or b for seal 3. For seal 3, a developed, severe cavitation was observed in the type c. Figs. 9 to 11 illustrate traces of the cylinder pressure with the incipient shock. Figure 12 shows the relationship between

Fig. 7 Effect of holding time per step on cavitation (seal 2)

Fig. 8 Cavitation state (developed type (c), 1700 rpm, $P_s = 1.50 \times 10^2$ kPa, seal 2)

Fig. 9 Cylinder pressure (seal 1) 2200 rpm, $P_s = 1.21 \times 10^2$ kPa, 0.49×10^2 kPa/div.

the suction tank pressure and the rotational speed corresponding to the shock pressure inception, suggesting a considerable effect of the sealing conditions on the cavitation. The reasons may be as follows: (i) Inertia effect of fluid is considerable and such an effect is maximum for seal 3 in this apparatus. (ii) For seal 1 the cylinder pressure hardly decreases due to a rather wide passage to the housing where the pressure is atmospheric. (iii) There are a sufficient number of gas nuclei, especially for seal 1. (iv) Bubbles are exposed to the fluctuating cylinder pressure, where number of repetitions is the greatest for seal 3.

It is therefore concluded for the cavitation independent of trapping that, not only the vaporous cavitation but also the gaseous one can be dominant depending on the cylinder pressure as well as the bubble condition. The cavitation effects on the pump delivery, erosion and so on are summarized as follows: Since the vaporous cavitation vanishes on the latter half suction stroke, at least in the

initial state, it significantly affects the erosion, vibration and noise, but a little the delivery. The decrease of delivery will depend on the bubbles which do not vanish on the suction stroke. In this respect, attention should be paid to the ease of air diffusion in the developing process of the vaporous cavitation. On the contrary, the air can relieve the shock accompanying the cavitation bubble collapse.

For conventional pumps, we should consider the following factors: (i) pressure distribution in the cylinder due to its rotation, (ii) jet formation out of the high pressure port to the low one, so on.

(a) 1300 rpm

(b) 1630 rpm

Fig. 10 Cylinder pressure (seal 2)
($p_s = 1.50 \times 10^2$ kPa, 0.49×10^2 kPa/div)

Fig. 11 Cylinder pressure (seal 3)
(1200 rpm, $p_s = 1.50 \times 10^2$ kPa,
 0.49×10^2 kPa/div)

Fig. 12 Inception of cavitation
independent of trapping

3.3 Case of water-glycol

The pump cavitation characteristics in a water-glycol were also examined at room temperature (about 18°C) due to the limitation of the apparatus. The sealing conditions around the valve plate were seals 1 and 2 described above, and the accelerative condition, $\Delta t = 40$ s, was the same as for the petroleum base fluid. In this case, no high speed photography is applicable, for the water-glycol is not so transparent as the petroleum base fluid.

The cavitating state corresponds to that of the type c for seal 1 at the shock pressure inception. Smaller bubbles than in the petroleum base fluid are observed in a row. For seal 2 the cavitating state is close to the type a, and bubbles are observed in the whole cylinder. The bubbles, however, are much fewer than in the petroleum base fluid, so that it is impossible to observe them in the increasing process of the cylinder pressure on the latter half suction stroke. Figures 13 and 14 illustrating the cylinder pressure at the incipient shock indicate that a shock pressure occurs in both cases when the cylinder pressure reaches about 5 kPa, and also that it is hardly possible to detect any difference between the two fluids. Figure 15 shows the relationship between the rotational speed and the incipient shock at a given suction tank pressure. Clearly the speed is less than that for the petroleum base fluid, since the water-glycol is larger in both density and viscosity.

4. Conclusion

In this paper, the cavitation appearance is observed in an axial piston pump whose main parts are made of acrylic resin. Also, the relationship between the cavitation and the measured cylinder pressure is discussed. The factors considered here

Fig. 13 Cylinder pressure
(water-glycol, seal 1)
(2100 rpm, $p_s = 1.21 \times 10^2$ kPa,
 0.49×10^2 kPa/div)

are such operational conditions as suction pressure and rotational speed, shape of the valve plate, sealing conditions around the valve plate and kinds of fluids, that is, a petroleum base and a water-glycol hydraulic fluid.

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Fig. 14 Cylinder pressure
(water-glycol, seal 2)
(900 rpm, $p_s = 1.21 \times 10^2$ kPa,
 0.49×10^2 kPa/div)

Fig. 15 Inception of cavitation
independent of trapping
(water-glycol)

Appendix

To clarify the state of the tested suction line, an equation is presented here. We can calculate numerically the cylinder pressure during the trapping period without cavitation (8), if we know the discharge coefficient (for example, 0.5~0.6 in the test pump) and the flow area between the valve plate port and the cylinder port.

Meanwhile the cushion line affects the cylinder pressure during the period independent of the trapping.

As described already, the suction tank pressure is also measured on the same horizontal line. The pipe line can be divided into the following five sections with different areas; the suction tank, the nylon hose, the valve plate port, the cylinder port and the cylinder bore. Considering the pressure losses due to area changes and laminar pipe friction, we obtain

$$p_c = p_s - \rho \frac{\partial q}{\partial t} \sum \frac{l_i}{A_i} - \frac{\rho}{2} \frac{q}{A_c} \left| \frac{q}{A_c} \right| - \frac{\rho}{2} \sum \zeta_i \frac{q}{A_i} \left| \frac{q}{A_i} \right| - 32\mu \sum \frac{l_i}{d_i^3} \left(\frac{q}{A_i} \right)$$

where ρ is density, μ viscosity, q flow rate, A_c sectional area of cylinder bore, A_i flow area, l_i length of flow passage, d_i diameter of flow passage, ζ_i loss coefficient. Using the experimental loss coefficients, the cylinder pressure on a suction stroke ($\omega t = 0 \sim 180^\circ$) is

$$p_c = p_s - 89 \cos \omega t - 22 \sin^2 \omega t - 3 \sin \omega t$$

where the unit is kPa, and these coefficients are given for the case where the temperature of the petroleum base fluid is 40°C and the rotational speed ω is 100 rad/s.

The inertia effects are considerable here, whose major portion appears in the nylon hose. When no shock pressure is detected, the measurements somewhat lag in phase comparing with the calculated value even for the case of seal 3, because of a leakage in the pump and the compressibility of fluid as well as pipe material.

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