A STUDY OF TWO-STEP THROTTLE IN WATER HYDRAULICS*

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ABSTRACT

In water hydraulic valve, cavitation is more likely to happen than in oil hydraulic one. Two-step throttle, which consists of two orifices, is an effective form to avoid or reduce cavitation damage. In this paper, cavitation index of two-step throttle is analyzed. For throttles with different structure, experiments are conducted for the research of flow and pressure characteristics. Test results indicate that the shapes of two-step throttle exert great influences on its anti-cavitation ability.

KEYWORDS

Water Hydraulic Valve Flow and Pressure Characteristics Two-step Throttle Cavitation

NOTATIONS

A_0 Area of inlet path
A_1 Area of throttle 1
A_2 Area of throttle 2
Q_1 Flow rate through throttle 1
Q_2 Flow rate through throttle 2
Q Flow rate through valve assembly
p_1 Inlet pressure
p_3 Outlet pressure
p_2 Pressure between throttle 1 and 2
k_1 Cavitation index of throttle 1
k_2 Cavitation index of throttle 2

* The project is supported by National Natural Science Foundation of China

k Cavitation index of single throttle
x Poppet lift
á Half-angle of poppet cone
C_d Discharge coefficient
C_q Flow coefficient
C_c Contraction coefficient
Re Reynolds number
p_c Vena contracta pressure
p_v Vapour pressure
d Inlet path diameter
a Area of vena contracta

INTRODUCTION

Water hydraulic system has many advantages such as environmental friendliness, safety, etc. and attracts more and more attention nowadays. However, as a pressure medium, water has its own disadvantages of low viscosity, high vapor pressure and high density and its vapor pressure increases rapidly when temperature rises. Because of high vapor pressure of water, cavitation is more likely to happen in a water hydraulic valve, especially when the pressure drop across valve orifice is large. The formation and collapse of vapor bubbles will result in local high temperature and high pressure, which is sometimes even higher than 700MPa. Cavitation can cause intensive noise, component vibration, energy loss and material erosion[1]. Besides, because of higher density of water than oil, the pressure impact resulting from cavitation in water hydraulic system is more serious than in oil one.

There are many methods for avoiding or reducing cavitation damage in water hydraulic components and systems, such as improving component and system design to keep adequate pressure in the pump inlet, controlling maximum fluid temperature and maximum flow velocity, increasing back pressure of valves and selecting anti-corrosion materials[2]. Previous experiences and practices showed that the geometry shape and size also exert strong effects on the formation and collapse of bubbles, therefore reasonable design of components, especially orifices and throttles, is very important to eliminate or reduce cavitation erosion.

Two-step throttle is a form testified to be effective in reducing cavitation damage. It has been used in water hydraulic pressure relief valves and flow valves, etc. But there is little literature on its features such as flow and pressure characteristics etc. In this paper, cavitation index of two-step throttle is analyzed. For throttles with different structure, experiments are conducted for the research of flow and pressure characteristics, and flow coefficient. Test results indicate that the anti-cavitation ability of two-step throttle is higher than the single-step one which makes the former, and the flow coefficient of a throttle using water as pressure medium is lager than that of one using oil as working medium.

CAVITATION CHARACTERISTICS ANALYSIS

Usually cavitation index is used to describe the trend of cavitation occurrence. It is defined as:

$$k = \frac{p_1 - p_3}{p_1 - p_v} \qquad (1)$$

If the cavitation index of a throttle or orifice takes small value, there is less trend of cavitation occurrence in it.

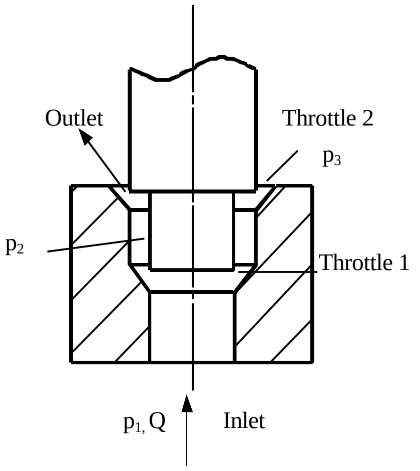

Fig. 1 A type of two-step throttle

Fig.1 shows the structure of a two-step throttle. It consists of two orifices or two throttles, throttle 1 and throttle 2. Suppose the cavitation indexes of the two throttles are k_1 and k_2 respectively. They can be presented as:

$$k_1 = \frac{p_1 - p_2}{p_1 - p_v} \qquad (2)$$

$$k_2 = \frac{p_2 - p_3}{p_2 - p_v} \qquad (3)$$

For a single-step throttle, i.e. one consisting of only one orifice, if the pressure drop across it is the same as in the two-step throttle, i.e. Äp=(p_1-p_3), its cavitation index is given by Equation (1).

Because p1 p_2 p_3, then k_1 k and k_2 k. That means the cavitation index at each orifice of a two-step throttle is smaller than that of a single-step throttle. Therefore, a two-step throttle has lower possibility of cavitation occurrence than a single-step one.

If p_3 is considered as atmosphere pressure, p2 can be expressed as:

$$p_2 = \frac{p_1}{\frac{A_2^{\,2}}{A_1^{\,2}} + 1} \qquad (4)$$

Substituting (4) into (2) and (3) yields:

$$k_1 = \frac{1 - \frac{1}{(\frac{A_2}{A_1})^2 + 1}}{1 - \frac{p_v}{p_1}} \qquad (5)$$

$$k_2 = \frac{1 - \left[(\frac{A_2}{A_1})^2 + 1\right]\frac{1}{p_1}}{1 - \left[(\frac{A_2}{A_1})^2 + 1\right]\frac{p_v}{p_1}} \qquad (6)$$

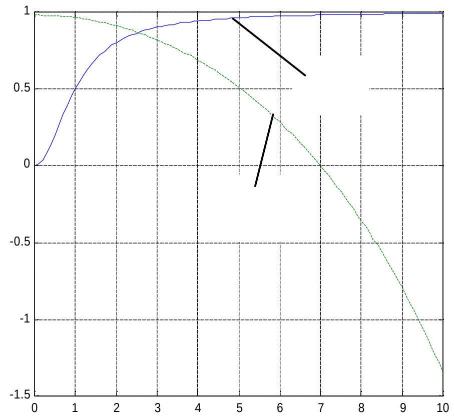

Fig. 2 Diagram of cavitation index

Equation (5) and (6) show that the cavitation indexes of two throttles are the function of the ratio of their flow area A_2/A_1. **Fig. 2** shows the relationship between k_1, k_2 and A_2/A_1. When k_1 increases with the increase of A_2/A_1, k_2 decreases. So in the designing of a two-step throttle, it is very important to select proper value of A_2/A_1 to keep both k_1 and k_2 at relative small value for the purpose of preventing cavitation occurrence.

EXPERIMENT RESULT

(1) Test Apparatus

In order to find out the differences of flow and pressure characteristics between single- and two-step throttles, experiments were carried out in two forms of two-step throttles and a single-step one. Test apparatus for this purpose is shown in Fig. 3. In the test, p_1 and p_3 were measured respectively by two pressure transducers installed at the upstream and downstream of the test assembly. Flow rate Q was measured by a flow-rate meter or a measuring cup or a scale, poppet lift x was measured by a displacement transducer attached at the end of the poppet.

In this research two kinds of two-step throttle, Assembly

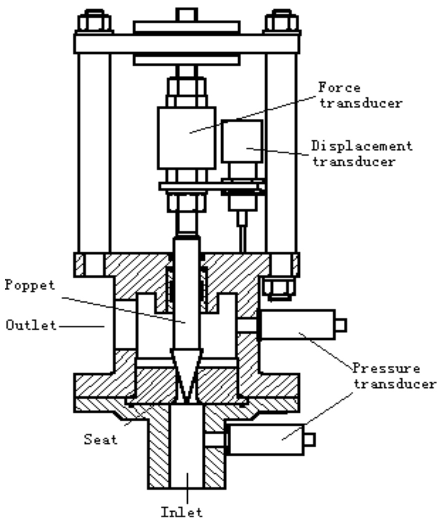

Fig. 3 Test assembly of valve characteristics

A and B, were tested. Assembly A, as shown in **Fig. 4** consists of a poppet of 30°cone angle and a seat with step shape bore. Assembly B, as shown in **Fig. 5**, consists of a poppet of 30°cone angle and a chamfered seat with a groove in it. A single–step throttle, referred as Assembly C (see **Fig. 3)**, which has a poppet of 30-degree cone angle and a sharp edged seat in this paper, was also used in the test. The inlet diameter, d, is 16 mm. For each assembly, test was conducted by varying upstream and downstream pressure while holding poppet lift x constant at a time. There were several poppet lifts used in the test. Pressure, flow rate and the poppet displacement were recorded.

(2) Flow and Pressure Characteristics

Fig. 6 and Fig. 7 show the Q-dp relationship of the three assemblies at poppet lift x=0.1mm and x=0.7mm, respectively. At small lift (x=0.1mm) Assembly A and Assembly C have larger flow gain than Assembly B. In this case, although Assembly C is a single-step throttle, it

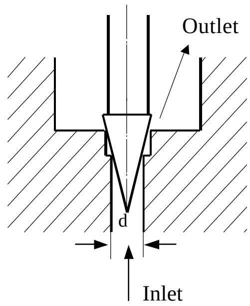

Fig. 4 Assembly A

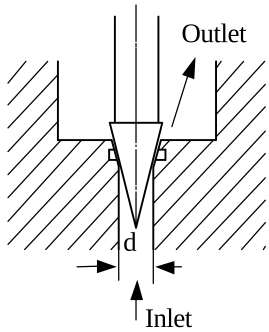

Fig. 5 Assembly B

has larger flow-pressure gain than Assembly A. At large lift (x=0.7mm), Assembly A and Assembly C still have larger flow gain than Assembly B. But this time Assembly A has larger flow gain than Assembly C, which is an inverted result with in the case of x=0.1mm. According to our test and previous documents[3] cavitation is easier to occur when poppet lift is large. At small lift, there is no cavitation observed in both single- and two- throttles. Because the former has less flow restriction than the latter its flow gain is larger than that of the latter. At large lift, cavitation choke is more likely to occur because under this condition cavitation has high tendence to occur. Assembly C has lower flow gain because the increasing of pressure drop can not increase the flow rate through throttle due to the cavitation choke. Larger flow gain means less possibility of flow saturation and cavitation occurrence. Experimental results show that Assembly A has lower cavitation sensitivity than Assembly B and C.

(3) Flow Coefficient

The relationship between the flow rate through a valve and the pressure drop across it is frequently described by the discharge coefficient, C_d, according to the equation[4]

$$Q = \frac{C_d a \sqrt{2(p_1 - p_c)}}{\sqrt{[1-(C_c a / A_0)^2}} \qquad (7)$$

In practice, the pressure at the vena contracta can be very difficult to measure, so it is difficult to calculate C_d. Flow coefficient C_q, which is based on the difference between the upstream and downstream pressures after the vena contracta, is then taken as an alternative measure to describe valve characteristics. Using flow coefficient, flow rate can by described as:

$$Q = C_q A_0 \sqrt{\frac{2(p_1 - p_3)}{r}} \qquad (8)$$

From Eq. (8), C_q can be calculated with measured p_1, p_3 and Q.

Fig. 8 shows the C_q-dp relationship of the three assemblies. In the test, pressure drop was kept at 2.0Mpa and poppet lift was changed from small to large value. **Fig. 8** reveals that the C_q of the throttles, which is between 0.82 and 0.95, does not change significantly with the increasing of lift x, that means the flow is in turbulent state even with small lift and low pressure drop. At small lift, Assembly C has larger coefficient than Assembly A and B because of its flow restriction is smaller than those of Assembly A and B. At large lift, the situation is inverted because of cavitation. With the variation of poppet lift, C_q of Assembly C experiences a fluctuation a little larger than those of Assembly A and B. That means flow rate through a two-step throttle varies less than that of a single-step throttle when the magnitude of pressure differential fluctuation is the same.

Fig. 9 is the C_q-Re relationship of the three assemblies when poppet lift was kept at 0.5mm. It shows that Assembly A and C have larger C_q than Assembly B and this trend becomes more clearer when Re is larger than 20,000. It can be judged that there is no cavitation occuring in Assembly A and C at this lift. The C_q of Assembly B begins to decrease when Re reaches 20,000, which may be due to cavitation. So although Assembly B is a two-step throttle, its anti-cavitation capacity is lower than Assembly C, a single-step throttle. That means not any two-step throttle has higher anti-cavitation ability than all single-step ones. Therefore, it is very important to select suitable structure of two-step throttle for the purpose of anti-cavitation.

CONCLUSI ONS

A. The flow coefficient of two-step throttle using water as pressure medium is between 0.82~0.95;

B. If properly designed, a two-step throttle can have better anti-cavitation capacity than single step throttle.

C. Under non-cavitation condition, two-step throttle has lower flow coefficient because of its large flow restriction compared with single-step throttle.

D. As for the three assemblies used in the test, the anti-cavitation ability of them is in the order of Assembly B, C and A, from low to high.

E. Assembly A is a kind of suitable two-step throttle that can be applied in water hydraulic elments.

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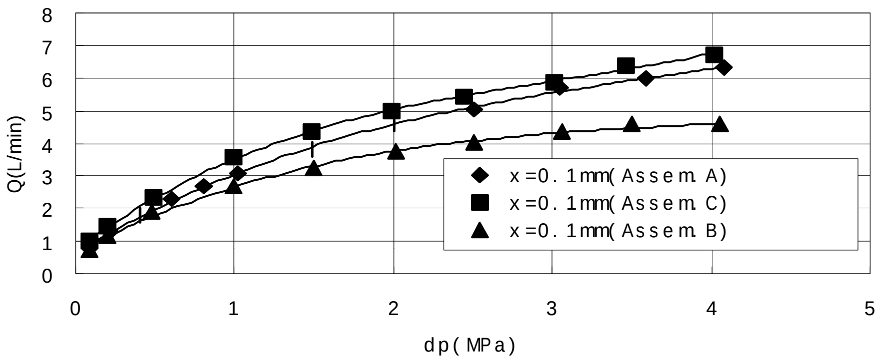

Fig. 6 Q-dp curves at x=0.1mm

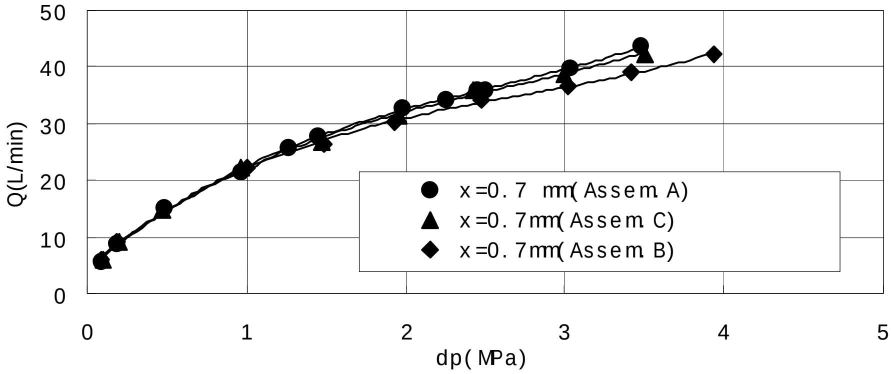

Fig. 7 Q-dp curves at x=0.7mm

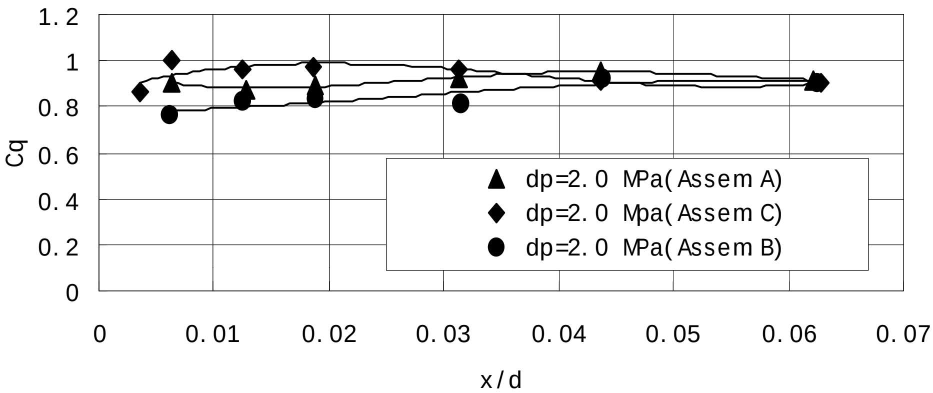

Fig. 8 Cq-x/d curves

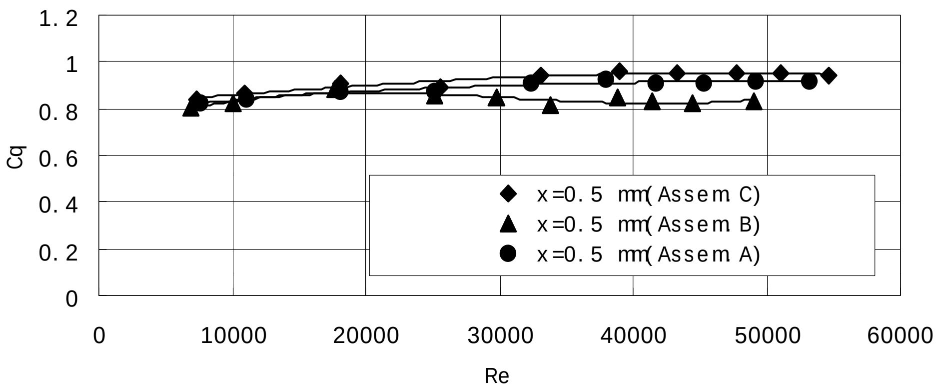

Fig. 9 Cq-Re curves