An experimental study on the discharge coefficient of a sharped-edged hydraulic orifice

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Abstract. Aiming at performing basic research on fluid mechanics of hydraulic orifices under high or low temperature conditions, in this study, a novel compact experimental module, which integrates the oil, the oil supply mechanism, the test valve with orifice and several sensors, was firstly developed, the experimental module can be wholly placed into a high/low temperature chamber to undertake experiments; Based on the integrated experimental module, an automatic measurement test rig was further developed. By using the test rig, experiments on flow characteristics of a sharp-edged hydraulic orifice, which uses the anti-wear hydraulic oil HM46 as the working fluid, were conducted in a temperature range of -10\textdegree C---+80\textdegree C, the Flow-Pressure Characteristics and Discharge Coefficient of the hydraulic orifice were obtained by curve fitting, the effects of different temperatures on the Discharge Coefficient and damping force were finally investigated. The results show that in the temperature range up to room temperature of 20\textdegree C, the Flow-Pressure characteristics, the Discharge Coefficient and damping force of the sharp-edged orifice are not sensitive to temperature changes, but when the temperature is below room temperatures, the discharge coefficient drops linearly, and the damping force increases with the decreasing of temperatures.

1. Introduction

Fluid power technologies are widely used in modern high-end railway vehicle systems \cite{1,2}, so it is meaningful to study the basic characteristics of hydraulic orifices which governing the service performance of key components in those systems. Ramamurthi et al. \cite{3} conducted experimental research on the flow characteristics of sharp-edged orifices when using demineralized water as the working fluids, Naveenji et al. \cite{4} performed simulation works on discharge coefficient during non-Newtonian flows through an orifice meter by using the Computational Fluid Dynamics (CFD) approach, however, the theory and data used are intrinsically based on classical experiments, Yu et al. \cite{5} and Tharakan et al. \cite{6} both investigated the effects of back pressure on orifice discharge coefficients, DYW Studied the effects of orifice geometric parameters on damping performance of an landing gear shock absorber and landing dynamics of the aircraft.

Previous works were mostly conducted in ambient temperature conditions, aiming at doing experiments on hydraulic orifices under high or low temperature conditions, in this work, a novel compact experimental module, which integrates the oil, the oil supply mechanism, the test valve with orifice and several sensors, was firstly developed, the experimental module can be wholly placed into a high/low temperature chamber to undertake experiments; Based on the integrated experimental module, an automatic measurement test rig was further developed. By using the test rig, experiments
on flow characteristics of a sharp-edged hydraulic orifice, which uses the anti-wear hydraulic oil HM46 as its working fluid, were conducted in a temperature range of -10℃~+80℃, the Flow-Pressure Characteristics and Discharge Coefficient of the hydraulic orifice were obtained by curve fitting, the effects of different temperatures on the Discharge Coefficient and damping force were finally investigated.

2. Flow characteristics of sharp-edged orifice

Figure 1 shows the mechanism of fluid passing through a sharp-edged hydraulic orifice. The cross section areas of the orifice and the contraction part are given by:

\[ A_i = \frac{\pi d^2}{4}, \quad A_2 = C_0 A_0 \]  

where \(d\) and \(A_0\) are respectively diameter and cross-section area of the orifice, \(A_2\) is cross-section area of the fluid contraction part, \(C_0\) is the contraction coefficient. Thus, by using the Bernoulli’s Equation and the Fluid Continuity Law, the flow energies and the flows at the cross-sections of the pipe and the contraction part can be respectively formulated by

\[ \frac{P_1}{\rho} + \frac{\alpha_1 v_1^2}{2} = \frac{P_2}{\rho} + \frac{\alpha_2 v_2^2}{2} + \frac{\zeta v_2^2}{2} \]  

and

\[ v_1 A_1 = v_2 A_2 = v_2 C_0 A_0 \]  

where \(P_1, A_1, v_1\) and \(\alpha_1\) are respectively the pressure, area, velocity and kinetic energy correction factor at the 1-1 cross-section, as shown in Figure 1; \(P_2, A_2, v_2\) and \(\alpha_2\) are respectively the pressure, area, velocity and kinetic energy correction factor at the 2-2 cross-section, \(\zeta\) is the coefficient of local resistance energy loss at 2-2 cross-section, \(\rho\) is oil density.

Thus, unifying Equations (2) and (3) to obtain:

\[ v_2 = \frac{1}{\sqrt{\alpha_2 + \alpha_1 \left(\frac{C_0 A_0}{A_1}\right) + \zeta}} \sqrt{\frac{2\Delta P}{\rho}}, \quad \Delta P = P_1 - P_2 \]  

where \(\Delta P\) is the differential pressure of the orifice, because \(A_0 \ll A_1\), and for turbulent flow \(\alpha_1 = \alpha_2 \approx 1\), so Equation (4) could be:

\[ v_2 = \frac{1}{\sqrt{1+\zeta}} \sqrt{\frac{2\Delta P}{\rho}} = C_v \frac{2\Delta P}{\rho} \]  

where \(C_v\) is named the speed coefficient and given by:
Thus, the flow passing through the sharp-edged orifice can be finally formulated by:

\[ q = v_2 A_2 = C_v C_0 \frac{2 \Delta P}{\rho} = C_d A_0 \sqrt{\frac{2 \Delta P}{\rho}} \]  

(7)

where \( C_d = C_v C_0 \) is the discharge coefficient of the orifice.

3. Experiment and analysis

3.1 A novel test rig development

Traditionally, the existing experimental equipment testing the fluid mechanics of orifices almost use the same mechanism, which employs a full and bulky hydraulic system [8] including the pump, valves and even an accumulator to supply pressure oil to the orifices, and the experiments are also conducted under room temperature conditions.

To perform experiment on fluid mechanics of orifices in a high or low temperature conditions, a novel compact experimental module, as shown in Figure 2(b), which borrows the idea of a railway hydraulic damper, was proposed [9]. The module integrates the oil, the oil supply mechanism, the testing damping valve with orifice (like the sharp-edged orifice in Figure 1(c)) and several sensors. Based on the proposed compact experimental module, an automatic measurement test rig was then developed, as shown in Figure 1(a).

Before an experiment, the compact testing module is prepared with the right orifice and wholly put into the high/low temperature chamber for at least 24 hours after the experimental temperature is reached, and then the experiment can be conducted.

![Figure 2](image)

Figure 2. (a) The developed test rig with a high/low temperature chamber, (b) The compact testing module with a damping valve, (c) A sharp-edged orifice in the damping valve.

3.2 Flow characteristics experiment and analysis

By using the developed test rig, experiments on a sharp-edged hydraulic orifice are conducted in the temperature range of -10°C~+80°C, the sharp-edged orifice has a length/diameter ratio of \( l/d = 0.36 \), and the common anti-wear hydraulic oil HM46 is used as the fluid.
As an example, Figure 3 demonstrate the experimental result and data processing method to obtain the Flow-Pressure characteristics and Discharge Coefficient of the orifice. Figure 3(a) shows that in ambient temperature conditions, the Flow-Pressure characteristics (fitted curve), which have an exponent of 0.5, agree well with the Equation (7); the discharge coefficient varies between 0.58~0.87, in the range of Reynolds Number up to 2300~3000, which mean that turbulent flows begin to occur in the orifice, the discharge coefficient varies between about 0.85~0.75 [10,11], at the high Reynolds Number region, the discharge coefficient approaches to a constant value of 0.75 or so.

Figure 4 shows the statistical datum from experiments of the sharp-edged orifice in the temperature range of -10℃~+80℃. Figure 4(a) shows that in the temperature range of 20℃~+80℃, i.e., up to room temperatures, the discharge coefficient in the range with high Reynolds Number almost remains a constant with the value of 0.7, however, in the temperature range of -10℃~+20℃, i.e., when the fluid temperature is below room temperatures, the discharge coefficient drops linearly from 0.7 to 0.4. Thus, the phenomenon indicates that with the temperature decreasing, viscosity of the fluid is increasing, so the energy losses of the fluid will also increase when it flows through the orifice. In addition, the declining speed of discharge coefficient has tight relationship with what kind of fluid used.

![Figure 3](image1.png)

**Figure 3.** Experimental result and data processing of a sharp-edged orifice with $l/d=0.36$: (a) Flow-Pressure characteristics and (b) Discharge Coefficient. (Temperature: $T=30℃$, Fluid: HM46)

![Figure 4](image2.png)

**Figure 4.** Statistical datum from the experiments of the sharp-edged orifice with $l/d=0.36$: (a) Discharge Coefficient in the range with high Reynolds Number versus fluid temperature and (b) Damping force versus fluid temperature. (Temperature range: $T=-10℃~+80℃$, Fluid: HM46)
Figure 4(b) demonstrates that in the temperature range of 20°C~+80°C, the damping forces produced by fluid passing through the orifice almost remain constants at different excitation speeds, but in the temperature range of -10°C~+20°C, i.e., when the fluid temperature is below room temperatures, the damping forces increase with the decreasing of temperatures, so this indicates that with the temperature decreasing, viscosity of the fluid is increasing, so the resistance of the fluid will also increase when it flows through the orifice, which will cause damping force to increase.

4. Conclusions
(1) The developed novel experimental module integrates the oil, the oil supply mechanism, the testing damping valve with orifices and sensors, so it has avoided the traditional bulky method of using a full hydraulic system for oil supply and can be wholly placed into a high/low temperature chamber to undertake experiments. The further developed test rig is actually a versatile and powerful platform for fluid mechanics research.

(2) When using the common anti-wear hydraulic oil HM46 as the working fluid, in the temperature range up to room temperature of 20°C, the Flow-Pressure characteristics and the Discharge Coefficient of the sharp-edged orifice are not sensitive to temperature changes, but when the fluid temperature is below room temperatures, the discharge coefficient drops linearly.

(3) In the temperature range up to room temperature of 20°C, the damping force produced by fluid passing through the orifice almost remain constant, but below that temperature range, the damping force increases with the decreasing of temperatures.

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