Investigation of flow through the two-stage orifice

Junxia Gao\textsuperscript{a,b,c} and Fenghe Wu\textsuperscript{a,c}

\textsuperscript{a}Department of Mechanical Engineering, Yanshan University, Qinhuangdao, People's Republic of China; \textsuperscript{b}Department of Mechatronics Engineering, Tangshan University, Tangshan, People's Republic of China; \textsuperscript{c}Heavy-duty Intelligent Manufacturing Equipment Innovation Center of Hebei Province, Qinhuangdao, People's Republic of China

ABSTRACT

In the field of engineering, understanding the flow characteristics of an orifice is key to accurately controlling pressure or flow; however, the transitional flow characteristics of the two-stage orifice has not been studied. The value of the discharge coefficient parameterizing the two-stage orifice flow equation is primarily based on that of the single classic orifice; however, this assumption leads to significant errors, because of the different numbers in the sudden contraction structure. Through theoretical derivation, the flow equations difference between the two-stage orifice and single classic orifice was compared and analyzed. Combining theoretical analysis, Computational Fluid Dynamics (CFD) simulation and experimental measurement, the transitional flow characteristics of the two-stage orifice were investigated using mineral oil. The comparison results of the three parts are essentially consistent. In this paper, the discharge coefficient and the pressure drop over the two-stage orifice were primarily focused on Reynolds numbers between 900 and 1700. In comparison with the single orifice, the results show that under the same dimensions ($d = 3$ mm), the discharge coefficient of the two-stage orifice is greater, and the transitional flow state of the two-stage orifice is different from that of the single orifice. Additionally, the pressure drop of the two-stage orifice is less than that of the single orifice under the same volume flow rate. The prestage cylindrical hole slows the changing trend of the flow field parameters, and the second-stage orifice with smaller diameter is mainly responsible for the pressure loss. The current research provides important support for accurate pressure and flow control of the two-stage orifice, and the role of the prestage cylindrical hole can also be a good reference in the structure design of micro-orifices.

1. Introduction

Orifices are widely used in many engineering applications such as orifice meters, hydraulic components or piping systems, for the sake of flow control (Nakayama, 1961), pressure control (Zhang, An, Liu, & Yan, 2016), buffering and shock absorption (Chen, 2006). There are two main structural types of orifices used in applications, namely, the single classic orifice (as shown in Figure 1) and the two-stage orifice (as shown in Figure 2).

The two-stage orifice, which has a hexagonal prism hole at the prestage, is widely used in mechanical engineering due to its design simplicity and flexible installation. Chen (2006) mounted a two-stage orifice between the two working chambers of a hydraulic cylinder to buffer the pressure impact of the robot’s legs touching the ground. Zhang et al. (2016) added a two-stage orifice in a reversing valve oil line to produce a pressure drop. In this paper, some two-stage orifices (as shown in Figure 2a) are installed in the hydraulic governing system for the steam turbine to produce a specific pressure or flow control.

Often the influence of the hexagonal prism hole of the two-stage orifice on the whole flow field is neglected in practical applications. The value of the discharge coefficient parameterizing the two-stage orifice flow equation is primarily assumed based on that of the single orifice, but in practice this assumption leads to significant errors (Zhang et al., 2016). However, no literature to date has studied the flow characteristics of the two-stage orifice, especially when the diameters of the inlet and outlet of the pipeline are not equal. The existing literature mainly focuses on flow characteristics of the single classic orifice in horizontal pipes with equal diameter using methods such as experimentation, empirical formula or numerical simulation.

According to studies on the characteristics of single classic orifices (Canbazoglu & Canbulut, 2005; Johansen, 1930; Lau, Edge, & Johnston, 1995; Lichtarowicz, Duggins, & Markland, 1965; Nakayama, 1961; Ramamurthi & Nandakumar, 1999; Reis & Hanriot, 2017; Schrank & Murrenhoft, 2013; Tu, Hrnjak, & Bullard, 2006), the
coefficients relating the volumetric discharge of incompressible fluids to the pressure drop across the orifice are well known over a large range of high Reynolds numbers \((Re)\). When \(Re < 150\), the flow through the orifice is steady and is free from periodic vorticity (Johansen, 1930). At sufficiently high Reynolds numbers, namely, \(Re > 10,000\), the discharge coefficient is nearly constant under conditions of turbulent flow (Lichtarowicz et al., 1965). However, over the range of transitional flow, namely, from steady to turbulent flow, appreciable variations of the discharge coefficient occur. The influence of factors such as type of orifice, diameter, length, pressure drop and Reynolds number on the discharge coefficient have not been investigated in detail and therefore, have not yet formed a wide connection.

Considering that the quantitative theory is not suitable for the transition state over a wide range of Reynolds numbers, a number of empirical formulas for discharge coefficients based on experimental data were proposed (Jankowski, Schmierer, Prenger, & Ashworth, 2008; Lichtarowicz et al., 1965; Merrit, 1967; Nakayama, 1961). The coefficient was expressed as an equation to match the experimental curves arranged by the Reynolds number and length-to-diameter \((L/d)\). However, no explanation has been provided as to why and how these factors are involved.

Additionally, with the development of computer technology and the rapid improvement of hard software capability, commercial Computational Fluid Dynamics (CFD) software enables researchers to devote more energy to considering the physical nature of computational flow problems, as well as the rationality of boundary (initial value) conditions and calculation results (Akbarian et al., 2018; Chau & Jiang, 2002, 2004; Faizollahzadeh Ardabili et al., 2018; Gao, Zhang, Liu, Sun, & Tian, 2018; Mou, He, Zhao, & Chau, 2017; Peng, Gui, & Fan, 2018; Wu & Chau, 2006; Zhang, Ma, Hong, Yang, & Fang, 2017). CFD analysis has been widely applied for orifice flow predictions in recent years (Araoye, Badr, & Ahmed, 2017; Di Rito, 2007; Reader-Harris, Barton, & Hodges, 2012; Roul & Dash, 2012; Schrank & Murrenhoff, 2013; Shah, Joshi, Kalsi, Prasad, & Shukla, 2012; Singh & John Tharakar, 2015; von Grabe, Riedel, Stammen, & Murrenhoff, 2013; Yau, Kua, & Balvinder, 2017).

The above results are all based on the single classic orifice, therefore, the fitness of the results to the two-stage orifice remains to be confirmed. Herein, we proposed that the two-stage orifice be regarded as a special case of two damping holes in series with zero spacing, and then the results on the flow characteristics of double orifices arranged in a series in the axial concentric position of the horizontal pipe (Araoye et al., 2017; Elger & Adams, 1989; He & Zhao, 2010; Mohan, Yogesh, & Seshadri, 2015), can be utilized to understand the flow characteristics of two-stage orifice.

He and Zhao (2010) discussed how the damped hole spacing affected the efficiency of the orifice energy dissipater. Araoye et al. (2017) studied the flow characteristics and the total pressure drop in multistage restricting orifices using CFD simulations and found that the orifice plate spacing determined the flow structure downstream the second orifice and the total pressure drop. Based on the previous studies, the inner sudden contraction structure affects the overall pressure drop of the two-stage orifice, especially downstream of the orifice. Therefore, it can be inferred that the transitional flow characteristics are different from those of the single classic orifice and that it is important to study the transitional flow characteristics of two-stage orifice.

This paper aims to investigate the transitional flow characteristics of the two-stage orifice using mineral oil, focusing on the discharge coefficient and pressure drop over the two-stage orifice. Through theoretical derivation, the difference of equations for the two-stage orifice

Figure 1. The structure of single classic orifice. (a) Thin orifice (b) Thick orifice

Figure 2. The common structural form of the two-stage orifice. (a) Tapered pipe threads (b) General screw threads.
and single classic orifice is compared and analyzed. Using the CFD model, some profiles associated with the transitional flow characteristics of the two-stage orifice and single classic orifice are plotted and studied. Experiments are conducted to validate the theoretical analysis and the CFD model. The comparison results of the three parts are essentially consistent.

2. Theoretical analysis of the discharge coefficient

The hexagonal prism hole in the prestage of the two-stage orifice is simplified as a cylindrical hole because of the similar flow characteristics (Rup & Sarna, 2011), and the inscribed circle diameter of the hexagonal prism hole is taken as the diameter of a cylindrical hole. The geometric structures of the two-stage orifice and the single orifice with the same $L/d$ ratio are shown in Figure 3, and the specific dimensions are shown in Table 1, where $L_f$ is the length of the prestage cylindrical hole in the flow direction, $L$ is the length of orifice in the flow direction, $d_f$ is the diameter of the prestage cylindrical hole, $d$ is the diameter of orifice, and $D_1$ and $D_2$ are the diameter of pipe inlet and outlet, respectively.

The discharge coefficient of the orifice can be calculated from Equation (1),

$$C_d = \frac{Q}{A \cdot \sqrt{2 \Delta p / \rho}} = \frac{u}{\sqrt{2 \Delta p / \rho}},$$

where $C_d$ is the discharge coefficient, $Q$ is the volume flow rate through an orifice, $A$ is the cross-sectional area of the orifice, $u$ is the flow velocity, $\Delta p$ is the pressure drop over the resistance and $\rho$ is the density of the fluid.

The expression for the Reynolds number is just shown as Equation (2).

$$Re = \frac{ud}{v},$$

where $v$ is the kinematic viscosity.

Under the state of turbulent flow with an incompressible fluid, a mathematical expression of the discharge coefficient has been obtained by combining the Bernoulli equation in different cross-flow sections, as shown in Figure 4, the continuity equation and the momentum equation.

The Bernoulli equation from 1-1 to 2-2, as well as the equation from 2-2 to 3-3 are respectively listed as follows.

$$\frac{p_1}{\rho g} + \frac{u_1^2}{2g} = \frac{p_2}{\rho g} + \frac{u_2^2}{2g} + \sum \xi_1 \frac{u_2^2}{2g},$$

$$\sum \xi_1 = \xi_{1-2} + \lambda_f \frac{L_f}{d_f},$$

$$\frac{p_2}{\rho g} + \frac{u_2^2}{2g} = \frac{p_3}{\rho g} + \frac{u_3^2}{2g} + \sum \xi_2 \frac{u_3^2}{2g},$$

$$\sum \xi_2 = \xi_{2-3} + \lambda \frac{L}{d},$$

where $p_i$ ($i = 1, 2, 3, 4$), $u_i$ ($i = 1, 2, 3, 4$) are the pressure and velocity at the sections in Figure 3 separately, $\sum \xi_1$ is the total resistance coefficient from 1-1 to 2-2, $\xi_{1-2}$ is the local resistance coefficient of the sudden contraction structure from 1-1 to 2-2, $\lambda_f$ is the frictional resistance coefficient along the wall of orifice from 1-1 to 2-2, $\sum \xi_2$ is the total resistance coefficient from 2-2 to 3-3, $\xi_{2-3}$ is the local resistance coefficient of the sudden contraction structure from 2-2 to 3-3, and $\lambda$ is the frictional resistance coefficient along the wall of orifice from 2-2 to 3-3.

If $m_1 = d_f / D_1$, $m_2 = d/d_f$, the velocity relationship between sections can be derived from the continuity equation:

$$u_1 = \left( \frac{d_f}{D_1} \right)^2 u_2 = m_1^2 u_2,$$

$$u_2 = \left( \frac{d}{d_f} \right)^2 u_3 = m_2^2 u_3.$$
The diffusion process from 3-3 to 4-4 can be explained by the momentum equation as follows:

\[
\rho \pi D_2^2 u_3 (u_3 - u_4) = (p_4 - p_3) \frac{\pi D_2^2}{4} .
\]  

If \( m_3 = d/D_2 \) and the value of \( m_4^2 \) can be negligible because \( m_3 < 1 \), Equation (12) can be obtained.

\[
p_4 = p_3 + 2m_3^2 \frac{\rho u_3^2}{2} .
\]  

Combining Equations (8), (9), (10) and (12), Equation (13) can be explained as follows:

\[
u_3 = \frac{1}{\sqrt{\left[1 + \sum \xi_a + \left(1 + \sum \xi_1\right) m_2^4 - 2m_3^2 \right]}} \times \sqrt{\frac{2(p_1 - p_4)}{\rho}} .
\]  

Comparing Equations (1) and (13), the discharge coefficient for the two-stage orifice can be described as Equation (14).

\[
C_d = \frac{1}{\sqrt{\left[1 + \sum \xi_2 + \left(1 + \sum \xi_1\right) m_2^4 - 2m_3^2 \right]}} .
\]  

If the values of \( m_2^4 \) can be negligible because \( m_2 < 1 \), the Equation (14) can be further simplified to

\[
C_{d,two-stage} = \frac{1}{\sqrt{1 + \sum \xi_2 - 2m_3^2}}
\]

\[
= \frac{1}{\sqrt{1 + \left(\xi_2 - \lambda \frac{L}{d}\right) - 2m_3^2}}
\]

\[
= f \left( \frac{1}{\sqrt{\xi_2 - \lambda}}, \frac{1}{\sqrt{\lambda}} \right) \bigg|_{m_3, L/d=\text{constant}}
\]  

(15)

Additionally, the discharge coefficient for the single orifice can be solved as shown in Equation (16).

\[
C_{d,single} = \frac{1}{\sqrt{1 + \sum \xi_a - 2m_3^2}}
\]

\[
= \frac{1}{\sqrt{1 + \left(\xi_{a-b} + \lambda \frac{L}{d}\right) - 2m_3^2}}
\]

\[
= f \left( \frac{1}{\sqrt{\xi_{a-b}}}, \frac{1}{\sqrt{\lambda}} \right) \bigg|_{m_3, L/d=\text{constant}}
\]  

(16)

where \( \sum \xi_a \) is the total resistance coefficient from a-a to b-b and \( \xi_{a-b} \) is the local resistance coefficient of the sudden contraction structure from a-a to b-b.

Since \( \xi_{2-3} \) or \( \xi_{a-b} \) is essentially a constant determined by experiments (Sheng, 1980), it can be inferred from Equations (15) and (16) that \( \lambda \), the frictional resistance coefficient along the wall of orifice, has great influence on the variation trend of the relation between the discharge coefficient and the Reynolds number. According to the Moody’s experiment curve (Sheng, 1980), in the transition zone from a hydraulic smooth pipe to a hydraulic rough pipe, the coefficient \( \lambda \) decreases with the increase of the Reynolds number and tends to be constant. That observation is the reason why appreciable variations of the discharge coefficient are accompanied with Reynolds numbers over the range of transitional flow. In practical application, the coefficient is determined according to the experience of technicians, assuming the pipeline is a hydraulic smooth pipe (Yuan, 2001).
Furthermore, comparing Equations (15) and (16), it can be found that when the frictional resistance coefficient $\lambda$ of the single orifice and the two-stage orifice is relatively close, the discharge coefficient of the two-stage orifice is apparently larger than that of the single orifice, that is $C_{d, \text{two-stage}} > C_{d, \text{single}}$, for $x_{a-b} > x_{2-3}$, which can be concluded by $m_1 < m_2$ (Sheng, 1980). This finding also means that under the same volume flow rate, the pressure drop of the two-stage orifice is less than the single orifice according to Equation (1).

In addition, Equations (15) and (16) indicate that, when the diameters of the inlet and outlet of the pipeline are not equal, the discharge coefficient of the two-stage orifice is mainly related to the outlet diameter of the orifice.

### 3. CFD model

The incompressible steady flow is considered mainly along the axis of the orifice. The flow field for two-dimensional geometry (as shown in Figure 3) is solved by the steady Reynolds-averaged continuity and momentum equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_j} = 0, \quad (17)$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} - \rho u_i' u_j' \right), \quad (18)$$

where $u_i$ and $x_i$ are the velocity and coordinate components respectively, and $t$ is the time; $u_i' u_j'$ is the Reynolds stress.

To solve Equations (17) and (18), the standard $k$-$\varepsilon$ model (Launder & Spalding, 1974) has been used as a turbulence model.

$$\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}, \quad (19)$$

where $\mu_t$ is the eddy viscosity, $C_{\mu} = 0.09$ is the empirical constant, $k$ is the turbulence kinetic energy and $\varepsilon$ is the rate of dissipation.

The transport equations in the standard $k$-$\varepsilon$ model are given as follows.

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon, \quad (20)$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1 \varepsilon} \frac{\varepsilon}{k} G_k - C_{2 \varepsilon} \frac{\rho^2}{k} \varepsilon \quad (21)$$

where $\mu$ is dynamic viscosity, $G_k$ is the generation of turbulence kinetic energy due to the mean velocity gradients, and $G_\varepsilon = \mu_t ((\partial u_i/\partial x_j) + (\partial u_j/\partial x_i))(\partial u_i/\partial x_j)$. The empirical model constants are $\sigma_k = 1.0$, $C_1 = 1.44$, $C_2 = 1.92$, and $\sigma_\varepsilon = 1.3$.

To improve the accuracy of the calculation, a block method is used to divide the structured grid, and the mesh refinement of the orifice and its adjacent area are performed.

The near-wall area adopts the scalable wall function. At the wall of the pipe and the orifice, the conditions of no slip boundary and no heat exchange with the outside world have been assumed.

The convection term is discrete in the second order upwind scheme, and the dispersion of the diffusion term uses the center difference scheme. The discrete equations of each variable are iterated by the SIMPLE (Semi Implicit Pressure Linked Equation) algorithm, and the numerical simulation process is solved by ANSYS Fluent 16.0 with the double precision solver. All the solutions were considered to be fully converged when the sum of residuals was below $10^{-5}$.

The value of the inlet velocity is set from 0.5 to 2.2 m/s for the orifice with a diameter of 3 mm and a pressure of 1 bar at the outlet. In all cases, the Reynolds number ranges from 900 to 1700. The fluid through the orifice is mineral oil with a density of 900 kg/m$^3$ and a kinematic viscosity of 30 mm$^2$/s at atmospheric pressure.

Based on the centerline axial pressure profiles with the inlet velocity of 2 m/s under different grid sizes, a grid independence has been performed. As shown in Figure 5, there has been an error reduction of predicted pressure drop for coarse and fine meshes, but the difference is less

![Figure 5. Effect of grid size on centerline axial pressure profile of the orifice.](image-url)
than 3% between 105,720 cells and 228,580 cells, which implies that the higher mesh sizes have negligible effect on the results. As a result, the final selection is 105,720 cells.

4. Experimental characterization

To validate the results obtained by the CFD simulations, measurements are executed on a test bench, which is mainly composed of a power supply unit, a test device designed independently, a flow sensor, two pressure sensors and a regulating valve (see Figure 6). The test devices were designed in the form of hydraulic manifold blocks. Pressure sensors and pressure gauges are installed on the top surface, and the orifice for testing is assembled inside the integrated block. The test fluid is mineral oil ISO VG46 with a kinematic viscosity of 46 mm²/s at 40°C and a density of 900 kg/m³. Figure 7 shows the assembled test apparatus.

The measuring error of the flow sensor used in the experiment is approximately 3% and the pressure is near 1%. The oil temperature in experiment is approximately 45°C–50°C.

![Figure 6. Schematic diagram of the test bench.](image1)

![Figure 7. Picture of the test device.](image2)

![Figure 8. Comparison of the discharge coefficient.](image3)

![Figure 9. The discharge coefficient obtained by orifice blocks (Schrank & Murrenhoff, 2013).](image4)
5. Comparison and discussion

5.1. Discharge coefficient

As shown in Figure 8, it can be clearly established that the discharge coefficient of the two-stage orifice is larger than that of the single orifice under the same diameter, which is consistent with the theoretical analysis. According to the results of this experiment, the experimental data are generally larger than those from the simulation. This observation can be explained by the instabilities of the transient flow and impossibility of an ideal sharp-edged orifice crafted in practical applications. Moreover, this phenomenon can be related with the test device using hydraulic manifold blocks. Lichtarowicz et al. (1965) mentioned that the experimental results of Kreith and Eisenstadt obtained by orifice blocks were consistently slightly higher than those of other investigators. As shown in Figure 9, the existence of this phenomenon is also confirmed by the experimental results of Schrank and Murrenhoff (2013).

For the relatively stable discharge coefficient shown in Figure 8, the single orifice is approximately 0.85 and the two-stage orifice is approximately 0.90 when Re is near 1700. Nakayama (1961) conducted a series of experiments using distilled water or dry air to investigate the

Figure 10. Discharge coefficient of single orifice (Nakayama, 1961).

Figure 11. Discharge coefficient of rounded nozzle (Nakayama, 1961).

Figure 12. Comparison of volume flow rate to pressure drop relation.

Figure 13. Contours of velocity magnitude by CFD simulation (m/s). (a) Contour of velocity magnitude (m/s), inlet velocity 1.8 m/s (b) Contour of velocity magnitude (m/s), inlet velocity 1.8 m/s
discharge characteristics of different nozzles and orifices. On the base of the experimental data read from the curves in Nakayama’s paper, the discharge coefficient versus Reynolds number curves are plotted in Figures 10 and 11. The viscosity of water or air is much lower than that of mineral oil, and that signifies the higher Reynolds number when the turbulence state is complete. Therefore, compared with Figures 8, 10 and 11, the overall variation trend of the discharge coefficient is consistent, although the range of Reynolds number is different. It can also be concluded that the trends in discharge coefficient of the two-stage orifice are different from those of the single orifice, but more similar to the rounded nozzle.

Additionally, the theoretical analysis also shows that the variation trend of the relation between the discharge coefficient and the Reynolds number is mainly affected by the frictional resistance coefficient along the wall of orifice. Figure 8 shows that when $Re > 1000$, the discharge coefficient of the two-stage orifice continues increasing with the increase in the Reynolds number. However, the discharge coefficient curve of the single orifice gradually becomes gentle. According to the Moody’s experiment

![Graphs showing pressure variation](image)

**Figure 14.** The pressure variation of axial position. (a) The pressure variation of axial position for two-stage orifice (b) The pressure variation of axial position for single orifice (c) Comparison of the pressure variation of axial position, inlet velocity 1.8 m/s
curve (Sheng, 1980), it can be concluded that the flow in the single orifice at the Reynolds number of 1000 is into the hydraulic rough pipe, but the flow of the two-stage orifice is still in a hydraulic smooth tube. Therefore, the transitional flow state of the two-stage orifice is different from that of the single orifice.

5.2. Pressure drop

The relationship between the volume flow rate and pressure drop through a resistance is given by Figure 12, which indicates that the simulation result correlates well with the test. Contours of velocity magnitude are obtained by CFD simulation, as shown in Figure 13. From Figures 12–14, information can be derived as follows:

1. When the pressure drop is greater than 0.8 bar, the gap between the experimental data and the simulation data varies, and the changing trend of the single orifice is more obvious. The transitional flow state of the two-stage orifice is different from that of the single orifice when the pressure drop is greater.

2. Under the same volume flow rate, the pressure drop of the two-stage orifice is less than that of the single orifice, which shows that the flow regime of the two-stage orifice is more stable.

From Figure 14(c), a translation phenomenon of the profiles at axial position from 50 mm to 54.5 mm, which is the position of the prestage of the two-stage orifice, can be clearly observed. It indicates that the prestage cylindrical hole slows the changing trend of the flow field parameters, and this result is consistent with the phenomenon observed in Figure 13. It also reflects the partial pressure principle of the two-stage orifice, that is, the second stage with a smaller diameter cylindrical hole is mainly responsible for the pressure loss. This finding demonstrates the feasibility of regarding the two-stage orifice as a special case of two damping holes in series with zero spacing.

6. Conclusion

In this paper, the transitional flow characteristics of the two-stage orifice were investigated using mineral oil and the combination of theoretical analysis, CFD simulation and experimental measurement. The comparison results of the three parts are essentially consistent. The discharge coefficient and the pressure drop over the two-stage orifice were mainly focused for the Reynolds numbers between 900 and 1700. The results are summarized as follows:

1. Under the same dimension \(d = 3\) mm, the discharge coefficient of the two-stage orifice is greater than that of the single orifice, and the coefficient is mainly related to the outlet diameter of the pipeline when the diameters of the inlet and outlet of the pipeline are not equal.

2. The variation trend between the discharge coefficient and the Reynolds number is mainly affected by the frictional resistance coefficient along the wall of orifice. The transitional flow state of the two-stage orifice is different from that of the single orifice.

3. Under the same volume flow rate, the pressure drop of the two-stage orifice is less than that of the single resistance, which means the two-stage orifice can enhance the stability of the flow field at the outlet of the orifice.

4. The prestage cylindrical hole slows the changing trend of the flow field parameters, and the second-stage orifice with the smaller diameter is mainly responsible for the pressure loss. It proves the feasibility of regarding the two-stage orifice as a special case of two damping holes in series with zero spacing.

The current research provides important support for accurate pressure and flow control of a two-stage orifice, and the role of the prestage cylindrical hole can also be a good reference in the structure design of micro-orifices. However, it is regrettable that no experimental data at a larger range of Reynolds numbers were obtained and no comparison of flow characteristics with different diameters of two-stage orifices were completed due to the restrictions on experimental conditions and time. In future work, we will conduct experimental studies on the transitional flow characteristics of two-stage orifices with smaller diameters at different ambient temperatures. It would be interesting to study the flow characteristics of the two-stage micro-orifice using mineral oil or water separately.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The work was supported by the Hebei Provincial People’s Government Degree Committee & Hebei Provincial Department of Education [grant number CXZZBS2018045]; Ministry of Science and Technology of the People’s Republic of China [grant number 2016YFC0802900], State Key Laboratory of Engine Reliability [grant number skler-201701], Hebei Provincial Natural Science Foundation [grant number E2017203372] and Ministry of Science and Technology of the People’s Republic of China [grant number 2013ZX04001-041].
References

Akbarian, E., Najafi, B., Jafari, M., Faizollahzadeh Ardabili, S., Shamshirband, S., & Chau, K.W. (2018). Experimental and computational fluid dynamics-based numerical simulation of using natural gas in a dual-fueled diesel engine. *Engineering Applications of Computational Fluid Mechanics, 12*(1), 517–534.

Araoye, A. A., Badr, H. M., & Ahmed, W. H. (2017). Investigation of flow through multi-stage restricting orifices. *Annals of Nuclear Energy, 104*, 75–90.

Canbazoglu, S., & Canbulut, F. (2005). A note on the flow coefficients of capillary tube and small orifice restrictors exposed to very low Reynolds number flow. *Industrial Lubrication and Tribology, 57*(3), 116–120.

Chau, K. W., & Jiang, Y. W. (2002). Three-dimensional pollutant transport model for the Pearl River estuary. *Water Research*, 36(8), 2029–2039.

Chau, K. W., & Jiang, Y. W. (2004). A three-dimensional pollutant transport model in orthogonal curvilinear and sigma coordinate system for Pearl river estuary. *International Journal of Environment and Pollution, 21*(2), 188–198.

Chen, Z. W. (2006). *Research on control system of hydraulically actuated single-legged hopping robot* (dissertation). Zhejiang University.

Di Rito, G. (2007). Experiments and CFD simulations for the characterisation of the orifice flow in a four-way ServoValve. *International Journal of Fluid Power, 8*(2), 37–46.

Elger, D. F., & Adams, R. L. (1989). An experimental study of oscillating flow through two orifices in series. *The Journal of the Acoustical Society of America, 85*(3), 1065–1073.

Faizollahzadeh Ardabili, S., Najafi, B., Shamshirband, S., Minaei Bidgoli, B., Deo, R. C., & Chau, K.-w. (2018). Computational intelligence approach for modeling hydrogen production: A review. *Engineering Applications of Computational Fluid Mechanics, 12*(1), 438–458.

Gao, X. P., Zhang, H., Liu, J. J., Sun, B. W., & Tian, Y. (2018). Numerical investigation of flow in a vertical pipe inlet/outlet with a horizontal anti-vortex plate: Effect of diversion orifices height and divergence angle. *Engineering Applications of Computational Fluid Mechanics, 12*(1), 182–194.

He, N., & Zhao, Z. H. X. (2010). Theoretical and numerical study of hydraulic characteristics of orifice energy dissipator. *Water Science and Engineering, 3*(2), 190–199.

Jankowski, T. A., Schmierer, E. N., Prenger, F. C., & Ashworth, S. P. (2008). A series pressure drop representation for flow through orifice tubes. *Journal of Fluids Engineering, 130*(5), 589–603.

Johansen, F. C. (1930). Flow through orifice holes at low Reynolds numbers. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 126*(801), 231–245.

Lau, K. K., Edge, K. A., & Johnston, D. N. (1995). Impedance characteristics of hydraulic orifices. *Proceedings of the Institution of Mechanical Engineers Part I Journal of Systems & Control Engineering, 209*(49), 241–253.

Launder, B. E., & Spalding, D. B. (1974). The numerical computation of turbulent flows. *Computer Methods in Applied Mechanics and Engineering, 3*(2), 269–289.

Lichtarowicz, A., Duggins, R. K., & Markland, E. (1965). Discharge coefficients for incompressible non-cavitating flow through long orifices. *Journal of Mechanical Engineering Science, 7*(2), 210–219.

Merrit, H. E. (1967). *Hydraulic control systems*. New York: John Wiley & Sons.

Mohan, K. H. M., Yogesh, K. K. J., & Seshadri, V. (2015). CFD analysis of flow through dual orifice plate assembly. *International Journal of Emerging Technology and Advanced Engineering, 5*(10), 136–144.

Mou, B., He, B.-J., Zhao, D.-X. & Chau, K.-w. (2017). Numerical simulation of the effects of building dimensional variation on wind pressure distribution. *Engineering Applications of Computational Fluid Mechanics, 11* (1), 293–309.

Nakayama, Y. (1961). Action of the fluid in the air-micrometer: 1st report, characteristics of small-diameter nozzle and orifice no.1, in the case of compressibility being ignored. *Transactions of the Japan Society of Mechanical Engineers, 26*(210), 1485–1492.

Peng, Q. L., Gui, L. J., & Fan, Z. J. (2018). Numerical and experimental investigation of splashing oil flow in a hypoid gearbox. *Engineering Applications of Computational Fluid Mechanics, 12*(1), 324–333.

Ramamurthi, K., & Nandakumar, K. (1999). Characteristics of flow through small sharp-edged cylindrical orifices. *Flow Measurement and Instrumentation, 10*, 133–143.

Reader-Harris, M., Barton, N., & Hodges, D. (2012). The effect of contaminated orifice plates on the discharge coefficient. *Flow Measurement & Instrumentation, 25*(3), 2–7.

Reis, M. N. E., & Hanriot, S. (2017). Incompressible pulsating flow for low Reynolds numbers in orifice plates. *Flow Measurement and Instrumentation, 54*, 146–157.

Roul, M. K., & Dash, S. K. (2012). Single-phase and two-phase flow through thin and thick orifices in horizontal pipes. *Journal of Fluids Engineering, 134*, 091301.

Rup, K., & Sarna, P. (2011). Analysis of turbulent flow through a square-sectioned duct with installed 90-degree elbow. *Flow Measurement & Instrumentation, 22*(5), 383–391.

Schranka, K., & Murrenhoff, H. (2013, July 7–11). CFD simulations and experiments of the Dispersed Two-phase flow through hydraulic orifices. Proceedings of the ASME 2013 fluids engineering division summer meeting, Incline Village. *Journal of Physical Chemistry B, V01CT17A006*.

Shah, M. S., Joshi, J. B., Kalsi, A. S., Prasad, C. S. R., & Shukla, D. S. (2012). Analysis of flow through an orifice meter: CFD simulation. *Chemical Engineering Science, 71*(9), 300–309.

Sheng, J. C. H. (1980). *Hydraulic fluid mechanics* (p. 139). Beijing: Machinery Industry Press.

Singh, V. K., & John Tharakan, T. (2015). Numerical simulations for multi-hole orifice flow meter. *Flow Measurement and Instrumentation, 45*, 375–383.

Tu, X., Hrnjak, P. S., & Bullard, C. W. (2006). Refrigerant 134a liquid flow through micro-scale short tube orifices with/without phase change. *Experimental Thermal & Fluid Science, 30*(3), 253–262.

von Grabe, C., Riedel, C., Stammen, C., & Murrenhoff, H. (2013). An analytic thermodynamic model for hydraulic resistances based on CFD flow parameters. *International Journal of Fluid Power, 14*(2), 17–26.

Wu, C. L., & Chau, K. W. (2006). Mathematical model of water quality rehabilitation with rainwater utilization — a case study at Haigang. *International Journal of Environment and Pollution, 28*(3), 534–545.

Yau, K. H., Kua, E. C., & Balvinder, S. (2017). Numerical investigation of a thick plate restriction orifice on the pressure drop
performance. *IOP Conference Series: Materials Science and Engineering*, 243, 012028.

Yuan, E. N. X. (2001). *Engineering fluid mechanics* (p. 125). Beijing: Petroleum Industry Press.

Zhang, H. D., An, Y. C., Liu, M. X., & Yan, J. J. (2016). Analysis and solution of the speed switch of a kind of press brake. *Chinese Journal of Hydraulic and Penumatics*, 3, 92–95.

Zhang, B., Ma, J. E., Hong, H. C., Yang, H. Y., & Fang, Y. T. (2017). Analysis of the flow dynamics characteristics of an axial piston pump based on the computational fluid dynamics method. *Engineering Applications of Computational Fluid Mechanics*, 11(1), 86–95.