No.2/2015

HIDRAULICA

HYDRAULICS-PNEUMATICS-TRIBOLOGY-ECOLOGY-SENSORICS-MECHATRONICS

ISSN 1453 - 7303
ISSN-L 1453 - 7303

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Address: 14 Cuţitul de Argint, district 4, Bucharest, 040558, Romania
Phone: +40 21 336 39 91; Fax:+40 21 337 30 40;
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with support from:
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HIDRAULICA Magazine is indexed by international databases:

ISSN 1453 – 7303; ISSN – L 1453 – 7303

Static Characteristics of the Orifices in a Pilot Operated Pressure Relief Valve

PhD. eng. **Sasko DIMITROV**[1], PhD. eng. **Simeon SIMEONOV**[2], PhD. eng. **Slavco CVETKOV**[3]

[1] "Goce Delcev" University - Stip, Macedonia, sasko.dimitrov@ugd.edu.mk

[2] simeon.simeonov@ugd.edu.mk, [3] slavco.cvetkov@ugd.edu.mk

Abstract: *In this paper the static characteristics of the sharp edged orifices have been investigated. Mathematical relationship between pressure loss and flow through the orifice has been developed and solved for orifices mainly used in pilot operated pressure relief valves. A CFD simulation of the flowing process has been done. A full CAD model of the volume for orifices with different geometric parameters was created and meshed at finite number of elements. As a result of the CFD computations, few diagrams have been presented and compared to the theoretical ones. The discharge coefficient and the pressure loss coefficient have been obtained.*

Keywords*: orifice, pressure drop, flow, CFD, simulation, discharge coefficient*.

1. Introduction

Functional drawing of conventional type, most frequently used in industry, pilot operated pressure relief valve is presented on fig. 1 [1]. Inlet parameter of the valve is the flow q_1 and the outlet parameter is the system pressure p_1 set at the pilot valve. When the system pressure is lower then p_1, both stages, the pilot and the main stage, are closed. When the system pressure reach the set value, pilot stage opens and small amount of pilot flow q_y is flowing through the orifices 1 and 2 and the pilot stage, but the main stage is still closed because of low pressure drop in the orifices 1, 2 and 3. When the pilot flow increases enough, the orifices 1, 2 and 3 causes enough pressure drop, pressure force in the upper chamber of the main stage is lower than the pressure force of the system pressure. In this case the main stage opens and all the flow is relieving to the tank. So, pressure drop through the valve orifices is the key factor for proper operation of the valve. Those orifices are sharp edged, i.e. short length orifices where linear pressure drop can be neglected, only quadratic pressure drop exist.

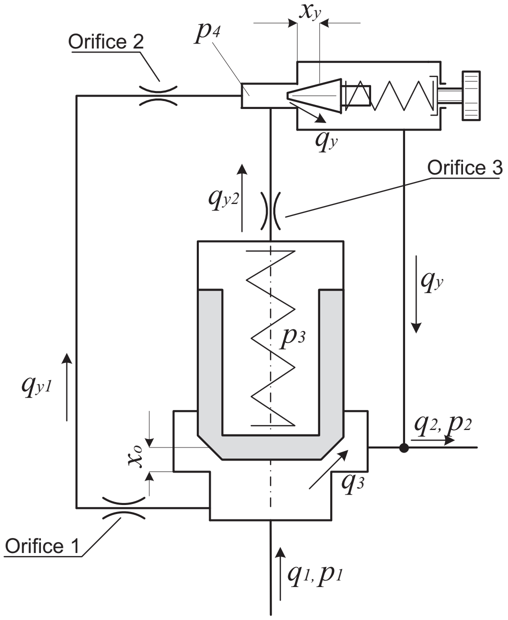


Fig. 1. Functional diagram of a pilot operate pressure relief valve

The flowing and pressure drop through the sharp edged short orifices have been investigated long time ago. In [2] a model for discharge coefficient in the orifice is introduced as a function of the Reynolds number. According to this model, discharge coefficient calculation requires iterative procedure because Reynolds number also depends on the flow rate. To avoid this iterative procedure, in [3] an empirical discharge coefficient model for orifice flow is recommended. Another model for the discharge coefficient is described in [4] by Borutzky. Those models provide a linear relation through the orifice for small velocities while for turbulent flows, they match the conventional square root characteristics. Also, the transition from the laminar to the turbulent regime is smooth [5].

In this paper a CFD method for simulation of the flowing process through the orifice is used, the pressure drop coefficient and the discharges coefficient have been determined and compared with numerical ones.

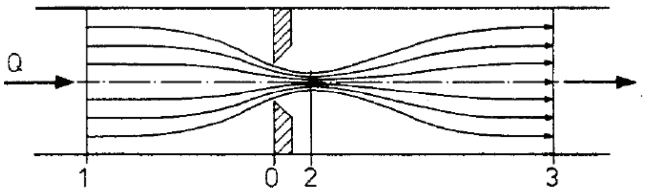


Fig. 2. The sharp edged orifice

2. Mathematical modelling

Steady state flowing process through an orifice is presented in fig.2. Well known dependence on flow of the pressure drop is [6]:

$$Q = \alpha_D \cdot A_0 \cdot \sqrt{\frac{2}{\rho} \cdot \Delta p} \tag{1}$$

where: Q –the flow through the orifice; α_D – the discharge coefficient; A_0 - the area of the orifice, $\Delta p = p_1 - p_3$- the pressure drop in the orifice.

Pressure drop in the sharp edged short orifice can be expressed by the equation:

$$\Delta p = \xi \cdot \frac{\rho}{2\cdot A_0} \cdot Q^2 \tag{2}$$

Where: ξ - the local resistant coefficient.

Comparing the eq. (1) and (2), the dependence among the discharge coefficient and the pressure drop coefficient, is:

$$\alpha_D = \frac{1}{\sqrt{\xi}} \tag{3}$$

For $Re = 10 - 20000$ and $l/d = 1.5 - 10$, Lichtarowicz [7] has recommended an expression for discharge coefficient calculation:

$$\frac{1}{\alpha_D} = \frac{1}{\alpha_{Dmax}} + \frac{20}{Re} \cdot \left(1 + 2.25 \cdot \frac{l}{d}\right) \tag{4}$$

Where d - the orifice diameter; l - the orifice length.

Experimentally Wobben [8] has determined the maximal value of the discharges coefficient and it is $\alpha_{Dmax} = 0.83$.

Reynolds number for circle area is $= \frac{v\cdot d}{\nu} = \frac{4\cdot Q}{d\cdot\pi\cdot\nu}$. Combining the last eq. for Re, into eq. (4) and introducing the correction factor $\left[\frac{20\cdot\nu}{d}\cdot\left(1 + 2.25\cdot(l/d)\right)\right]^2$, the final equation for flow calculation in a sharp edged orifice has been obtained:

$$Q = \alpha_{Dmax} \cdot \frac{\pi \cdot d^2}{4} \cdot \sqrt{\frac{2}{\rho} \cdot \Delta p + \left[\frac{20 \cdot \nu}{d} \cdot \left(1 + 2.25 \cdot (l/d)\right)\right]^2} - \\ -\alpha_{Dmax} \cdot 5 \cdot \pi \cdot d \cdot \nu \cdot \left(1 + 2.25 \cdot \frac{l}{d}\right) \qquad (5)$$

Knowing the geometric parameters of the orifice, applying eq. (5), it is possible to obtain the static characteristic of the orifice, i.e. the flow through the orifice depending on the pressure drop in the orifice.

3. CFD simulation of the flowing process through the orifices

To identify the discharge coefficient and the pressure drop in the orifice a series of steady-state CFD computations was performed with commercial CFD software package FLUENT. Three different sizes of orifices have been investigated: 0.6 mm, 0.8 mm and 1.0 mm. CAD model of the fluid volume has been created and it has been divided into around 310000 elements, depending on the size of the orifice. The meshing model of the 0.8 mm orifice is presented on fig.3.

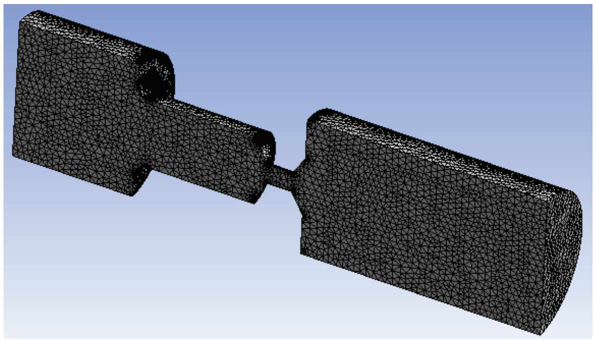
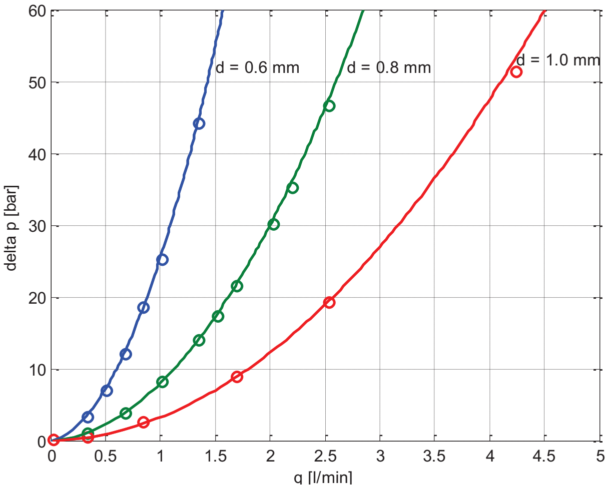
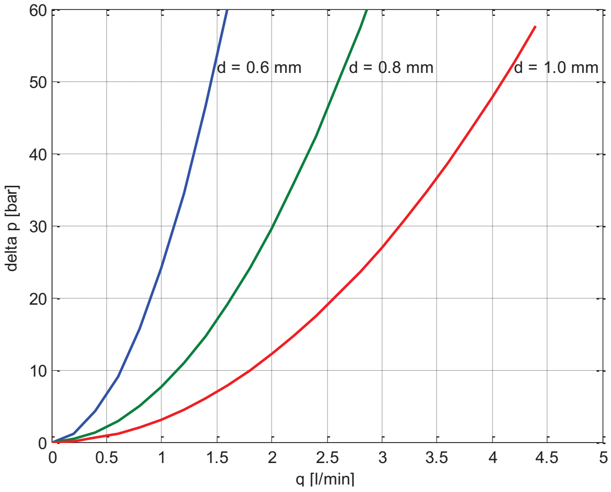


Fig.3. The CFD meshed geometry

As an input parameter was set the flow in the orifice. The output parameter, calculated by FLUENT, is the pressure drop through the orifice.
The results obtained by CFD simulation and the solution of the eq. (5) have been shown on fig.4. It is evident that there in very good match of the results between CFD simulation and the presented theory.





○ CFD; —— eq. ( )

Fig. 4. The static characteristics of the orifices

Fig. 5. The theoretical static characteristics of the orifices

For simplicity of calculation, very often the pressure drop in the sharp edged orifice can be approximated by the eq. (2). According to this relation, for the local resistant coefficient $\xi = 1.48$,

the curves on fig. 5 have been obtained. It can be seen that there is good match between CFD simulation and relation (5) (fig.4) and the approximated eq. (2) fig. 5. Applying the eq.(3), the flow coefficient is $\alpha_D = 0.822$, i.e. it tends to $\alpha_{Dmax} = 0.83$.
The values of the flow coefficient depending on the Reynolds number have been presented on fig. (6). For turbulent regime of flowing the flow coefficient has constant value, but in the laminar regime of flowing, the flow coefficient is not constant, i.e. it varies depending on the average velocity of flowing in the orifice. Usually the pilot flow in the pressure relief valves is around $1.0 - 1.5\ [l/min]$. So the Re number does not exceed the value of 1500. For simplicity of calculation, in the dynamic model of the pilot operated pressure relief valve an average value of 0.8 for flow coefficient can be taken.

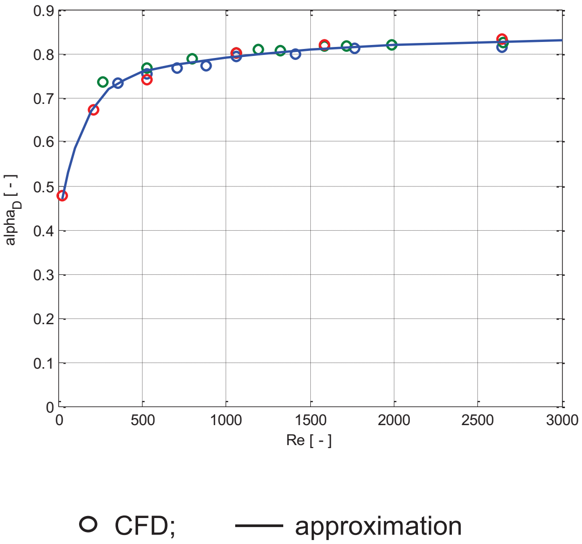


Fig. 6. The discharge coefficient of the orifices

Fig. 7 and fig.8 depict the pressure and velocity distribution for 0.8 mm sharp-edged orifice along the axis of the orifice. The pressure and velocity distribution do not differ qualitatively for different orifice diameters. The pressure drops quickly in the nozzle, then at the end of the nozzle the pressure little increase and then decrease and stay approximately constant. The velocity sharply rises in the nozzle and at the end of the nozzle begins to decrease.

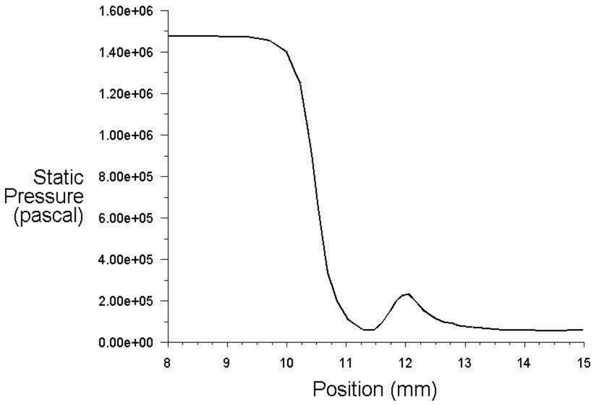


Fig.7. The pressure distribution along the orifice axis

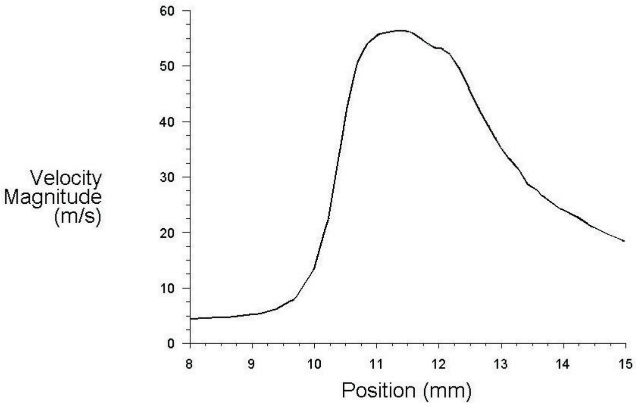


Fig. 8. The velocity distribution along the orifice axis

Typical velocity contour and velocity vectors of $0.8\ mm$ orifice diameter, with $1.35\ l/min$ and $14\ bar$ pressure drop in the orifice is presented on fig. 9 and. Fig.10. The velocity contours and velocity vectors do not differ qualitatively for different orifice diameters. As it is expected, the maximal velocity occurs at the nozzle where the diameter is the lowest.

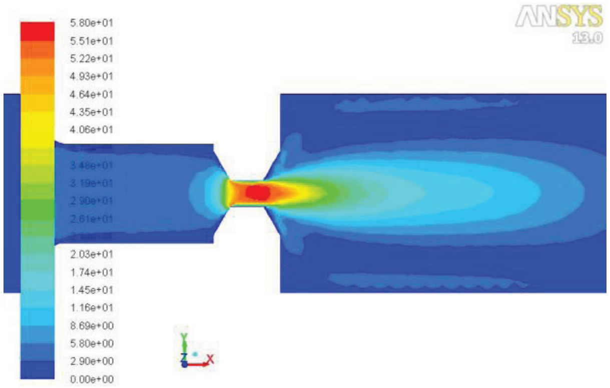


Fig. 9. The velocity contour

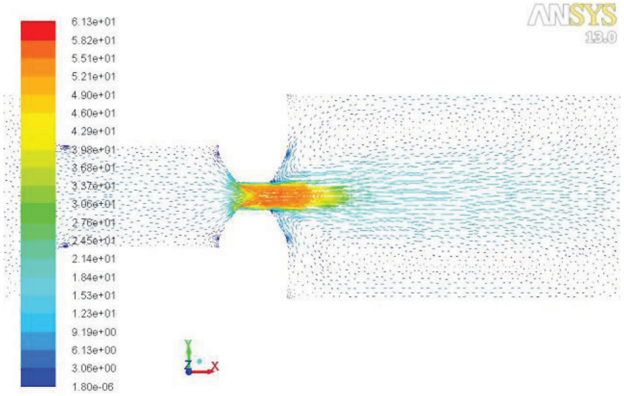


Fig. 10. The velocity vectors

4. Conclusions

Mathematical relationship between flow and pressure loss in the sharp edged orifices has been developed in this paper. This mathematical model was confirmed with CFD simulation. CAD model of the flowing volume was created and simulation of the flowing process has been made. Graphically was compared the results of the CFD simulation and the solution of the eq. (5). The flow coefficient depending on the Reynolds number was obtained and presented graphically on fig.6. The pressure and velocity distribution along the orifice axis was depicted and the velocity contour and velocity vectors were shown (fig. 9 and fig.10).

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