Research Article

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The novel solution of ball valve with replaceable orifice. Numerical and field tests

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Abstract: The article presents the results of numerical calculations and experimental results of a flow through the orifice. Such a measuring device was built-into the ball valve that gave unique possibility of the orifice exchange without the pipeline disassemble. The advantages of using the prototypical solution has been described. This patented solution has been tested extensively for the durability and tightness. The article contains comparison between flow character in the case of single-hole orifice and a multi-nozzle one. The prototypical measuring device has been produced and assembled in compressed air system in the Power Plant Opole, that gave experimental verification of theoretical approach.

Keywords: Flow meter, simulation, gas flow, design

Nomenclature

F gravitation (from N-S equation)
p air pressure, bar (or kPa)
p1 air pressure at the inlet, bar
Q mass flow at the inlet, Nm³/h
q_{vn} volumetric flow of air, Nm³/h
q_m mass flow of air, kg/h
q_v volumetric flow of air, m³/h
v velocity (from N-S equation)
t time (from N-S equation)
T_p air temperature, °C
Δp air pressure difference, kPa
Δp1 pressure difference on the edge of orifice hole, kPa

Δp2 pressure difference on the edge of the hole closer to the front face of the orifice, kPa

Δp3 pressure difference on the edge of orifice hole located further on the orifice plane, kPa

Greek symbols

β coefficient of contraction
ρ_p density of air, kg/m³
ρ density (from N-S equation)

1 Introduction

Measurement of gas flow in power industry require various accuracy. Orifice method is the one of standardized [1], however its precision depends on pipe length in front of and behind the orifice, and a relation between the pipe diameter and orifice hole diameter. Small diameter of orifice hole generates high flow resistance. Here one can place the conflict between measurement accuracy and flow resistance. One of possibility of accuracy improvement is application of solution patented by ZPDA Ostrow Wielkopolski [2].

Another problems that exist in described construction are more additional places of leakage. It's a consequence of more complicated construction, as the orifice is built into ball valve. Hence there are typical possible places of leakage like in typical ball valve. However the patented construction enables fast trouble-free and safe replacement of the orifice. Such solution allowed to carry-out measurement temporarily, that does not generate resistance in permanent way, since the orifice can be removed.

In order to localize the leakage ways and durability of described construction at different temperatures relevant tests have been carried-out [3].

Possibility of the orifice exchange enabled application of patented multi-nozzle orifice [4] that generates lower flow resistance. Multi-nozzle orifice characterize the same coefficient of contraction β .

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Manufacturers of fluid flow measuring devices in recent years have begun searching for solutions characterized by lower hydraulic losses and allowing for increased accuracy of measurement. For this purpose, consideration has been given to multi-nozzle orifices currently used by many research centers. Finding specific information about the results of research is very difficult. Figure 1 shows examples of the holes arrangement on the orifice disk. This type of research is extremely important in an era of times where savings are sought everywhere. In large plants, such as, power plants, consumption reduction by several tenths of a percent per year may turn out to be a significant saving.

Figure 1: Example of multi-nozzle flanges a) 13-hole flange analyzed by Malavasi *et al.*, B) 6-hole flange designed by Huang c) example of the flange analyzed by Zhao *et al* d) flange used by Emerson Rosemount in its gauges [5]

Numerical calculation using the Navier-Stokes equation were performed in case of various configuration of holes position (Figure 1) and described in [5]. Then the flanges for the DN 100 diameter according with Figure 2 were produced and subjected it to field tests.

The orifices shown in Figure 2 have the same coefficient of contraction β .

Assembly of the prototype valve in the compressed air system in the Opole Power Plant gave possibility of verification of the numerical calculations results with the experiment.

Figure 2: Measuring orifice a) standardized one-hole flange b) multi-hole flange developed by ZPDA from Ostrow Wielkopolski

2 Object of research

Figure 3a presents a ball valve prototype with a replaceable measuring orifice (diameter DN100), and a cross section of the valve in Figure 3b.

Figure 3: Valve prototype with measuring orifice a) view, b) section with a description of the main elements

The prototype was built into ball valve with the so-called a trunnion-mounted ball. The solution is that the ball in the valve is supported by two pins gripped in the bearing bushes. The pins are used to rotate the ball. The replaceable orifice, mounted inside the ball hole, acts as an element of the measurement system only during full opening of the passage. The accumulation of the medium in front of the orifice creates a pressure difference in front of and behind it. In order to measure the differential pressure, in the pins holes are drilled in such a way that one hole is in front of and the other behind the orifice. Figure 4 shows the prototype of the valve with impulse channels connected to the spindle and differential pressure transducer.

The valve body is made of P355NH steel, pin - X6CrNiTi 18-10 steel, ball X20Cr13, orifice - austenitic steel 1.4541 - Figure 5.

This selection of construction materials allows measurements also in environment of the natural gas or oil. Removal of the cover (Figure 3a) allows the replacement of the orifice with a different coefficient of contraction β

Figure 4: The cross-section of the prototype, 1 - Valve body, 2 - Ball, 3 - Measuring orifice, 4 - Spindle, 5 - Pressure impulse channel, 6 - Impulse tube, 7 - Five-way valve, 8 - Differential pressure transducer, 9 - Inlet connection flange, 10 - Outlet connection flange

Figure 5: Multi-nozzle flange

or the use of a multi-nozzle orifice without the need to dismantle the entire device and the long-term interruption in medium transfer.

Preliminary research [6] on the multi-nozzle flange indicates that the advantage of using it is that the flow losses through the orifice made according to the patented invention are significantly smaller than in the case of a cylinder-shaped orifice. In addition, when the liquid is flowing, the nozzles made according to the invention are more resistant to the formation of cavitation, which allows measurements at higher flow rates. The research on the prototype is carried out under the Operational Program - Intelligent Development (POIR 01.01.01-00-0013 / 15 "Development of a device for measuring the flow of utilities on industrial mains").

3 Preliminary research

Before mounting the prototype of the valve in the compressed air system in the Opole Power Plant, the internal and external leak testing of the valve prototype DN100 was carried out. Then, for a prototype with a single-hole measuring orifice, calculations were made according to the standard using a dedicated application. The normative calculations made for a single-hole flange were compared with the results obtained using the CFD ANSYS calculation software. Calculations have been carried out using resources provided by Wrocław Centre for Networking and Supercomputing (<http://wcss.pl>) grant No.444. Numerical calculations of a multi-nozzle or single-hole flange with the same value of the coefficient of contraction β were carried out for the same initial conditions as were given by the power plant employees:

- mass flow at the inlet: $Q = 2000 \text{ Nm}^3/\text{h}$,
- air pressure at the inlet: $p_1 = 8 \text{ bar}$,
- air temperature: $T = 25^\circ\text{C}$.

To carry out the calculations the following assumptions were made:

- non-stationary simulation
- turbulence model: k - epsilon,
- grid model: unstructured.

The numerical mesh was constructed with elements of the tetra type in volume and of the prism in the boundary layer.

Parameters of mesh were the following:

- nodes number: 2 113 315
- elements number: 9 028 942
- element quality (average): 0,828
- aspect ratio (average): 0,18834
- skewness (average): 0,2048
- accuracy: $1 \cdot 10^{-5}$

Boundary conditions – given flow, calculated pressure difference with assumed pressure of compressed air equal to 8 bar.

4 Numerical calculation of air flow through the prototype

Fluid mechanics is defined by the non-linear Navier-Stokes differential equations (1) defined by the principles of the

momentum behavior and the fluid stream energy.

$$\frac{\delta g}{\delta t} + (g * \nabla)g = F - \frac{1}{\rho} \nabla p + g \nabla^2 g \quad (1)$$

where:

$(g * \nabla)g$ – transfer of momentum caused by the movement of liquids,

$\frac{1}{\rho} \nabla p$ – change of momentum caused by pressure force,

$g \nabla^2 g$ – friction forces

F – gravitation.

Knowledge of velocity fields, fluid pressures, temperature gradients, mass and heat flows is of great importance for effective and highly efficient design of devices.

Performing correct calculations using equation (1) using CFD (Computational Fluid Dynamics) software involves using packages for numerical calculations that have inbuilt programs that allow to go through the entire process of preparing a simulation from a geometry task to generating a grid and presenting the results. Basic blocks of CFD programs:

1. Preparation of geometry - implementation of the so-called "Water body", then giving the "water body" finite volume and compaction of the mesh near the elements that may cause flow disturbances and the task of boundary conditions (preprocessing);
2. Calculation of the solution (solving);
3. Graphical presentation of results (postprocessing).
4. To prepare the geometry (determining the diameter of the tube, the diameter of the holes of the multi-hole flange and the diameter of the one-hole flange, the length of the tube sections through and behind the orifice) were used for measurements on the site and information obtained from ZPDA Ostrow Wielkopolski. Figure 6 shows a fragment of the prototypical valve installed on the installation of compressed air.

Figure 6: Fragment of the installation with the prototype valve with a measuring orifice

An orifice with a diameter of $\varnothing 51$ mm was assumed for calculations, while for a multi-nozzle six holes with a diameter of $\varnothing 21$ mm on the division diameter of $\varnothing 60$ mm were assumed.

Figure 7: Three-dimensional model of the installation fragment with a measuring orifice

Figure 7 shows the "water body" of the valve prototype with a measuring orifice.

To increase the accuracy of the numerical calculation of the orifice set perpendicular to the air flow direction, the grid density at the inlet edges of the orifice holes has been increased (Figure 8), which allowed convergence of the simulation results.

Figure 8: Increased density of nonstructural mesh with a boundary layer for a multi-nozzle orifice

Figure 9 presents the results of numerical speed calculations for a single-hole, and in Figure 10 for a multi-nozzle orifice.

Analyzing the position of velocity vectors, it can be seen that the maximum velocity begins to stabilize after about 3 lengths of 3D diameter (Figure 9) for a single orifice and for a multi-hole 1.5D (Figure 10).

The illustration of the flow through the orifices of the valve obtained on the basis of solved equations of fluid mechanics allows to analyze the values of pressure gradients and velocities. Apart from the flow axis for a single-hole flange, one can notice a change in the direction and sense of velocity vectors, which may indicate the occurrence of

turbulence. Analyzing the direction and sense of velocity vectors in the case of the multi-nozzle flange, it can be seen that it changes to the opposite one in the central part of the flow. In these places the phenomenon of returning flow may occur. In the case of a multi-hole orifice, there will be more vortex sites. It results from them (Figure 10) that the main streams can be deflected in the direction of the symmetry axis of the pipeline.

Figure 9: Velocity vectors for a single-hole orifice

Figure 10: Velocity vectors for a multi-nozzle orifice, a) view in the plane of the cross-section, b) axonometric view

Bores $\varnothing$ 2 mm in the nut holding the orifice are used for measurement of the differential pressure. Pressure on the orifice hole edge was numerically calculated (Δp_1). In order to measure the pressure in the bores of the nut necessary is to calculate the pressure on the edge closer to the orifice flange (Δp_2) and in the opposite side of the same bore (Δp_3).

Pressure measurements resulting from narrowing are shown in Table 1.

Figure 11: Pressure measurement points and differential pressure, p1 (Δp_1) - measurement on the edge of the orifice hole, p2 (Δp_2) - measurement on the edge of the hole closer to the front face of the orifice, p3 (Δp_3) - measurement on the edge of the orifice hole located further on the orifice plane, a) view of pressure measurement points in the valve cross-section, b) view of the measurement locations on the sketch of the calculation program

Table 1: Calculated air pressure difference for single-hole and multi-nozzle flanges

	Single-hole flange	Multi-nozzle flange
Δp_1	8,2 kPa	10,8 kPa
Δp_2	13,8 kPa	17,2 kPa
Δp_3	9,9 kPa	13,2 kPa
Mean pressure in the differential pressure measurement channel ($\Delta p_2 + \Delta p_3$)/2	11,8 kPa	15,2 kPa

5 Field tests of the prototype

The valve with a single-hole flange was assembled. In order to collect flow data it was decided to use a normative orifice. In further tests, the installation of a multi-nozzle flange is planned, but it must take place during the planned shutdown, during which every service action must be planned.

Table 2 presents the results obtained during the stay at the power plant.

The average of the results of the air volume flow measurements is $295,3 \text{ Nm}^3/\text{h}$ and this value differs from the assumptions, where the maximum value of $2000 \text{ Nm}^3/\text{h}$ was assumed. Therefore, for the prototype with a single-hole flange mounted, additional numerical calculations were

Table 2: Table of recorded results

Lp.	q_{vn} $\frac{Nm^3}{h}$	q_m $\frac{kg}{h}$	q_v $\frac{m^3}{h}$	p kPa	T_p °C	ρ_p $\frac{kg}{m^3}$	Δp kPa
1	295,5	398,8	41,0	790,7	29,4	9,1	0,5
2	298,4	402,7	41,4	790,6	29,4	9,1	0,5
3	293,2	395,7	40,7	790,7	29,4	9,1	0,5
4	295,8	399,2	41,0	790,7	29,3	9,1	0,5
5	294,5	397,5	40,9	790,5	29,4	9,1	0,5
6	294,3	397,2	40,8	790,6	29,4	9,1	0,5
7	295,1	398,3	40,9	790,7	29,4	9,1	0,5
8	296,1	399,6	41,1	790,6	29,3	9,1	0,5
9	294,9	398,0	40,9	790,8	29,4	9,1	0,5
10	295,2	398,4	41,0	790,7	29,4	9,1	0,5

Figure 12: The results of numerical simulation in the form of a velocity line

carried out, assuming the results of the flow rate obtained on the prototype in the field trial as the value of the input data for numerical calculations.

Figure 12 presents the results of numerical tests of a system with a single-hole measuring orifice using the same mesh density and type of turbulence as in calculations for maximum values.

6 Discussion

Geometry of the channels and orifice used in numerical simulation was constructed basing on delivered documentation. Length of the channels were implemented with respect to measurements of existed installation.

When comparing the pressure difference for a single-hole flange, determined by means of the numerical method, which is 11,8 kPa, with analytically obtained according to the Standard [1] – 11,465 kPa, one can notice a

large convergence of results allowing to accept numerical calculations as correct. The difference, which is 0,335 kPa, may be due to the fact that the flange roughness is not included in the numerical method.

The numerical tests show us the real nature of the flow. It can be seen that the inlet bend disturbs the flow in front of the orifice and may cause false results. Minimal losses result in inactive branches of the pipeline because they cause vortices and recirculation. At the same time, the value of the pressure difference was read, which is $\Delta p = 0,469$ kPa. The difference with the results read from the measuring devices differs slightly (rounded value $\Delta p = 0,5$ kPa). The accuracy can be regarded as sufficient. Good simulation and experimental results caused the desire to obtain better results by using, for example, multi-hole flanges. In order to verify the validity of the idea of using a multi-hole flange, it was decided to conduct simulation tests for a 6-hole orifice. In order to be able to compare, numerical assumptions were assumed as for a single-hole flange. A clear shortening of the section with disturbed flow behind the barrier in the form of an orifice was observed when using the multi-hole model. The length of the section has been reduced by half. Comparing the values presented in Table 1, it can be concluded that the pressure drop across the multi-hole flange is greater at the same flow rate, which results in a higher sensitivity of the measuring system that is the orifice. Smaller true flow rate suggests use a multi-nozzle or a single-hole flange with smaller hole, however it undoubtedly increase the flow losses.

7 Conclusions

The results of tests and CFD calculations work can be concluded with the following conclusions:

- A prototype with a measuring orifice can perform two functions: a shut-off valve and a measuring element.
- For a multi-hole flange, it is possible to install in pipeline systems where there are not sufficient lengths of rectilinear sections; the leveling of the stream at this type of orifice occurs on a shorter distance behind the valve.
- Execution of a non-structural grid with a boundary layer allowed convergence of computer simulation results.
- The differential pressure obtained in the calculation for a multi-nozzle orifice is 3,4 kPa higher. This difference may be due to the interaction of a larger number of air turbulences.
- The results of the pressure difference obtained due to analytical calculations in accordance with the adopted international standard and the results obtained from simulations differ by 0,335 kPa, which indicates well-established and well-accepted initial simulation conditions.
- Lack of a normative document allowing for calculations for a multi-nozzle orifice causes that the use of computer calculations using CFD is a method that is the basis for its selection.
- Additional simulations made after the acceptance of results obtained during field tests have allowed to notice that real measurements may be burdened with higher measurement uncertainty. It can be due to air flow through inactive legs. In addition, the increased uncertainty results from the fact that the results of standard calculations for the maximum flow are entered into the pressure transducer, while the actual flow is about 10 times smaller.

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