# INFLUENCE OF THE ORIFICE SHAPE ON MASS FLOW MEASUREMENTS OF AIR–WATER MIXTURE

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ABSTRACT

Flow measurements using differential pressure meters are common in industrial applications. In such cases, the flow of gas is often accompanied by conditions that can lead to liquid condensation. As a consequence, flow measurements basically involve gas–liquid mixture metering. For this reason, errors occur in the metering equipment resulting from the variations in the characteristics of the continuous phase that is present in the flow. In addition, the existence of a dispersed phase leads to the development of flow disturbance and pressure pulsations. Therefore, new methods and tools are being sought to enable the measurements of gas–liquid mixture flows that will offer a suitable accuracy of measurement in the instances of flow interference in the form of a liquid phase. This paper reports the results of a study into the application of orifice plate meters for gas–liquid mixture flow metering. The analysis of the influence of the geometry of an orifice meter on the measurement of a two-phase mixture flow was carried out for this purpose. Experimental tests were carried out by application of a standard orifice and three slotted orifice meters with various designs. The experiments included the measurements of air flow containing small amounts of dispersed water in the form of droplets. The analysis also involved the level of differential pressure that is obtained as a result of applying orifice meters, and the level of the permanent pressure loss caused by the installation of an orifice plate. The results of the research were compared with the results obtained for the standard orifice.
*Keywords: standard orifice, slotted orifice, two-phase flow, gas–liquid flow, experimental research, Lockhart–Martinelli parameter.*

## 1 INTRODUCTION

A variety of orifice meters are applied in gas flow measurements in many industry branches. When gas is transported in industrial applications, condensation of liquids contained in the gas often occurs. The occurrence of small liquid droplets results in an error due to the change in the physical properties of the fluid flow when flow measurements are performed by application of orifice meters. This is due to the loss of the homogeneous structure of the gas phase, which becomes a two-phase mixture consisting of gas and liquid phases. The use of standard methods for measurement of homogeneous fluids leads to the significant levels of the measurement error. Therefore, measurements involving two-phase mixtures form some of the most challenging problems facing flows metrology. Such measurements involving the mass flow rates of gas–liquid mixtures play an important role in many areas of science and technology, e.g. in meteorology, chemistry, power engineering, as well as petrochemical and chemical industries [1]. This is due to the fact that the presence of a dispersed phase results in the variations of the physical properties of the continuous phase [2].

Another area in which the present method can be applied is associated with the transport of natural gas saturated with liquid in which the volumetric fraction of the liquid phase does not exceed 5%, i.e. wet gas [3]. Due to the current feasibility of extracting gas from such from sources of sea bed mining, desert, arctic and other inaccessible areas, it is necessary to use metering systems with high reliability, small size and built at a relatively low cost [4], [5]. Yet another group of applications are waste composting processes [6] where mainly wet gas flows occur. In many research centers and scientific institutions, research has been

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conducted over the past years with the purpose of improving existing techniques and developing new ones to be applied for measuring flows of two-phase mixtures. Often such metering applies equipment with considerable dimensions, complex design and high cost of performance. Therefore, the demand for metering equipment with a simple design and low cost of development is a current challenge for engineering. Due to their simple design, low cost of production and reliability of operation, differential pressure meters offer some of the cheapest and best performance flow measurement solutions for application in industry. In the recent reports, there are examples of the using orifice plate meters in the measurement of mixtures comprising gas and small amounts of liquids [7], [8].

## 2 MEASUREMENTS OF GAS–LIQUID MASS FLOW RATES APPLYING ORIFICE PLATES

The measurements of the fluid flow rates by application of the orifice plates consist in the use of a constriction of the flow cross-section. This constriction leads to an increase in the fluid velocity, and along with the change in the velocity, the static pressure decreases and a differential pressure is developed at the orifice. The resulting differential pressure $\Delta P$ forms a reliable source serving for determination of the fluid mass or volume [9]. Among the orifice meters, we can distinguish orifice plates, nozzles and Venturi tubes [10]. In this work, various types of orifice meters were applied in experimental research. The schematic of the measurement system is presented in Fig. 1.

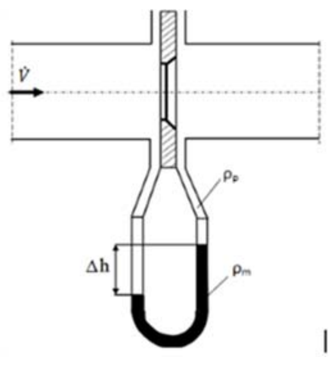



Figure 1: Operating principle of orifice plate.

The use of orifice meters specified in the norm [10] offers the possibility of calculating mass flow rates on the basis of differential pressure measurements. The mass flow rate is calculated on the basis of eqn (1):

$$\dot{m} = \frac{C}{\sqrt{1-\beta^4}}\varepsilon\frac{\pi d^2}{4}\sqrt{2\Delta P\rho}, \tag{1}$$

where $C$ is discharge coefficient, ε is expansion number relative to fluid compressibility, $\beta$ is beta ratio of the orifice, d is orifice diameter, $\Delta P$ is differential pressure at orifice plate, $\rho$ is fluid density.

## 2.1 Standard orifice

Due to its simple design, the standard orifice is commonly used in fluid flow metering. The advantages of the standard orifice also include its long service life. Since such orifices have no moving parts, they can be used for measurements involving liquids, gas and suspensions. They can perform fault-free under extreme operating conditions and provide reliable metering solutions in a wide range of pressures and temperatures. Another advantage of using standard orifices includes the possibility of their easy replacement without the need to dismantle large piping sections [9], [11].

The metering using orifice plates produced to the current standard provides considerable accuracy of measurements only for the case of single-phase flows. The presence of a second phase, i.e. liquid in the gas flow leads to the variations in in the differential pressure and its pulsations, fluctuations in the density of the fluid and expansion number, etc. Therefore, the use of standard orifices is not recommended for measuring wet gases or multiphase mixtures [12].

For many years, research has focused on the development of methods that can offer the possibility of using orifices for metering wet gases and two-phase mixture flows. In addition, other solutions based on ultrasound methods, laser techniques, process tomography and other complex systems are sought so as to provide reliable measurements [1].

The reason for wet gas formation is often associated with a decrease in temperature or pressure, when condensation processes occur in the pipeline leading to the conditions in which small amounts of liquid in the form of droplets are condensed on the pipeline walls. And it is known that even small amounts of liquid in the flow of gas can lead to flow disturbance.

The Lockhart–Martinelli parameter forms one of the most commonly applied parameters defining the relative fraction of liquid in a two-phase flow. It is defined by eqn (2) [3], [4], [7].

$$X_{LM} = \frac{m_L}{m_G}\sqrt{\frac{\rho_G}{\rho_L}}, \tag{2}$$

where $m_L$ and $m_G$ are mass flow rates of the liquid and gas phases, respectively, and $\rho_L$, $\rho_G$ are the liquid and gas densities. For the wet gas, the value of the $X_{LM}$ parameter does not exceed 0.35.

Another way in which it is possible to determine if a given two-phase mixture is in the wet gas range is associated with learning about the parameter called Gas Volume Fraction (GVF, eqn (3)) and for this case the value should not be smaller than 95% [4]:

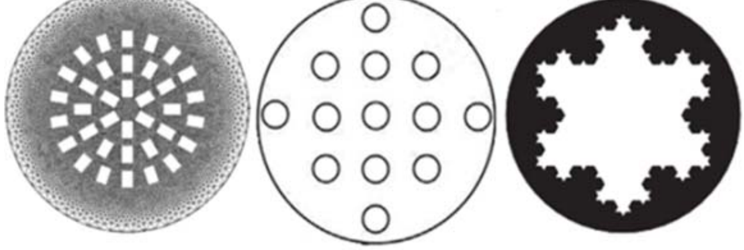
$$GVF = \frac{V_G}{V_{TP}}, \tag{3}$$

where $V_G$ is the volumetric flow rate of the gas phase, and $V_{TP}$ is the volumetric flow rate of the two-phase mixture.

## 2.2 Slotted orifice plate

One of the ways in which wet gas metering can be feasibly performed is based on the use and selection of an adequate design of a slotted orifice plate. The reports in the area list a variety of equipment that offers a derivative of the standard orifice. Such solutions often apply special orifices, including slotted and fractal-shaped orifices, perforated plates, etc.

(Fig. 2) as well as other designs that comprise slots laid out in various arrangements (square, triangle, oval) [12]–[16].



(a) (b) (c)

Figure 2: Examples of special orifices. (a) Slotted; (b) Perforated plate; (c) Fractal.

Morrison, among others, investigated a new type of orifice. In a study reported in Morrison et al [11], a comparison between the slotted orifice and a standard one was performed for the case of a single-phase flow. The results demonstrated that the slotted orifice generates a smaller value of the differential pressure and ensures faster pressure recovery of downstream of the orifice plate.

Geng et al. [3] performed numerical and experimental examinations of the performance of the standard and slotted orifice for single and two-phase flows. This study demonstrated that the slotted orifice performs better than the standard one in terms of the requirements regarding straight pipe sections used to stabilize the flow, stabilization of the velocity profile downstream of the orifice plate, and elimination of the effect of the liquid hold-up upstream of the orifice plate. This study also showed that orifices with a small value of β ratio tend to be more sensitive to the occurrence of the liquid phase in the flow.

The study by Kumar and Bing [17] also involved the analysis of solutions of the orifice meter. Numerical studies were conducted with regard to the optimal design of a slotted orifice in terms of the pressure recovery downstream of the orifice plate and involved the measurements of the values of the pressure drop resulting from its installation. In simulation studies, four orifice plates with various slot shapes were applied, including rectangular and circular, and the results were compared with those gained for a standard orifice. The study found that the design of the perforations does not have a major impact on the pressure recovery, however, rectangular slots with a length to width ratio equal to $1/w=3.0$ demonstrate a better static pressure recovery in comparison to orifices with lower values of this ratio.

The study by Annamalai et al. [18] focused on the homogenization of a two-phase mixture downstream of the orifice meter. The results demonstrated that it is possible to apply a slotted orifice as a stream conditioner that is capable of converting a majority of the flow patterns into a homogeneous mixture. The tests involve the analysis of the homogeneity of a two-phase gas–liquid mixture flow as a result of applying a slotted orifice in a horizontal tube for various conditions upstream of the orifice. The conditions of the tests included the bubble and slug flows. This study demonstrated that optimal homogeneity of two-phase flow occurs at a distance of 1.5 to 2.5D downstream of the slotted orifice. Therefore, it was found that the slotted orifice meter is not sensitive to the conditions of the flow downstream of the orifice.

Due to the design of the standard orifice, when the gas flow contains even a small volume ratio of the liquid phase the liquid is retained upstream of the orifice meter. This leads to flow disturbance and, as a consequence, a positive bias of Δp is obtained. In the case of a slotted orifice, the use of concentrically arranged slots in the orifice plate can limit the effects of the initial flow disturbance. By separating the flow of the mixture in the entire cross-section of the pipeline, the effect of the liquid accumulating in the obstacle was eliminated and the formation of considerable vortex structure downstream of the obstacle was prevented.

The objective of the present study involves the determination of the effect of the orifice plate geometry on the differential pressure recorded in the gas–liquid mixture flow and permanent pressure loss.

## 3 EXPERIMENTAL SETUP

The experimental part of the study was carried out on a setup, whose diagram is presented in Fig. 3. The air into this installation was fed via a compressor (1). The air was routed for the experiment via a throttling valve (2), which provided a constant pressure value. The flow rate of the air was regulated by a valve (3). The parameters of the air flow were controlled by a measuring system comprising a pressure sensor (4) and a temperature sensor (10) and an orifice plate (5,6). Water was supplied from the water network to a chamber (7) in which the two-phase mixture was formed, and the flow rate was regulated by a valve (9). The flow rate of the water was measured by a rotameter (8). The horizontal section of the pipeline comprised a system designed for testing slotted orifice plates (11) that could be removed and replaced. The differential pressure resulting from the installation of the slotted orifice plates was measured with a differential pressure transducer (5). The static pressure value in the pipeline was measured with a sensor (4).

A separator (12) was applied to remove the air from the liquid at the end of the measuring section in the installation. The values of signals from the measurement sensors were recorded continuously by a dedicated card on a PC throughout the duration of the experiment.

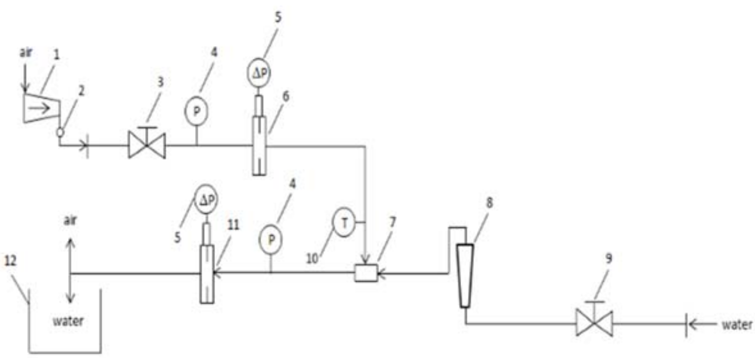



Figure 3: Setup applied for two-phase flow measurements. 1: Compressor; 2: Reducing valve; 3: Air flow regulation valve; 4: Pressure sensor; 5: Differential pressure transducer; 6: Differential pressure meter; 7: Mixing chamber; 8: Rotameter; 9: Liquid flow regulating valve; 10: Temperature sensor; 11: Slotted orifice; 12: Liquid vessel.

In order to perform measurements into the distribution of static pressures downstream and upstream of the tested orifice plate, an experimental section of the pipeline was designed and built comprising a series of pressure tapping points (Fig. 4). In this section, nonlinear distribution of static pressure tapping points was applied. The largest number of measuring points in terms of distribution was selected to occur just before and after the orifice plate.

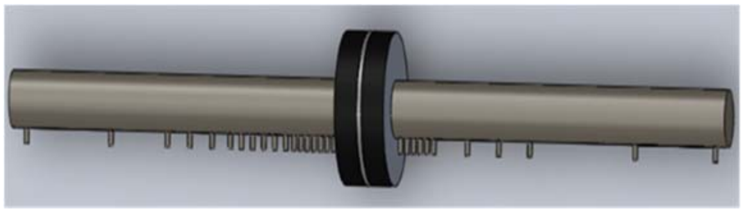


Figure 4: View of measuring section applied for determination of the static pressure downstream and upstream of the orifice plate.

The measurements were carried out for two mass flow rates of air, which were equal to 0.06 kg/s and 0.086 kg/s, respectively. After the gas flow was stabilized, water was fed into the installation in the range of flow rates from 0.06 kg/s to 0.16 kg/s.

The experimental part of the study involved a standard orifice and three slotted orifices with various layouts of the perforations were applied (Fig. 5).

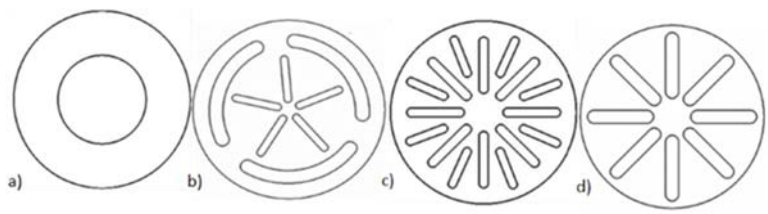



Figure 5: Orifice plates applied in the experimental research. (a) Standard orifice; (b) Slotted orifice 1; (c) Slotted orifice 2; (d) Slotted orifice 3.

The size and number of slots were selected in such a way that the beta ratio for all orifice plates and equal to $\beta = 0.5$. The value of $\beta$ is derived from eqn (4):

$$\beta = \sqrt{\frac{A_{slots}}{A_{pipe}}}, \qquad (4)$$

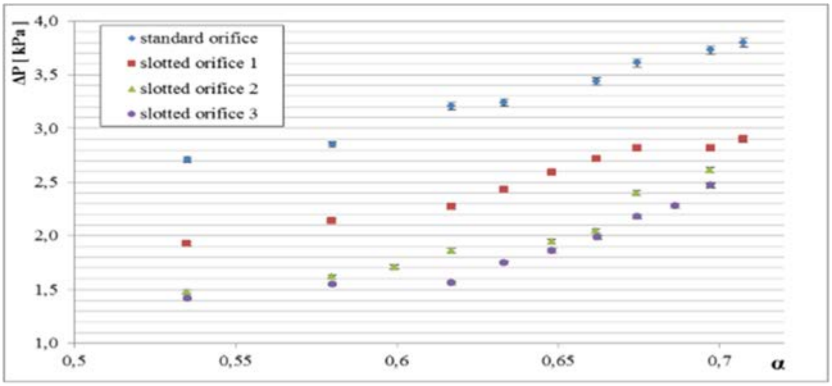
where $A_{slots}$ is surface area of the slots and $A_{pipe}$ is cross-sectional area of the pipe.

## 4 RESULTS OF EXPERIMENTAL RESEARCH

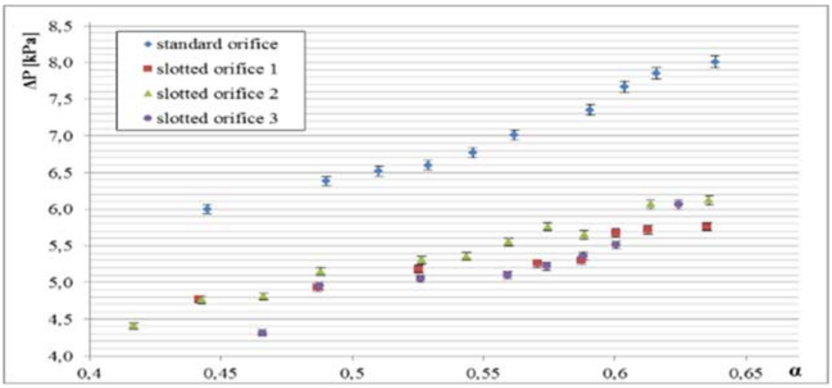
Fig. 6 contains the results of the measurements of the differential pressure as a function of the mass fraction of liquid in the constant gas flow rates, for 0.06 kg/s and 0.087 kg/s, respectively. The values in terms of the mass fraction of the liquid were determined on the basis of the measurements of gas and liquid flows by application of the following relation (eqn (5)):

$$\alpha = \frac{m_L}{m_L + m_G}, \qquad (5)$$

where $m_L$ and $m_G$ are mass flow rates of the liquid and gas, respectively.




(a)

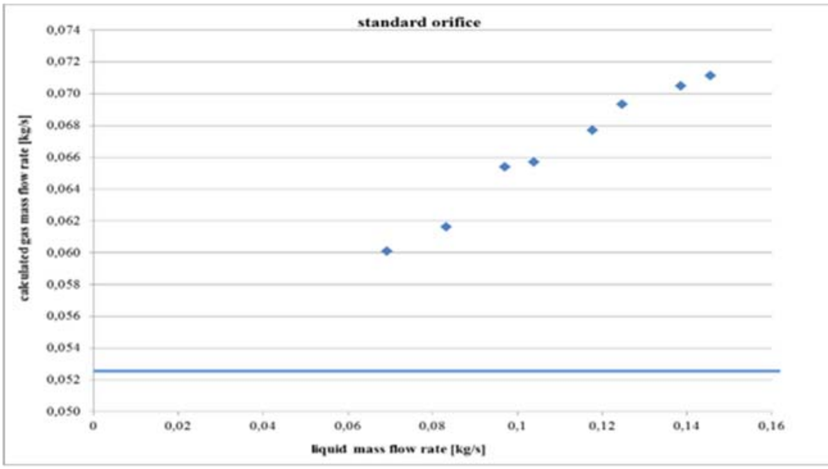



(b)

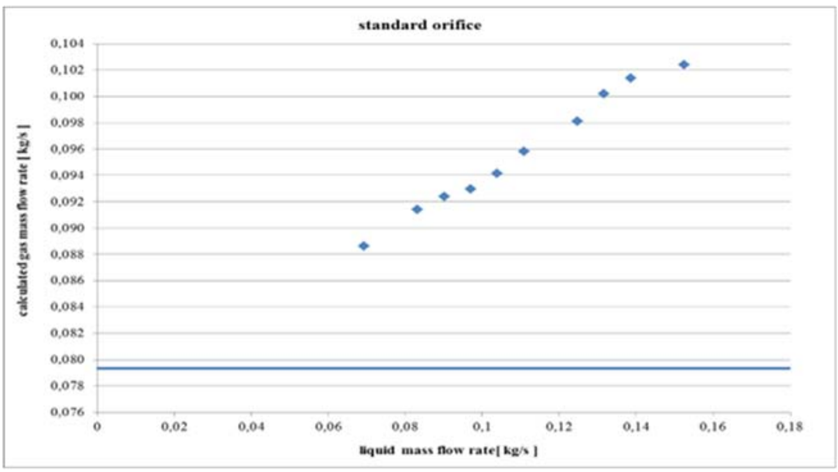
Figure 6: Dependence between the differential pressures and water mass fraction for the airflow rates equal to: (a) 0.06 kg/s; (b) 0.087 kg/s.

On the basis of the analysis of the results of the measurements presented in Fig. 6, the study found that the presence of liquid in the constant air flow leads to a change in the differential pressure developed at the orifice. The greater mass fraction of the liquid in the air flow results in a greater differential pressure. The distribution of the pressure depending on the mass fraction of the liquid is non-linear. It was observed that for the case of the air–water mixture flows, in comparison to the standard orifice, the slotted orifice generates a smaller differential pressure. The slotted orifice with a radial arrangement of slots demonstrates the smallest sensitivity to changes in the mass fraction of the liquids. This is due to the fact that throughout the entire cross-section of the pipeline there is a steady local decrease in the diameter ratio of the perforations. The liquid passes freely through the obstacle along with the gas, and only a small ratio of it is stopped by the orifice. The arrangement of the slots along the entire cross-section of the pipe leads to the liquid drop entrainment by the gas flow. In the case of a standard orifice, a large part of the liquid is held up downstream of the orifice, the flowing liquid accumulation that leads to additional, unfavorable flow disturbances.

The charts in Fig. 7 present a comparison of the mass flow rate of the gas taking into account the differential pressure measured between the single-phase gas flow and flow gas containing small amounts of liquid.




(a)




(b)

Figure 7: Dependence between calculated gas mass flow rate and liquid mass flow rate for the different inlet airflow rates.

The charts above contain the results of a comparison between the mass flow rates of gas and the mass flow rate of water that was measured in the investigated orifices plates. The gas mass flow rate was calculated on the basis of eqn (1) taking into account the differential pressure developed at the orifice plate during the gas–liquid fluid flow. The horizontal lines on the diagrams show the mass flow rates for the case of single-phase gas flow.

We can also note that along with the increase in the flow rate of water, the measurement error of the flow rate of the gas increases. As a result of the application of the standard orifice in the flow of gas with a small amount of liquid, the measured flow rate of gas accounting for the gas–liquid differential pressure is 12–28%.

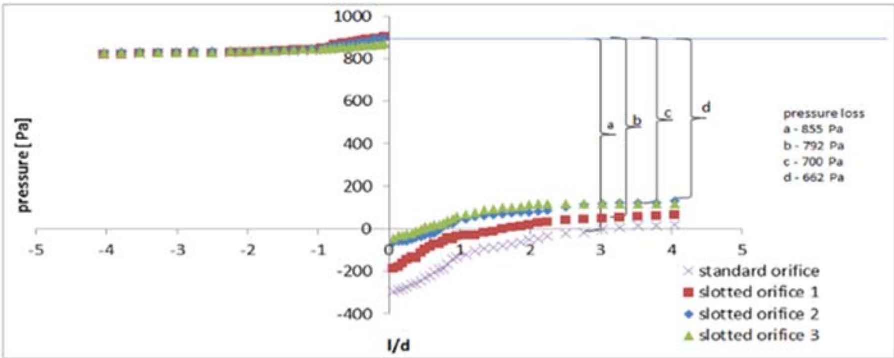



Figure 8: Distribution of pressure along the pipeline and determination of permanent pressure loss.

The results of the measurement of the static pressure distribution downstream and upstream of the orifice plate are presented in Fig. 8. Under the same flow conditions, the use of a standard orifice results in a greater differential pressure caused by its presence compared to the case of the use of a slotted orifice. In terms of metrology parameters, this forms an advantage since in the earlier case, an increase in the measurement sensitivity is gained. However, as a result of the application of slotted orifice plate, pressure recovery occurs faster than in the case of a standard orifice. Also, permanent pressure loss is smaller when slotted orifices are used. The smallest permanent pressure loss, which is equal to 662 Pa, was recorded in the slotted orifice design marked by 3, whereas the largest one was recorded the standard orifice, whose permanent pressure loss is 855 Pa.

## 5 CONCLUSIONS

The tests carried out in this paper demonstrate that the design and distribution of the perforations on the surface of slotted orifices affect the length of the hydraulic stabilization zone of the flow and the value of permanent pressure loss. This is due to the separation of the flux into several or a dozen or so smaller ones. In this case, a large recirculation zone is not developed, which normally occurs when a standard orifice is applied, and forms the principal reason for generation of energy losses. The hydraulic stabilization width of the flow depends on the design of the slotted orifices and it is smaller compared to the case of a standard orifice. In addition, the presence of perforations has a positive effect on flow homogenization and reduction of pulsations, which are the sources of an additional measurement error. A certain disadvantage of slotted orifices is associated with the decrease in the differential pressure, as the sensitivity of metering is limited. This requires further research related to finding a compromise between the advantages and disadvantages of slotted orifices in specific engineering applications. This applies particularly with regard to determining the optimal design, arrangement and number of slots in the specific flow conditions.

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