CORRECTION OF WET GAS FLOW MEASUREMENTS APPLYING STANDARD ORIFICE

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ABSTRACT

Differential pressure measurements are commonly applied in industrial conditions, due to the fact that measurements that apply them are simple and offer relatively high accuracy. In gas installations, the liquid is often condensed in the form of a droplet present in the gas. When the liquid is transported along with gas, this leads to a significant increase in the differential pressure and incorrect indications of measuring equipment. In addition, the presence of the liquid phase in the flow leads to interference and pressure pulsations. This article reports the results of a study concerned with finding a solution that can offer a way to correct the over-reading of the measured gas flow rate depending on the mass fraction of the liquid in it. The standard orifice was subjected to an experimental study, and then on the basis of this analysis, an algorithm for a computer over-reading model was developed. The experiment involved the measurement of airflow with a small amount of dispersed water in the form of droplets. The results were compared with other correction methods familiar from the literature.
Keywords: air–water flow, experimental research, over-reading, standard orifice, two-phase flow, wet gas.

1 INTRODUCTION

In many industries, various types of orifices plates and slotted orifices are applied for gas flow measurements. During the transport of gas in industrial conditions, we have to do with the conditions when liquids carried with gas can be condensed. The occurrence of small liquid droplets leads to measurement error performed using differential pressure flow meters resulting from the change in the physical properties of the measured gas flow. As a result, pure gas takes the form of a two-phase gas–liquid mixture. The standard relations applied in the gas measurements offer significant levels of measurement error [5, 9, 22, 24].

Another area in which the above problem can occur includes the areas of natural gas extraction where very often the flow of wet gas, that is, one in which the volume fraction of the liquid phase does not exceed 5% [11]. There are many examples in the literature of the use of differential pressure flow meters in the measurements of mixtures containing gas and small amounts of liquid [2, 3, 8–12, 17, 21, 22]. In many research centers, studies are underway with the purpose of developing new equipment and improving existing techniques applied for the measurements of wet gas flow. Often such equipment has large dimensions, complex design, and its use is associated with the high cost of manufacture [10, 14, 16]. Thus, there is a great need for equipment with a relatively simple design and low cost of production. Due to the simplicity of construction, low cost, and operational reliability, differential pressure flow meters are some of the cheapest and most common types of equipment applied in flow measurements.

2 OPERATING PRINCIPLE OF DIFFERENTIAL PRESSURE FLOW METERS

The measurement of flow rates of liquid by applying differential pressure measurements involves the use of a contraction of the flow cross-section (Fig. 1). The flow of gas through the contraction leads to an increase in the velocity of the fluid flow, which in turn results in

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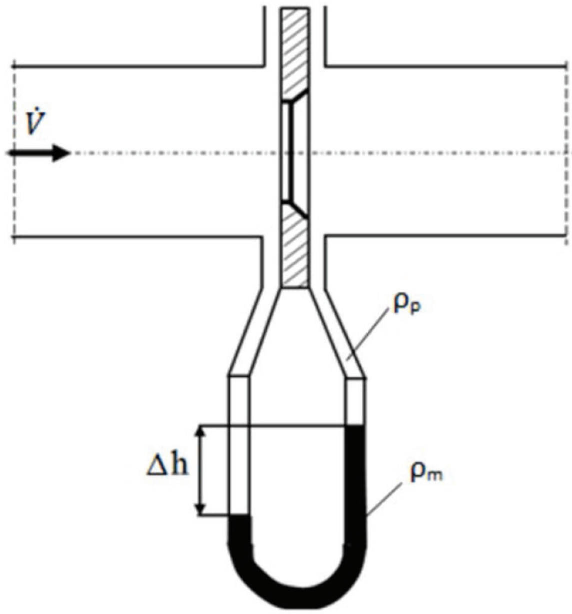

Figure 1: Operating principle of orifice plate [25].

the formation of differential pressure downstream of the meter in relation to the upstream section of the pipeline [25].

Due to the great popularity of this type of flow meters, standards have been applied to define the design of the contraction. As a result of applying an orifice plate as the solution, it is possible to use a standard orifice without the need of performing calibrations of the flow meter. The use of orifice meters specified in the standard [25] provides the possibility of measuring mass flow rates based on the differential pressure measurements. The mass flow rate is calculated based on the following formula:

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

where C is the discharge coefficient, ε is the expansion number relative to fluid compressibility, β is the beta ratio of the orifice, d is the orifice diameter, ΔP is the differential pressure at orifice plate, and ρ is the fluid density.

The application of the standard orifice ensures high accuracy of measurement only in the conditions of single-phase flows. The presence of the liquid phase in the gas flow leads to the variations in the differential pressure and its pulsations, as well as changes in the density of the fluid and the expansion factor [3, 12, 16]. Therefore, the use of standard orifices is not recommended for applications involving measurements of wet gases or multiphase mixtures.

3 WET GAS MEASUREMENT

The measurement of wet gas flow is associated with a variety of technical difficulties [15, 16]. Even small amounts of liquid in the gas flow can lead to flow disturbances [5, 9, 22]. The

Lockhart–Martinelli parameter forms one of the most common parameters employed in the determination of the relative fraction of liquid in a two-phase mixture flow. It is defined by the formula (2). For a wet gas, the value of the X_{LM} parameter should not exceed 0.35 [3, 11, 12, 21].

$$X_{LM} = \frac{\dot{m}_L}{\dot{m}_G}\sqrt{\frac{\rho_G}{\rho_L}}, \tag{2}$$

where $\dot{m}_G$ and $\dot{m}_L$ correspond to the mass flow rates of the gas and liquid phases, respectively, and ρ_L and ρ_G denote liquid and gas densities, respectively.

The second parameter applied to characterize the flow of wet gas is gas volume fraction (GVF). This is the ratio of the volumetric flow rate of the gas phase to the flow rate of the two-phase mixture. The boundary value for differential pressure flowmeters is GVF>95% [5, 12].

$$GVF = \frac{\dot{V}_G}{\dot{V}_{TP}}. \tag{3}$$

There are a number of alternative methods described in the literature and applied to adjust the results of the measurements of differential pressure flow meters depending on the parameters characterizing wet gas [3, 20, 24]. The most common one involves the determination of the correction which is employed to express the response of a flow meter to the existence of the wet gas flow, so-called over-reading (OR) factor, combined with measures applied to correct the results given in terms of this factor. The parameter OR (4) is defined as the ratio of the current gas mass stream $\dot{m}_{G,apparent}$ to the mass flow rate of pure gas [3, 23].

$$OR = \frac{\dot{m}_{G,apparent}}{\dot{m}_G} \cong \sqrt{\frac{\Delta p_{TP}}{\Delta p_G}}, \tag{4}$$

$$\dot{m}_{G,apparent} = \frac{c}{\sqrt{1-\beta^4}}\varepsilon A\sqrt{2\rho_G \Delta p_{TP}}, \tag{5}$$

$$\dot{m}_G = \frac{c}{\sqrt{1-\beta^4}}\varepsilon A\sqrt{2\rho_G \Delta p_G}. \tag{6}$$

The apparent mass flow rates and the actual gas mass flow are determined based on the eqns (5) and (6), respectively, where C is the discharge coefficient, β is the beta ratio, ε is the expansion factor, ρ_G is the gas density, Δp_{TP} is the differential pressure created during the flow by gas–liquid mixture, and Δp_G is the differential pressure for the dry gas flow.

The determination of the value of the OR parameter is not unambiguous, and many models can be found in the literature. An outline of the most familiar models is presented below.

1. Murdock model [17]

Murdock model is expressed in the form of a correlation representing the two-phase flow theory. It was developed based on a large data set for stratified two-phase flow. Murdock was the first to propose an applicable dependence [17]. The model is limited only to the wet gas flow as it was demonstrated by Murdock that the type of flow pattern has a big influence on the measurement error in the form:

$$OR = 1 + 1.26X_{LM}. \tag{7}$$

The assumption that the over-reading correction is linear is valid only within a narrow range of measurements. Therefore, modifications have been made to the initial release of the model. In 1998, Phillips Petroleum updated the Murdock correction using wet gas measurement data for the case of differential pressure flow meters [17].

$$OR = 1 + 1.5X_{LM}. \tag{8}$$

2. Lin model [13]

The correlation proposed by Lin deals with the flow through the orifice and applied for stratified flow patterns. Lin investigated the outcomes of interactions at the interface of the phases. Lin also introduced a variable value of the coefficient θ_v.

$$OR = 1 + \theta_v X_{LM}, \tag{9}$$

where:

$$\theta_v = 2.04032 - 1.85145\frac{\rho_G}{\rho_L} - 2.24484\left(\frac{\rho_G}{\rho_L}\right)^2 + 9.1817\left(\frac{\rho_G}{\rho_L}\right)^3 - 8.42128\left(\frac{\rho_G}{\rho_L}\right)^4 + 2.32846\left(\frac{\rho_G}{\rho_L}\right)^5.$$

3. Chisholm model [6, 7]

In 1977, Chisholm published a general over-reading model to describe two-phase flow through the standard orifice. The Chisholm model includes assumptions with regard to stratified flow expressed in terms of shear forces between phases. As a result, it was possible to take into account the influence of pressure regardless of the Lockhart–Martinelli parameter. Therefore, Chisholm correlation represents the function of X_{LM} and pressure.

$$OR = \sqrt{1 + \left(\left(\frac{\rho_l}{\rho_g}\right)^{1/4} + \left(\frac{\rho_g}{\rho_l}\right)^{1/4}\right)X_{LM} + X_{LM}^2}. \tag{10}$$

4. Smith and Leange model [19]

The Smith and Leang model was developed to apply to a standard orifice as well as a venture tube. It can be applied to take into account the presence of liquid by introducing a parameter that accounts for the reduction of the cross-sectional area of the pipe area by the liquid:

$$OR = \frac{1}{0.637 + 0.421(1-\alpha) - \frac{0.00183}{(1-\alpha)^2}}, \tag{11}$$

where $1-\alpha$ is the mass flow rate of gas.

5. De Leeuw model [8]

This is the only one of the first models that applies to the flow of wet gas through the venture tube. De Leeuw stated that the error resulting from the presence of the liquid in the gas flow is relative not only on the pressure and X_{LM} parameter but also on the Froud number:

$$OR = \sqrt{1 + \left(\left(\frac{\rho_l}{\rho_g}\right)^{n} + \left(\frac{\rho_g}{\rho_l}\right)^{n}\right)X_{LM} + X_{LM}^2}, \tag{12}$$

where n:

$$n = \begin{cases} 0.041 & 0.5 \le Fr_g \le 1.5 \\ 0.606\left(1 - e^{-0.746 Fr_g}\right) & Fr_g \ge 1.5 \end{cases}$$

where

$$Fr_g = \frac{v_g}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}}.$$

6. Steven model [21]

This correlation is one of the most recent developments. Steven investigated a 150 mm venturi flow meter with a beta factor of β=0.55. The types of examined flow included a gas flow rate in the range from 400 to 1000 m^3/h for pressures of 2 MPa, 4 MPa, and 6 MPa. The volume fraction of liquid was from 0.1% to 5%. Steven's results confirmed De Leeuw's idea that the value of the over-reading factor is dependent on the Froud number and the pressure.

$$OR = \frac{1 + AX_{LM} + BFr_G}{1 + CX_{LM} + DFr_G}, \tag{13}$$

where

$$\begin{cases} A = 2454.51\left(\frac{\rho_G}{\rho_L}\right)^2 - 389.568\frac{\rho_G}{\rho_L} + 18.146 \\ B = 61.695\left(\frac{\rho_G}{\rho_L}\right)^2 - 8.349\frac{\rho_G}{\rho_L} + 0.223 \\ C = 1722.917\left(\frac{\rho_G}{\rho_L}\right)^2 - 272.92\frac{\rho_G}{\rho_L} + 11.752 \\ D = 57.837\left(\frac{\rho_G}{\rho_L}\right)^2 - 7.679\frac{\rho_G}{\rho_L} + 0.195 \end{cases}. \tag{14}$$

4 EXPERIMENTAL SETUP

In order to compare the quality of over-reading resulting from the application of particular models discussed above, an experimental installation was designed and built to perform tests of the standard orifice for various mass fractions of the liquid flow. A two-phase mixture consisting of air and water was applied for this.

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 airflow 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

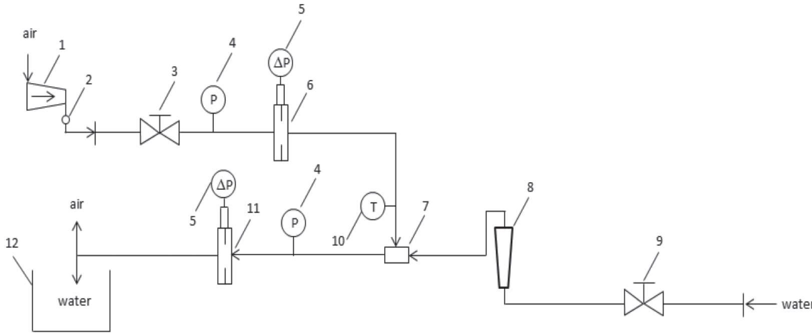

Figure 2: Diagram of experimental setup applied in the experiments applying two-phase gas–liquid flow.

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 signals from the measurement sensors were recorded continuously by a dedicated card on a PC throughout the duration of the experiment.

In experimental research, a standard orifice with the beta factor of β=0.5 was applied.

5 OVER-READING MODEL DEVELOPED BY THESE AUTHORS

The authors of the article developed their own model for determining gas flow. This model is based on calculating the value of pressure that would occur on an orifice if the flow of dry gas occurred through it. This basic calculation involves the knowledge of the mass fraction of gas and the pressure value measurement for the wet gas flow. The relation was derived empirically based on a series of measurement data (Fig. 3).

$$\Delta p_{TP} = A \cdot \alpha^4 + B \cdot \alpha + C \tag{15}$$

where α is the liquid mass fraction.

Figure 3 contains the results of the comparison of the results of calculated pressure Δp_{TP} based on the formula (15) with the data gained for measurements for two selected flow rates.

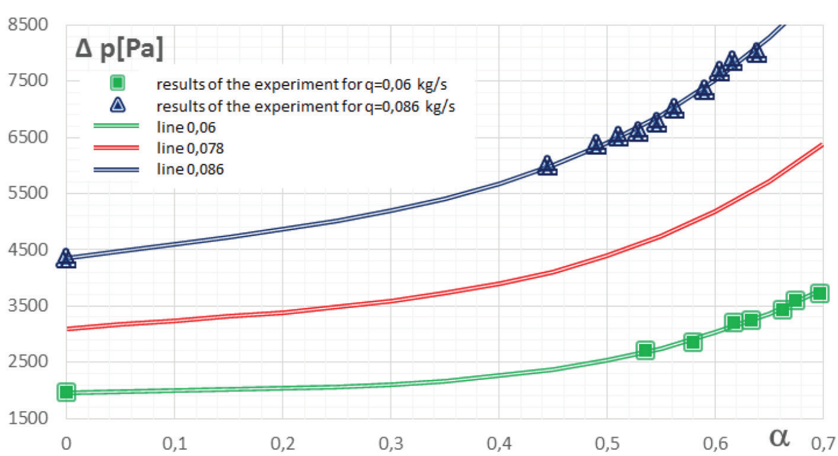

Figure 3: Dependence between differential pressure and liquid mass fraction.

The 0.078 line was established for an intermediate gas flow rate value of 0.078 kg/s. The analysis of experimental data demonstrates that the non-linearity of the measuring curve increases following an increase in the gas flow. The theoretical lines 0.06, 0.078, and 0.086 can be used to represent the characteristics of the effect of water in the measured airflow on the value of the measured pressure. This indicates that the function (15) was developed in an adequate manner.

Coefficients A, B, and C are expressed by equations in which the pressure that accompanies a given flow rate of dry gas. The equations were formulated based on the experimental results for the air–water mixture (Fig. 4).

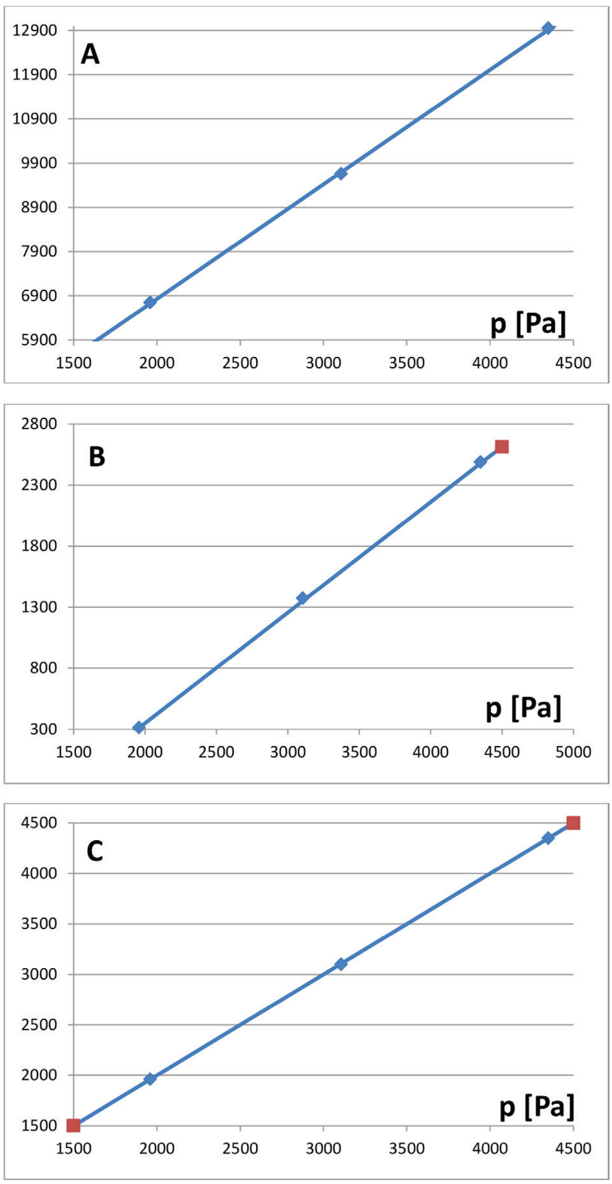

Figure 4: Relation between A, B, and C factors and pressure for dry air.

Based on the relations presented in Fig. 4, it was possible to derive mathematical functions to define the linear relations of the A, B, and C factors with the value of the pressure difference that accompanies dry gas flow.

$$\begin{cases} A = 2.59 \cdot \Delta p_G + 1650 \\ B = 0.905 \cdot \Delta p_G - 1460 \\ C = \Delta p_G \end{cases} \tag{16}$$

After substituting eqn (16) into eqn (15), we can calculate the pressure value Dp_G, which is equal to the pressure that would accompany the flow of dry gas. This pressure forms the basis for calculating the value of gas flow rate based on the relation in eqn (6).

6 RESULTS OF EXPERIMENTAL STUDY

A series of experimental tests were carried out for two airflows of 0.06 and 0.086 kg/s. On this basis, the value of gas flow rate was derived using various correction models (Fig. 5). The models of Lin, Petreleum, and Murdock gave very similar results. However, in these models, the value of the gas flow rate was overestimated. This greater value of the over-reading

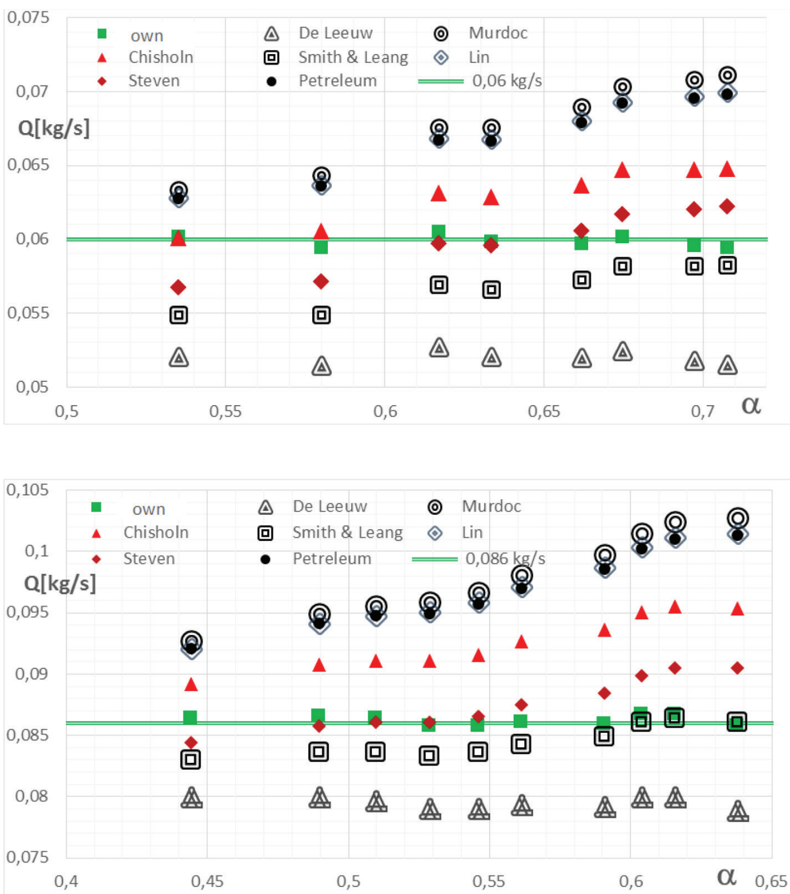

Figure 5: Results of correction of measured airflow rate for (a) gas flow rate of 0.06 kg/s and (b) gas flow rate of 0.086 kg/s.

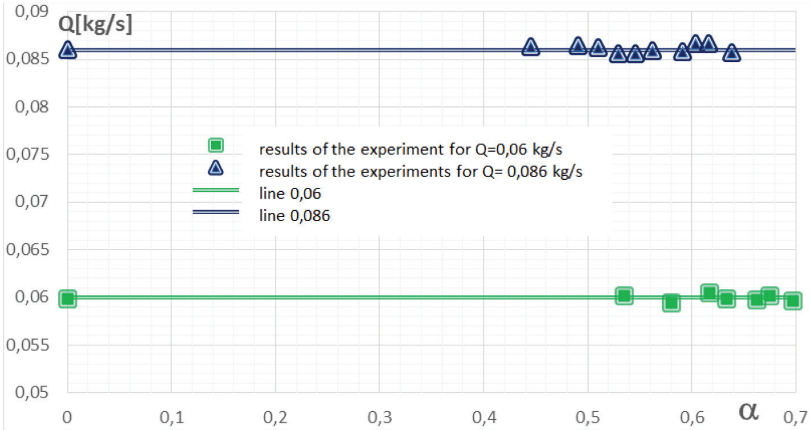

Figure 6: Results of correction of airflow rate by the model proposed by these authors.

factor is recorded in the conditions when we have to do with a greater flow rate of water relative to the airflow. A similar tendency was also demonstrated in the model Chisholm. However, we can note that this model performed much better for small flow rates of gas. For larger flow rates, the results gave excessive values of the gas flow rate. It was also noted that the Steven model performs better for larger gas rates. In the case when flow rates of water are considerable, this model gave excessive values of the water flow rate, whereas, for low flow rates of water, the results are underestimated. The De Leeuw model can be successfully applied for the correction of the effect of the large volume of water that is contained in the airflow; however, the recorded gas flow rate was underestimated. The value of OR resulting from the use of the model proposed by Smith and Leang was much lower; yet, in this model, we have to do with the effect of water concentration in the airflow.

The results of the comparison of literature models demonstrated significant discrepancies in the results that were derived from each model. Hence, we need to look for other methods of correction of over-reading recorded in the measurements, as it is difficult to propose a universal method. Figure 6 shows the results of the correction model proposed by the authors. This model provides a significant level of convergence between the actual flow rates of gas for both small and large ranges. However, it requires individual calibration for each orifice plate that is applied.

7 CONCLUSIONS

The conducted analysis concern with the comparison of the OR parameter demonstrated that the existing comprehensive correction models for wet gas flow measurement lead to significant errors. Much better conformity of the results is obtained by the application of the model proposed by these authors. However, this model requires an experimental selection of the linear coefficients of over-reading functions individually for a selected orifice. This may significantly impede its use in some applications.

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