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A new correlation of wet gas flow for low pressure with a vertically mounted Venturi meter

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ABSTRACT

Wet gas metering has become an increasingly important technique for many industries. However, the over-reading phenomenon reduces the accuracy of Differential Pressure meters. This research fills the vacancy of correlations and presents a new correlation for low pressure between 0.82 and 1.52 MPa with a vertically mounted Venturi meter to calculate the over-reading coefficient accurately. Based on the correlational analysis, the over-reading coefficient is a function of the Lockhart-Martinelli parameter, density ratio, and gas Froude number. The constant coefficients in this correlation are obtained by nonlinear regression. Effect of low gas velocity with gas Froude number under 1.5 is taken into consideration as well. The average relative error is 1.9% and the root mean square error is 3.0%. Furthermore, a new method to calculate the over-reading coefficient for industrial applications is put forward due to the difficulties of online measurements of the Lockhart-Martinelli parameter which is substituted with the void fraction. The void fraction is calculated by an empirical correlation using quality and an approximate algorithm is utilized to obtain gas Froude number. For this new method, the average relative error is 2.3% and the root mean square error is 3.7%. This quality-based method will be helpful to resolve the limited applicability of gamma-ray attenuation for wet gas flow metering in industry regarding vertical low pressure conditions.

1. Introduction

Wet gas flow is a gas-liquid two-phase flow with a small amount of liquid entrained in the gas phase. The definition of wet gas can vary depending on the perspectives of reservoir engineering, measurement systems, or commercial sales of the products [1]. For the convenience of communication, much effort is put into unifying the definition of the wet gas flow. According to the International Organization for Standardization [2], wet gas flow is defined as a gas-liquid two-phase flow with a gas volume fraction more than 95%. Wet gas flow widely exists in life and industry. For example, water may condense due to increasing pressure in the production lines and changing conditions in the well [3]. Besides, gas from separation systems may also contain liquid.

Wet gas has become an increasingly important topic for the oil and gas industry, nuclear industry and metallurgical industry, and its measurement has been paid much attention [3]. One method to meter wet gas in industry is to separate the mixture and measure the gas and liquid flow rate in a single phase, respectively [4]. However, high cost, large scale, and difficult-to-transport properties limit the use of the separation method. Therefore, the non-separation method has become mainstream in recent decades. One of the favored meters for wet gas flow is the Venturi meter which features a simple structure and reliable durability and has been used in many laboratories for the reason that the Venturi meter is much more predictable and repeatable than the Orifice meter for a wide range of flow conditions.

However, the readings of Differential Pressure (DP) meters (e.g. Orifice, Venturi or V-Cone meters) for wet gas flows are always affected by liquid presence [3]. The interaction between the gas and liquid phase brings energy loss. While measuring the pressure drop between the upstream and throat tapping, a higher pressure drop reading is observed, and a higher gas flow rate is obtained in turn. This phenomenon is referred to as over-reading which means the pressure drop is not only determined by the total mass flow rate but also by other factors such as void fraction (the cross-sectional area locally occupied by the gas phase of a wet gas flow) or quality (the mass fraction of gas in wet gas flow) or more [5]. Therefore, an accurate correction for wet gas is required and

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another device is usually required to get the void fraction.

As a DP meter, the over-reading phenomenon of the Orifice meter was researched before Venturi and many derived correlations were applied in industry. Murdock [6] in 1962 proposed a correlation which is a linear function of Lockhart-Martinelli parameter with the gradient value 1.26 for general two-phase flows such as vapor-water, air-water, and natural gas-water mixtures. James [7], Smith and Leang [8] also proposed their correlations in the following years. In 1967, Chisholm [9] developed a two-phase flow Orifice meter correlation when the density change of gas or liquid through the orifice is negligible and this correlation also allows for the interfacial shear force between different phases. Later in 1997, de Leeuw [10] firstly established the wet gas measurement model for Venturi meters and found that the liquid induced error is dependent on the pressure, Lockhart-Martinelli parameter and gas Froude number. Then, Steven [3] compared five Orifice meter correlations and two Venturi meter correlations and undertook a detailed analysis of all the correlations with a new empirical correlation presented based on the analysis. Yuan et al. [11] also established a wet gas correlation based on new dimensionless parameters. However, as seen in Table 1, researches on wet gas flow were mainly conducted for high pressure conditions which is more than 1.5 MPa. Many Researchers in China set lower pressure but it is still not qualified for vertically mounted Venturi meters. Therefore, a new correlation to calculate the gas flow rate is worth researching for lower pressure in a vertical Venturi meter.

While more accurate empirical correlations emerge successively, more stringent requirements on wet gas flow metering have stimulated the development of new wet gas measurement techniques which provided much support to the development of robust and accurate wet gas metering systems [12]. Ying et al. [13] designed a novel double differential pressure device composed of one Cone device and one Venturi tube for wet gas metering. Only DP meters are used without any other device. New technologies such as gamma-ray attenuation [14,15], ultrasound [16], tomography [17] and the near infrared spectrum [18] have been researched to measure multi-phase flows. Among these methods, gamma-ray attenuation is considered a good option for online measurements due to its accuracy and non-instructive characteristics [12]. However, radiation protection requires careful attention to operators. Besides, radioactive sources in some areas are extremely restricted and the strict management limits the use of this technique. Therefore, a new method which is appropriate and convenient for industrial applications is also required to meter multi-phase flows.

On the other hand, with the rapid development of computers in recent decades, numerical simulation has become an important way to study the behavior of multi-phase flows. He et al. [19] and Baylar et al. [20] adopted a combination of numerical simulation and experiment for Venturi research and got a more comprehensive understanding of the over-reading phenomenon. Suggestions for the size and structure of Venturi were provided for design. Therefore, the analysis through numerical simulation, combined with experiments, can better serve the research of multi-phase flows for the convenience and low cost.

The objective of this paper is to study the wet gas flow and develop a new correlation for low pressure with a vertically mounted Venturi meter. This correlation is a function of the Lockhart-Martinelli parameter, gas Froude number, and gas to liquid density ratio and taking consideration of gas Froude number under 1.5. It will be compared with other commonly used correlations and is shown to be capable of giving more accurate predictions based on experimental data. However, online measurements of the Lockhart-Martinelli parameter are difficult for multi-phase flows [21]. Furthermore, a new method for wet gas metering is proposed to solve the difficulties. Given the information of quality, an empirical correlation of wet gas is selected to calculate void fraction which serves as an intermediate variable. Combined with the density ratio and an overstimulated gas Froude number, the void fraction can be used to get the accurate gas mass flow rate. The quality of wet gas can be obtained with low cost and difficulty. Therefore, this quality-based method will be helpful to resolve the limited applicability of gamma-ray attenuation for industrial applications when it comes to upward low-pressure wet gas.

2. Theory of over-reading phenomenon

When only gas passes through a vertical Venturi meter, the mass flow rate is expressed as Eq. (1).

$$M_g = \frac{C\varepsilon A_0}{\sqrt{1-\beta^4}}\sqrt{2\Delta p_g \rho_g} \tag{1}$$

where M_g is the gas mass flow rate, C is the discharge coefficient of Venturi, ε is the gas expansion coefficient, A_0 is the area of the Venturi throat, β is the diameter ratio of Venturi, Δp_g is the gas differential pressure between the upstream and throat tapping, ρ_g is the gas density. When a small amount of liquid is entrained in an equal amount of gas, the wet gas mass flow rate is expressed as Eq. (2).

$$M_{tp} = \frac{C\varepsilon A_0}{\sqrt{1-\beta^4}}\sqrt{2\Delta p_{tp} \rho_g} \tag{2}$$

Table 1
Existing over-reading correlations.

Models	Correlations	Pressure (MPa)
Murdock [6]	$OR = 1 + 1.26X$	3.96–4.03
Modified Murdock [3]	$OR = 1 + 1.5X$	4.5
Chisholm [9]	$OR = \sqrt{1 + \left[\left(\frac{\rho_g}{\rho_1}\right)^{0.25} + \left(\frac{\rho_1}{\rho_g}\right)^{0.25}\right]X + X^2}$	–
de Leeuw [10]	$OR = \sqrt{1 + \left[\left(\frac{\rho_g}{\rho_1}\right)^{n} + \left(\frac{\rho_1}{\rho_g}\right)^{n}\right]X + X^2}\begin{cases} n = 0.41 & 0.5 \le Fr_g \le 1.5 \\ n = 0.606(1 - e^{-0.746Fr_g}) & Fr_g \ge 1.5 \end{cases}$	1.5–9.5
Smith and Leang [8]	$OR = \frac{1}{0.637 + 0.421x - \frac{0.00183}{x^2}}$	0.132–0.263
Steven [3]	$OR = \frac{1 + aX + bFr_g}{1 + cX + dFr_g}\begin{cases} a = 2454.51\left(\frac{\rho_g}{\rho_1}\right)^2 - 389.568\left(\frac{\rho_g}{\rho_1}\right) + 18.146 \\ b = 61.695\left(\frac{\rho_g}{\rho_1}\right)^2 - 8.349\left(\frac{\rho_g}{\rho_1}\right) + 0.223 \\ c = 1722.917\left(\frac{\rho_g}{\rho_1}\right)^2 - 272.92\left(\frac{\rho_g}{\rho_1}\right) + 11.752 \\ d = 57.387\left(\frac{\rho_g}{\rho_1}\right)^2 - 7.679\left(\frac{\rho_g}{\rho_1}\right) + 0.195 \end{cases}$	2, 4, 6

Note: OR is the over-reading coefficient, X is the Lockhart-Martnelli parameter, Fr_g is the gas Froude number, and x is the quality of wet gas flow.

where M_{tp} is the wet gas mass flow rate, Δp_{tp} is the actual two-phase differential pressure between the upstream and throat tapping. Thus, the over-reading coefficient OR is defined as Eq. (3).

$$OR = \frac{M_{\mathrm{tp}}}{M_{\mathrm{g}}} = \sqrt{\frac{\Delta p_{\mathrm{tp}}}{\Delta p_{\mathrm{g}}}} \tag{3}$$

Provided that gas and liquid can both be considered to be incompressible, Eq. (4) can be derived by theoretical consideration allowing for the interfacial shear force between different phases [9].

$$OR = \sqrt{1 + \left[S\left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}\right)^{0.5} + \frac{1}{S}\left(\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{g}}}\right)^{0.5}\right] X + X^2} \tag{4}$$

where ρ_{l} is the liquid density, S is the slip ratio for gas and liquid phase, X is the Lockhart-Martnelli parameter defined as Eq. (5).

$$X = \frac{M_{\mathrm{l}}}{M_{\mathrm{g}}}\sqrt{\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}} \tag{5}$$

where M_{l} is the liquid mass flow rate.

However, the physical phenomenon of two-phase flows is still complicated and the slip ratio cannot be solved by theoretical analysis. Consequently, researchers have turned to calculate the over-reading coefficient using empirical correlations. Many empirical correlations are derived from Eq. (4) indicating that this equation well describes the physical mechanism of wet gas flows. Table 1 introduces correlations commonly used. The gas Froude number Fr_g , liquid Froude number Fr_l , and quality x are defined as Eq. (6), Eq. (7) and Eq. (8), respectively.

$$Fr_{\mathrm{g}} = \frac{U_{\mathrm{sg}}}{\sqrt{gD}}\sqrt{\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}} - \rho_{\mathrm{g}}}} \tag{6}$$

$$Fr_{\mathrm{l}} = \frac{U_{\mathrm{sl}}}{\sqrt{gD}}\sqrt{\frac{\rho_{\mathrm{l}}}{\rho_{\mathrm{l}} - \rho_{\mathrm{g}}}} \tag{7}$$

$$x = \frac{M_{\mathrm{g}}}{M_{\mathrm{g}} + M_{\mathrm{l}}} \tag{8}$$

where D is the pipe diameter, U_{sg} and U_{sl} are the superficial gas and liquid velocity, respectively.

3. Experiment facility

3.1. Wet gas flow test loop

A Schematic diagram of the wet gas flow test loop is depicted in Fig. 1. This test loop is located at Daqing Oil Engineering Institution in China including a three-phase separation system, a power circulation system, a standard metering system, a three-phase mixing system, and a vertical test system.

The oil, water and natural gas from Daqing Oilfield were used as the experimental medium with their properties listed in Table 2. The mixture of oil, water, and natural gas firstly entered the separation system and was separated into three single phases. An electric heating device was provided to better separate the oil and water. Then the oil pump, water pump, and compressor drove the oil, water, and natural gas into single-phase metering systems to get the reference flow rate of every single phase, respectively. After passing through the mixing system, the mixture went into the vertical test system where the Venturi was located. Valves located downstream of the oil-water mixer could adjust the liquid flow rate. The natural gas adjusting tank solely controlled the

Table 2
Properties of fluid.

Fluid	Density (kg·m^{-3}) under standard condition
Oil	856.0
Water	1001.5
Natural gas	0.92

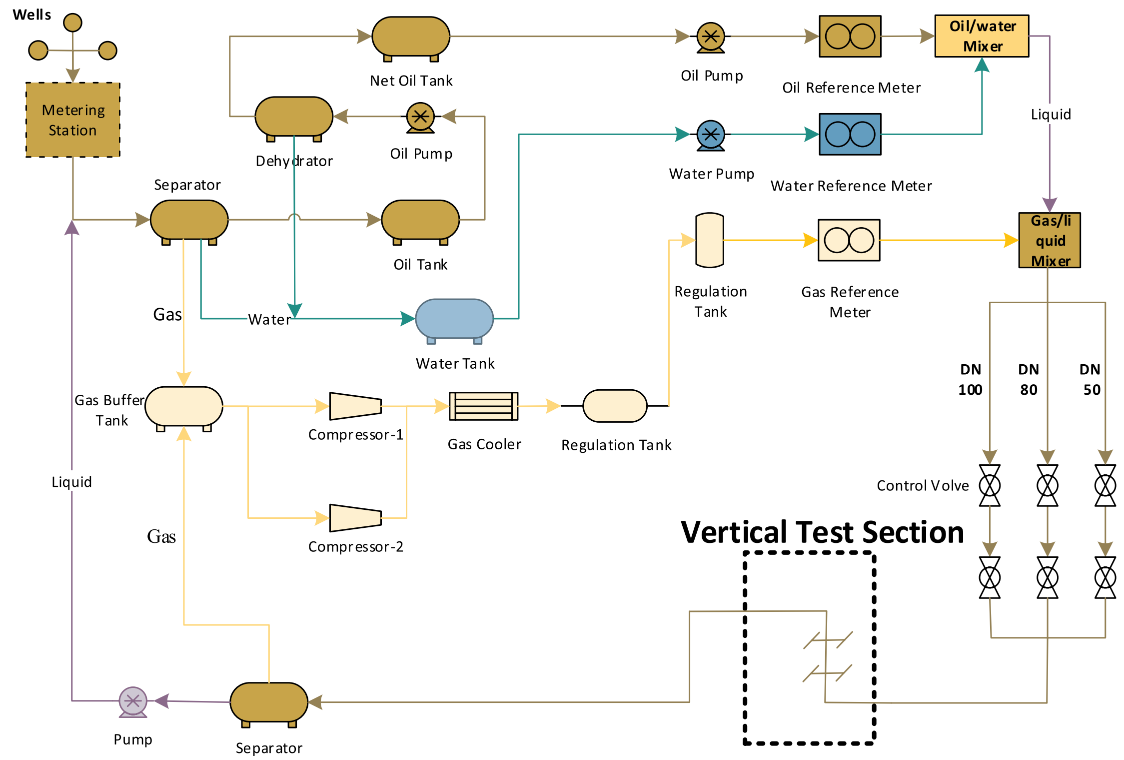

Fig. 1. Schematic diagram of the wet gas flow test loop.

natural gas flow rate. Then the mixture again entered the separation system for the next cycle. The circulation of the experimental medium was guaranteed by the power circulation system including the oil pump, water pump, and compressor.

The Venturi meter was installed vertically at the test section. The inlet diameter d was 42.77 mm, the diameter ratio β was 0.4, the discharge coefficient C was 0.995, and the natural gas expansion coefficient ε was approximately equal to 1 in industry.

3.2. *Experimental range and condition*

The operating pressure was between 0.82 and 1.52 MPa, Lockhart-Martinelli parameter between 0.03 and 0.3, and gas Froude number between 0.5 and 2. Each experimental condition was measured for more than 10 min to reduce accidental errors in experiments.

The gas and liquid Froude number of each experimental condition are calculated as shown in Fig. 2 including two types being water-gas and oil-water-gas. The distribution of data in the vertical flow pattern map which is presented in the *Gas/liquid separators-type selection and design rules manual* published by Royal Dutch Shell shows that experimental conditions all go for the annular flow pattern. This is different from the situation of a horizontal channel where the inertia and gravity act in different directions. For a vertical Venturi meter, stratified flow pattern rarely appears, because the inertia and gravity act in the same direction helping to form a symmetrical flow pattern. Besides, liquid with lower velocity is easier to be pushed to the wall of pipe by gas which promotes the formation of annular flow. Therefore, the annular flow covers the largest area in the vertical flow pattern map shown in Fig. 2.

4. New correlation and comparisons

4.1. *Establishment of a new correlation*

A new correlation is proposed to calculate the over-reading coefficient for low-pressure wet gas flows. In Eq. (4), the over-reading coefficient is a function of slip ratio, density ratio, and Lockhart-Martinelli parameter. Normally, the slip ratio is determined from empirical correlations. Several models including Lockhart-Martnelli [22] model and Jia-Cai model [23] indicate that the slip ratio is related to the pressure and void fraction which is affected by gas velocity. It is summarized that the over-reading coefficient is considered to be affected by the Lockhart-Martinelli parameter, pressure and gas Froude number [3,19]. Here Lockhart-Martinelli parameter represents the effect of liquid content and gas Froude number represents the effect of gas velocity. The pipe diameter and diameter ratio of the Venturi slightly affect the over-reading coefficient which is excluded in this paper. Note that the influence of pressure and density ratio are substantially the same. Therefore, it can be concluded that the slip ratio will be a function of gas Froude number and density ratio. Due to the complexity of slip ratio, a substitution with gas Froude number is taken. To simplify the equation form, Z is defined in Eq. (9).

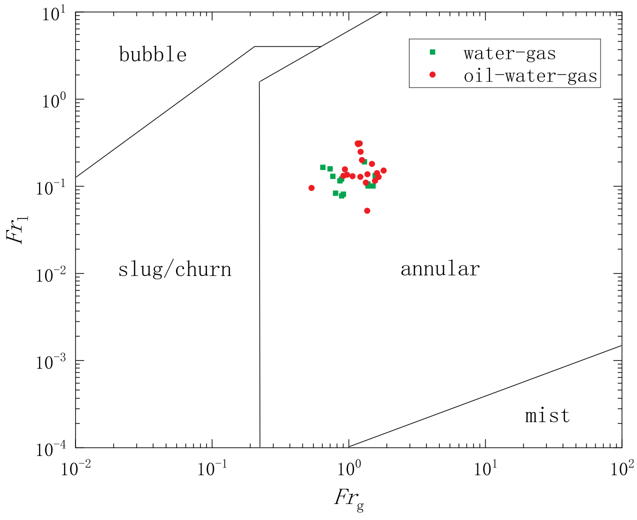

Fig. 2. Experimental data distribution in the vertical flow pattern map.

$$Z = S\left(\frac{\rho_g}{\rho_l}\right)^{0.5} + \frac{1}{S}\left(\frac{\rho_l}{\rho_g}\right)^{0.5} \tag{9}$$

Then, Z becomes a function of gas Froude number and density ratio given in Eq. (10).

$$Z = f\left(Fr_g, \frac{\rho_g}{\rho_l}\right) \tag{10}$$

Based on the correlational analysis and experimental data fitting given in the following text, a function of Z will be established. Then, the new correlation will be compared with other correlations in Table 1 for verification.

The Lockhart-Martinelli parameter, density ratio, and gas Froude number are calculated based on reference data including volume flow rate, temperature and pressure all obtained through single-phase measurements. The uncertainties of meters for water, oil, and gas phase flow rate are 0.2%, 0.2%, and 1%, respectively. The pressure and temperature uncertainties are 0.05% and 0.10%, respectively.

It is generally accepted that the over-reading coefficient increases as the Lockhart-Martinelli parameter increases, gas Froude number increases or pressure decreases keeping other parameters constant [19]. Correlations introduced in Table 1 show the main contribution of the Lockhart-Martinelli parameter. Taking account of gas Froude number and density ratio but essentially retaining the form of Eq. (4) which is derived from the mathematical analysis for the expectation that this correlation works well, the new correlation is described as Eq. (11).

$$OR = \sqrt{1 + \left(a + bFr_g\right)\left(c + d\frac{\rho_g}{\rho_l}\right)X + X^2} \tag{11}$$

where a, b, c, and d are constants to be calibrated.

Multiplying the gas Froude number and density ratio together as Z is a highly feasible operation. The constants in Eq. (11) will reflect the contributions of gas Froude number and density ratio to the over-reading coefficient. Compared with de Leeuw's correlation [10], Eq. (11) takes consideration of low gas velocity and transforms gas Froude number from latent variable to dominant variable for wider applications. Based on data from experiments, the values of the four constants are obtained by nonlinear regression with the software *1stOpt* (a robust nonlinear regression program based on universal global optimization algorithm). The optimization algorithms of Levenberg-Marquardt and General global optimization method are used in software settings, and results are listed in Table 3. The constant b is positive, which means faster gas velocity results in higher over-reading coefficient when keeping other parameters constant. As the pressure increases, the density ratio of the gas and liquid phase also increases. It seems that the constant d should be negative, unlike b due to the negative correlation between pressure and over-reading coefficient. However, the increase of pressure resulting in both changing of gas and liquid density, not only

Table 3
Constants fitting from experimental data.

constants	value
a	3.213
b	2.083
c	1.181
d	3.249

affects the density ratio but also changes the gas Froude number in a complicated way seen in Eq. (6) because the pressure is relative to both density and superficial gas velocity. Experimental conditions also cover a limited pressure range and are not enough to show the obvious contribution of pressure.

4.2. Comparisons of correlations

The method of evaluating performances of the above correlations is the comparison of average relative error and root mean square error (RMSE) as shown in Table 4. Murdock's correlation [6] and Chisholm's correlation [9] are excluded, for the gradient is modified in 1998 [3] and Chisholm's correlation [9] is in the same form with the de Leeuw's correlation [10] which takes consideration of gas Froude number. The relative errors for all experimental conditions predicted by models are transformed into positive values to reduce the offset phenomenon when positive errors and negative errors both exist. RMSE is a frequently used indicator of the differences between values predicted by a model and ones from experiments and is defined as Eq. (12).

$$RMSE=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{OR_{\text{predicted}}(i)-OR_{\text{reference}}(i)}{OR_{\text{reference}}(i)}\right)^2} \tag{12}$$

The distribution of predicted over-reading coefficients is depicted in Fig. 3. Smith and Leang's correlation [8] has the worst performance indicating the poor applicability of correlation directly between over-reading coefficient and quality. Therefore, searching for the correlation between the over-reading coefficient and quality may not be appropriate for industrial applications, though the quality is easy to get. Modified Murdock's correlation [3] has the second worst performance resulting from the operation that the effect of pressure and gas velocity are all described by a gradient number 1.5 suggested by Phillips Petroleum. However, this number for the pressure of 4.5 MPa may not be applicable for low pressure (0.82–1.52 MPa) and high gas volume fraction (>95%). Furthermore, it is not accurate enough and also not acceptable to describe the effect of pressure and gas velocity only with a constant. Here, more calculations provide support for this viewpoint. A linear fitting based on experimental data gets the new modified gradient number 2.706 and the result is shown in Fig. 4. The over-reading coefficient is still closely related to the Lockhart-Martinelli parameter. The average relative error and RMSE are 3.5%, 5.7%, respectively. The accuracy has been improved a lot but is still not good enough to compare with that of de Leeuw's correlation [10]. Therefore, the linear correlation between the over-reading coefficient and Lockhart-Martinelli parameter is not accurate enough. To get accurate real gas mass flow rate, more appropriate and complicated correlations need to be researched.

Steven's correlation [3] has the limitations for pressure and gas mass flow rate:

$$2\ \ MPa<P<6\ \ MPa,\quad 0.111\ \ m^3/s<M_g<0.278\ \ m^3/s$$

The maximum of pressure and maximum gas mass flow rate in experiments are 1.52 MPa and 0.16 m^3/s, respectively. Due to the mismatch of conditions, larger errors are extenuating. As shown in Fig. 3, predicted over-reading coefficients are generally less than reference resulting from lower pressure. A numerical investigation [19] presents that a liquid annular jet is more easily formed under lower pressure. This is exactly consistent with the annular flow pattern. The shear stress τ consists of the wall and interfacial shear stress expressed as Eq. (13).

$$\tau=\frac{1}{2}\left[f_w\rho_l\left(1-\alpha\right)u_l^2+f_i\rho_g\alpha\left(u_g-u_l\right)^2\right] \tag{13}$$

where f_w is the wall friction factor, f_i is the interfacial friction factors, α is the void fraction, u_g is the gas phase velocity, and u_l is the liquid phase velocity. When the pressure is lower leading to greater difference in density, the buoyancy of gas becomes more significant, the same as the velocity difference between gas and liquid. Thus the interfacial friction increases and in turn the total shear stress increases due to the little change of liquid velocity [24]. A two-phase flow momentum equation is described as Eq. (14) and the pressure gradient increases with the total shear stress. Therefore, lower pressure will result in a higher over-reading coefficient.

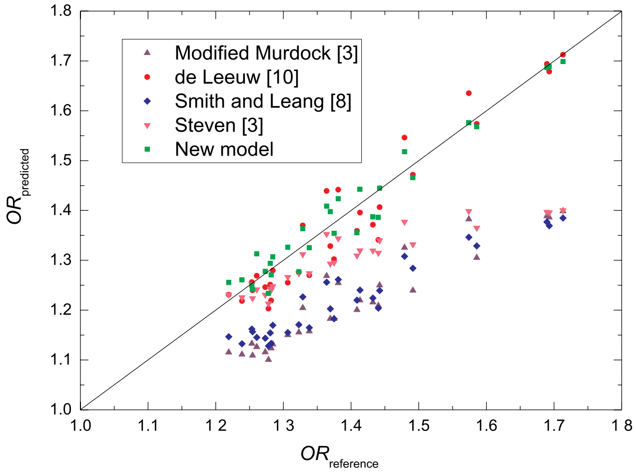

Fig. 3. Distribution of predicted over-reading coefficients.

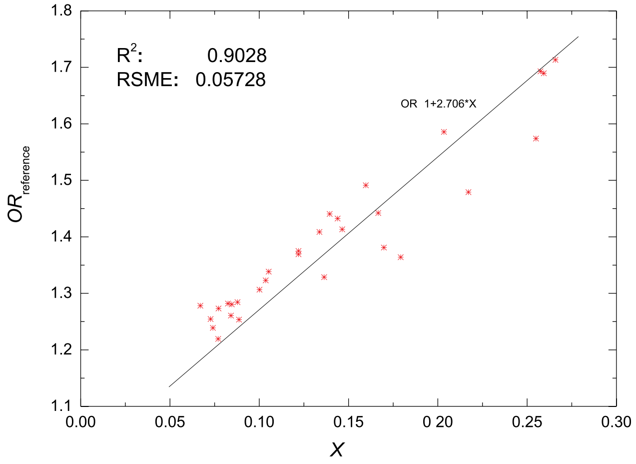

Fig. 4. Linear fitting of over-reading coefficients.

Table 4
Comparison of correlations for wet gas flows.

Model	Average relative error (%)	RMSE(%)
Modified Murdock [3]	6.9	10.5
de Leeuw [10]	2.8	4.7
Smith and Leang [8]	12.0	18.5
Steven [3]	6.2	12.6
New model	1.9	3.0

$$-\frac{\partial P}{\partial z}=\rho_{tp}g+\frac{4}{D}\tau+\frac{1}{A}\frac{\partial}{\partial z}\left\{AG^2\left[\frac{(1-x)^2}{\rho_l(1-\alpha)}+\frac{x^2}{\rho_g\alpha}\right]\right\} \tag{14}$$

where ρ_{tp} is the mixture density, A is the area of pipe and G is the mass flow rate per unit area of the channel.

Among existing correlations, de Leeuw's correlation [10] has the best performance to predict over-reading coefficients. The average relative error and RMSE are 2.8%, 4.7%, respectively. The effect of gas velocity and pressure is included in the exponential term. Therefore, this correlation features high precision. When the gas Froude number is less than 1.5 which means the gas velocity is relatively slow, the value of n will be constant. In other words, the effect of gas velocity is negligible when the gas Froude number is small. However, this is inconsistent with experiments in low pressure depicted in Fig. 5. The over-reading reference coefficient is also changing with gas Froude number under 1.5. The water-gas and oil-water-gas mixture have the same negative correlation between the over-reading coefficient and gas Froude number. Therefore, de Leeuw's correlation [10] still needs to be improved for gas Froude number under 1.5.

The Froude number is a dimensionless number defined as the ratio of inertia to gravity which is important for vertical upward two-phase flows. $Fr_g^{0.5} + Fr_l^{0.5} = 1$ is a flow reversal point proposed by Wallis [25] for the judgment whether or not the pull of gravity can delay the rise of liquid phase. Experimental conditions ($1.040 < Fr_g^{0.5} + Fr_l^{0.5} < 1.731$) partially go near for the transition area. Thus the gravity effect exists and delays the rise of liquid phase, in turn, affects the void fraction and finally changes the over-reading coefficient. For this reason, the new correlation further takes the gas Froude number as a dominant variable considering that the liquid Froude number is negligible compared with gas Froude number. In this way, the effect of gas velocity when the gas Froude number is less than 1.5 will also be taken into account.

The new correlation proposed in the paper has better performance than other existing nonlinear correlations for low pressure shown in Fig. 6. The gas mass flow rate calculated by the corresponding prediction model and reference values is shown in Fig. 7 too. It is only slightly different from de Leeuw's correlation [10] because both correlations are in the form of Eq. (4). Besides, the two correlations have similar predictions. In the research of Xu [5], de Leeuw's correlation [10] also has the smallest over-reading error and the equation of exponent n has been modified by software *TableCurve 3D*(a nonlinear surface fitting software package which could provide optimal model by fitting massive built-in frequently encountered models). This new correlation takes a different approach and multiplies the gas Froude number and density ratio together taking consideration of gas Froude number under 1.5. Compared with de Leeuw's correlation [10], the average relative error, RMSE are improved by 33.3%, 35.1%, respectively. Therefore, the verification of the new correlation for low pressure (0.82–1.52 MPa) is realized. Higher accuracy is a major feature with the average relative error 1.9% and RMSE 3.0%.

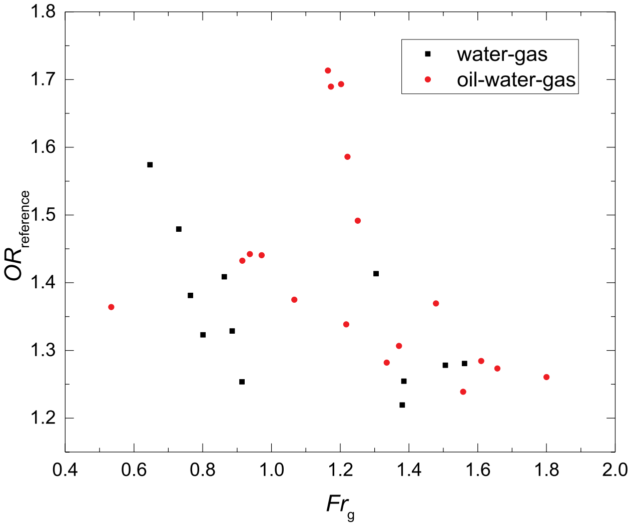

Fig. 5. Relationship of the over-reading coefficient and gas Froude number.

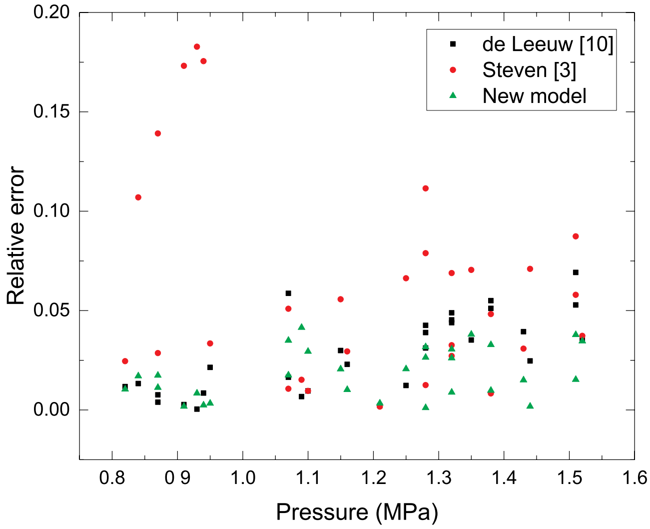

Fig. 6. Relative errors of three correlations.

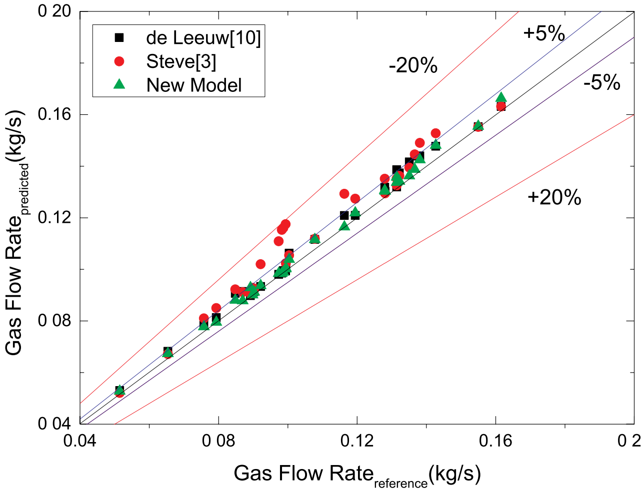

Fig. 7. Predicted gas mass flow rate and the reference values.

5. Correlations for industrial applications

The correlations introduced in Table 1 mostly require the information of Lockhart-Martinelli parameter and gas Froude number. Correspondingly, the gas and liquid mass flow rate and gas velocity must be simultaneously obtained first. However, online measurements of the Lockhart-Martinelli parameter and gas Froude number are difficult and not practical in multi-phase flow [21]. Therefore, these correlations cannot be easily used in industry.

Here, a new method is proposed to meter the gas flow rate for lower pressure in a vertical Venturi meter for industrial applications. Due to the poor applicability of correlation directly between the over-reading coefficient and Lockhart-Martinelli parameter, void fraction is taken as a substitution for the Lockhart-Martinelli parameter and serves as an intermediate variable. These two physical parameters can both describe the effect of liquid existence. The more proportion liquid occupies, the larger Lockhart-Martinelli parameter is and the smaller void fraction is. Therefore, the reciprocal form of void fraction will actually be a substitution for the Lockhart-Martinelli parameter. Based on fitting calculations, for better accuracy, the quadratic term of Lockhart-Martinelli parameter is directly replaced by the quadratic term of void fraction while a negative proportional coefficient (-e) is added to maintain consistency. Therefore, a new correlation using void fraction is described as Eq. (15).

$$OR = \sqrt{1 + \left(a + bFr_{\mathrm{g}}\right)\left(c + d\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}\right)\frac{1}{\alpha} - e\alpha^2} \tag{15}$$

Another problem is the calculation of gas Froude number. An approximate algorithm is considered to solve this problem. The pressure drop is measured when the mixture of oil, water, and natural gas passes through a Venturi meter. Providing that the pressure drop of wet gas approximately equals the pressure drop of gas ($\Delta p_{\mathrm{tp}} \approx \Delta p_{\mathrm{g}}$), the overstimulated gas mass flow rate is calculated by Eq. (1) and an overstimulated gas Froude number is obtained in turn. The influence of an overstimulated gas Froude number and the difference between the Lockhart-Martinelli parameter and void fraction will be partly eliminated by the adjustment of constants from experimental data fitting. The density ratio can be directly calculated for the reason that the pressure and temperature are obtained easily with high accuracy.

However, the measurement of void fraction α is still not easy. Gamma-ray attenuation is usually used but brings radiation protection problems that the public are concerned about. Therefore, the Armand [26] correlation expressed as Eq. (16) is utilized while the quality can be easily obtained with safety and low cost.

$$\alpha = (0.833 + 0.167x)\left(1 + \frac{1 - x}{x}\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}\right)^{-1} \tag{16}$$

According to Pranav [27], for $0.75 < \alpha < 1$, this empirical correlation is one of the three best correlations for upward vertical two-phase flow. Besides, precise quality measurement is relatively simple and feasible in industrial applications. Therefore, Eq. (16) will be an appropriate choice to calculate void fraction using quality.

Based on experimental data, void fraction is firstly calculated as a variable for Eq. (15) and then the values of the five constants are obtained by same nonlinear regression algorithm mentioned above. The optimization algorithms of Levenberg-Marquardt and General global optimization method are used, and the results are shown in Table 5.

The average relative error, RMSE are 2.3%, 3.7%, respectively. Compared with de Leeuw's correlation [10], the average relative error, RMSE are improved by 17.7%, 21.5%, respectively. Replacing of Lockhart-Martinelli parameter with void fraction may lead to higher errors. Besides, an empirical correlation based on specific data will also lead to additional errors. To our satisfactory, predictions for wet gas flows with the maximum relative error within 5% shows that Eq. (15) is of significant value for industrial applications combined with Eq. (16). It creates great convenience and reaches sufficient accuracy for industrial online measurements of wet gas flows. Using a Venturi meter combined with a device measuring quality, an accurate gas flow rate can be obtained through this method which is capable of satisfying requirements in industry.

6. Conclusions

In this paper, the wet gas through a vertical Venturi meter has been researched. The new correlation proposed is compared with existing correlations. The following conclusions can be made:

(1) According to the vertical Shell flow pattern map, wet gas flows generally go for the annular flow pattern for pressure between 0.82 and 1.52 MPa and Lockhart-Martinelli parameter between 0.03 and 0.3. A direct relationship between over-reading coefficient and quality has poor performance. The linear relationship between the over-reading coefficient and Lockhart-Martinelli parameter is also not accurate enough.

(2) A new correlation which is a function of the Lockhart-Martinelli parameter, gas Froude number and density ratio to predict over-reading coefficients for wet gas flows is proposed with high accuracy taking gas Froude number under 1.5 into consideration. Based on experimental data, the average relative error, RMSE are 1.9%, 3.0% which are improved by 33.3%, 35.1%, respectively, compared with de Leeuw's correlation [10].

Table 5
Constants fitting from data.

constants	value
a	2.229
b	0.108
c	2.141
d	3.723
e	6.089

(3) A quality-based method to predict over-reading coefficient accurately for wet gas flow is put forward for industrial applications. Void fraction is calculated using an empirical correlation based on quality while an overstimulated gas Froude number is obtained with an approximate algorithm. Based on experimental data, the average relative error, RMSE are 2.3%, 3.7% which are improved by 17.7%, 21.5%, respectively, compared with de Leeuw's correlation [10]. Using a Venturi meter combined with a device measuring quality, this method is of significant value for industrial online measurements of wet gas flows.

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