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Pressure Drop of Wet Gas Flow through DP Flowmeters and New Measurement Model

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1 INTRODUCTION

Wet gas is a sub-set of gas-liquid two-phase flow, which widely exists in industrial processes, especially in the natural gas industry. The accurate flow rate measurement of wet gas is of great importance. Differential pressure (DP) flowmeters, such as orifice plate flowmeters, Venturi flowmeters and V-Cone flowmeters, are the most commonly used meters in wet gas flows due to their low capital expenditure and robust performance.

The mostly common approach to realize two-parameter measurement is the so-called "dual-DP method", which can be subdivided into dual-throttle-device method and single-throttle-device method. The metering principles of dual-DP method is on the basis of over-reading correlations. The gas and liquid flow rates are obtained by solving the combined correlations. The drawback of such method is error propagation, which results in the prediction error of the liquid phase flow rate being much larger than that of the gas phase. Besides, the method may fail in particular cases (the equations have no solution). The other alternative approach is to utilize the fluctuation of DP signals. However, the prediction accuracy is not satisfied.

To reveal the underlying physics of prediction errors, the characteristics of differential pressure signals are investigated. Experiments show that: the two-phase differential pressure is mainly caused by gas phase and is slightly affected by the liquid phase; in the case of low liquid loading, the frictional pressure drop can be decreased due to the presence of the thin liquid film on the wall (lubrication effect), resulting in that the two-phase differential pressure, pressure loss and pressure loss ratio decrease at first and then increase as the liquid loading increases; the fluctuation of the differential pressure is stochastic, causing the fluctuation characteristic parameters having the properties of poor stability and repeatability, which therefore makes it difficult to be applied to industrial wet gas metering.

To address the aforementioned demerits of the traditional metering methods, we have developed new measurement models. Firstly, we bring in flow pattern modulation. By swirling flow, downward annular flow is formed and maintained. Annular flow is stable and symmetrical, thus facilitating the improvement of prediction accuracy. Secondly, we proposed a new correction factor named two-phase mass flow coefficient, which is defined as the ratio of the sum of the gas and liquid mass flow rates to the apparent gas mass flow rate. Experimental results show that the new factor exhibits better linearity and is more sensitive to the change of liquid loading in comparison with the over-reading. Such properties will greatly benefit the flow rate measurement, for it can make the fitting equations simple and reduce the fitting errors. Finally, we proposed a metering method which can independently predict the liquid flow rate, thus minimizing the influence of error propagation. We have manufactured flowmeter prototypes and field tests demonstrate that the newly proposed measurement model can accurately predict the gas and liquid flow rate with an error of ±4% and ±10% respectively.

2 OVERVIEW OF METERING METHODS BASED ON DP FLOWMETERS

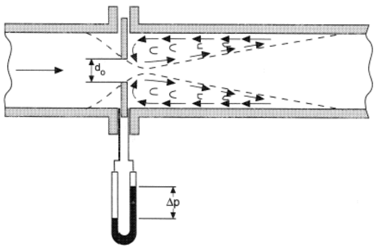


Fig. 1 DP flowmeter [1]

The DP flowmeter utilizes the conservation laws of mass and energy (namely, continuity equation and Bernoulli's equation). A reduction of the cross-sectional area of a conduit will create a pressure drop across the flowmeter, which is generally referred to as the differential pressure. When the flow velocity increases, more pressure drop is created. The pressure drop is related to the velocity of the flow and therefore the flow rate. Figure 1 shows the principle of a DP flowmeter (orifice plate).

The physical geometry that causes the change of area is called a "throttle device (TD)", including the orifice plate, V-cone, and Venturi tube. The different standard DP meters on the market all operate with the same generic flow equation and the different parameters in this generic flow equation are all dependent on the primary element used. The generic mass flow rate equation of DP meters for a single-phase flow is shown in Eq. (1).

$$m = EC_{\mathrm{d}}\varepsilon A\sqrt{2\rho\Delta P} \tag{1}$$

where *m* is the mass flow rate, *E* is the velocity of approach, $E = \frac{\beta^2}{\sqrt{1-\beta^4}}$, *β* is the equivalent diameter ratio, C_d is the discharge coefficient, *ε* is the expansibility factor (*ε* = 1 for incompressible fluid), *A* is the inlet cross-sectional area of a DP meter, *ρ* is the fluid density, and *ΔP* is the differential pressure.

Generally, there exists two measurement scenarios in industry, of which the first one is single-parameter measurement, namely the fluid flow is wet gas but the main focus is on the measurement of the gas flow, and the other one is two-parameter measurement, namely both the gas and liquid flows are required to be accurately measured. It is the second scenario that is of vital significance. For instance, in natural gas industry the asset contains both valuable natural gas and hydrocarbon liquid flow. The operator is required to accurately measure the gas and liquid hydrocarbon flows.

For single-phase flow, the differential pressure is a single-valued function of the flow rate. While for gas-liquid two-phase flow (wet gas flow), the differential pressure is dependent on both the gas and liquid flow rates. As a result, it is difficult to predict the gas and liquid flow rates with the only input of the differential pressure. To address this issue, many researchers have developed different approaches, of which the commonly used metering methods are those applying dual DPs and those based on DP fluctuation.

2.1 Metering methods applying Dual-DPs

Metering methods applying dual DPs indicates the approaches that attempt to predict both the gas and liquid flow rates with the input of two sets of differential pressure. Note that the term "differential pressure" here refers to the general pressure difference that includes the traditional differential pressure. Moreover, this method can be subdivided into dual-TDs-dual-DPs and single-TD-dual-DPs.

Dual-TDs-dual-DPs flowmeter is also referred to as "combined type wet gas flowmeter" that uses two or more single-phase DP flowmeters in series. This is a wet gas flow measurement by difference technique. For example, dual slotted orifice plates [2], dual cones [3, 4], a long throat Venturi tube and a V-Cone [5], etc. Figure 2 shows two examples of this type.

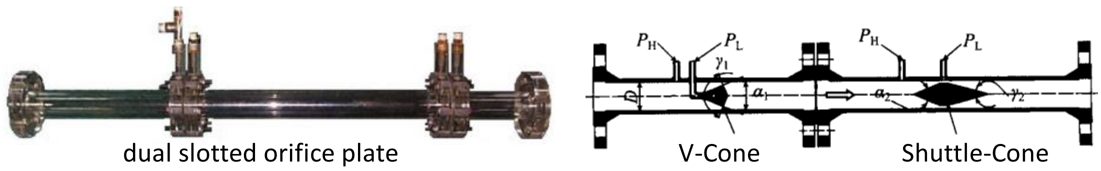


Fig. 2 Combined type wet gas flowmeter [2,3]

The following is a description of the principles of using two single-phase DP flowmeters in series to predict the gas and liquid flow rates in real time. For any given wet gas flow condition, the two single-phase DP flowmeters react differently and therefore each meter can have a unique correlation where that meter's differential pressure is related to the gas and liquid flow rates and possibly other parameters (such as the gas-to-liquid density ratio, etc.) by some function. That is:

Flowmeter 1: $$\Delta P_1 = f_1\left(m_g, m_l,\ \rho_g/\rho_l,\cdots\right) \tag{2}$$

Flowmeter 1: $$\Delta P_2 = f_2\left(m_g, m_l,\ \rho_g/\rho_l,\cdots\right) \tag{3}$$

where all parameters except the gas and liquid flow rates are known. Therefore, by algebraic manipulation these equations can be rearranged to give:

$$m_g = f_1^*\left(\Delta P_1, \Delta P_2,\ \rho_g/\rho_l,\cdots\right) \tag{4}$$

$$m_l = f_2^*\left(\Delta P_1, \Delta P_2,\ \rho_g/\rho_l,\cdots\right) \tag{5}$$

where f_1^* and f_2^* denote the appropriate rearranged functions.

From these expressions the gas and liquid flow rates can be found. If the simultaneous equations (Eqs. (2)-(3)) are not algebraically possible, then the solutions can be found by iteration.

The single-phase DP flowmeters in series method theoretically works for any combination as long as the flowmeters used have significantly different responses to wet gas flows. The method works better the larger the difference.

A disadvantage of the Dual-TDs-dual-DPs method is the relatively high head loss created by the multiple throttle devices (and thus the possibility of phase change resulted from that high head loss). To address this issue, the single-TD-dual-DPs method has been proposed, which means that only one throttle device is installed in the pipeline but two or more sets of differential pressure are read.
According to the conservation equations of mass and energy, when the fluid passes through a throttle device, the pressure in a DP flowmeter drops due to the transfer of pressure energy into kinetic energy and then recovers within a certain distance due to the recovery of pressure energy. However, the pressure cannot recover to the initial value due to the permanent energy loss caused by friction and turbulent dissipation. After the recovery of pressure energy, the static pressure continues to drop due to the friction of the fluid with the pipe. Figure 3 shows the typical pressure profile through a DP flowmeter. The upstream-throat pressure difference is the traditional differential pressure (ΔP_t); the throat-downstream pressure difference is the expansion differential pressure (ΔP_r); the upstream-downstream pressure difference is the permanent pressure

loss (ΔP_m). Theoretical analysis and experimental results show that all the three DPs are also related to the flow rate and thus can be applied as a characteristic parameters in flow rate measurement, as shown in Eqs. (6)-(8). Therefore, the gas and liquid flow rates can be found by combining Eq. (6) with Eq. (7) or Eq. (8).

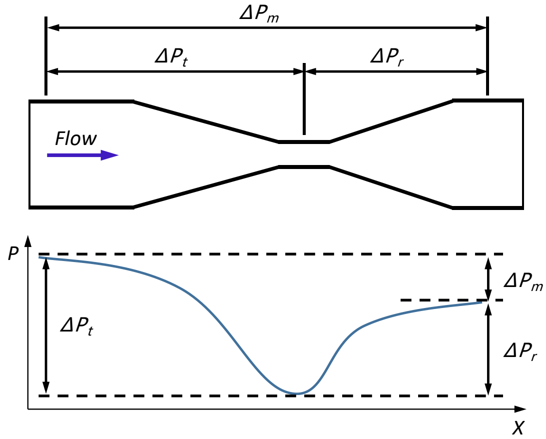


Fig. 3 Typical pressure profile through a DP flowmeter (Venturi tube)

Upstream-throat DP: $$\Delta P_t = f_1\left(m_g, m_l,\ \rho_g/\rho_l, \cdots\right) \tag{6}$$

Throat-downstream DP: $$\Delta P_r = f_2\left(m_g, m_l,\ \rho_g/\rho_l, \cdots\right) \tag{7}$$

Upstream-downstream DP: $$\Delta P_m = f_3\left(m_g, m_l,\ \rho_g/\rho_l, \cdots\right) \tag{8}$$

Figure 4 shows an example that utilizes the upstream-throat and the throat-downstream DPs based on a V-Cone throttle device [6]. Figure 5 shows an example that utilizes the upstream-throat and the upstream-downstream DPs based on a Venturi tube throttle device [7]. As for the upstream-downstream DP, namely the permanent pressure loss, the common practice is to divide it by the upstream-throat DP, giving a non-dimensional parameter called pressure loss ratio (*PLR*), as defined by Eq. (9).

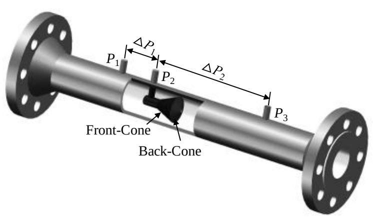


Fig. 4 V-Cone flowmeter [6]

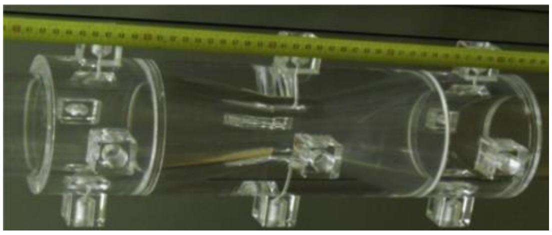


Fig. 5 V-Cone flowmeter [7]

$$PLR = \frac{\Delta P_m}{\Delta P_t} \tag{9}$$

2.2 Metering methods Based on DP Fluctuation

It is well-known that, due to the non-uniform distribution of phases, turbulence, interaction between each phases and interaction between fluid and the pipe wall, flow parameters such as pressure and differential pressure exhibit fluctuation when the gas-liquid two-phase flow (wet gas) passes through the throttle device. In-depth study reveals that the fluctuation contains a wealth of information relevant to the flow, and whereupon the frequency and magnitude of the fluctuation can be considered as characteristic parameters. The differential pressure fluctuation has been applied in flow regime identification [8] and aiding wet gas metering [9].

The application of the DP fluctuation relies on the fast response sensor system that can obtain high-frequency readings of differential pressure signals across a throttle device. The pressure, temperature, and differential pressure (P, T, ΔP) as well as the frequency and magnitude of the differential pressure fluctuation ($\omega_{\Delta P}$, $\delta_{\Delta P}$) are related to the gas and liquid flow rates through semi-empirical correlations or a neural network as shown in Eqs. (10)-(11). Thus, flow rate measurement of the wet gas flow can be implemented by using only one throttle device and one differential pressure sensor, making the metering system simplified and cost-effective.

$$m_g = f_1\left(P, T, \Delta P,\ \omega_{\Delta P}, \delta_{\Delta P}, \rho_g/\rho_l, \cdots\right) \tag{10}$$

$$m_l = f_2\left(P, T, \Delta P,\ \omega_{\Delta P}, \delta_{\Delta P}, \rho_g/\rho_l, \cdots\right) \tag{11}$$

where f_1 and f_2 denote semi-empirical correlations derived from given database or complex neural network functions which are continually being improved with each additional data set.

Shaban [10] has attempted to measure the gas and liquid flow rates by the application of machine learning techniques (one type of neural networks) to differential pressure signals. Shen [11] managed to measure the gas mass fraction and the total mass flow rate of air-water two-phase flow. Zheng [12] managed to predict the gas and liquid flow rates by the usage of differential pressure fluctuation.

3 EVALUATION OF TRADITIONAL METERING METHODS

DP flowmeters are popular for single-phase gas flow applications. In natural gas industry, operators often do not know whether a natural gas production flow will be wet before production starts, and a single-phase gas DP meter is chosen for the application. Even when operators know a natural gas flow will be wet from the outset, single-phase gas DP meters are still a common choice. In many cases, it is not economically justifiable to purchase a commercial wet gas flowmeter. Though the single-phase gas DP flowmeter will give an incorrect gas flow rate prediction, it is often considered better to have some flow information rather than none. Therefore, a single-phase gas DP flowmeter will be used to measure the wet gas flow [13].

It is generally accepted that when a single-phase gas DP flowmeter is used to meter the wet gas flow, the liquid presence in a gas flow causes the differential pressure from the flowmeter to be higher than what would be read if the gas phase of the wet gas flowed alone. Consequently, the gas mass flow rate prediction due to the two-phase (i.e. wet gas) differential pressure will be larger than the actual value. The uncorrected gas mass flow rate prediction is generally termed the apparent gas mass flow rate, $m_{g,\text{apparent}}$, as is shown in Eq. (12).

$$m_{g,apparent} = EC_d \varepsilon A\sqrt{2\rho_g \Delta P_{tp}} \tag{12}$$

where ΔP_{tp} is the two-phase (wet gas) differential pressure read from the flowmeter.

The positive deviation associated with single-phase DP flowmeters when they are used with with wet gas flows is often call the "over-reading (OR)", which is defined as the ratio of the apparent gas mass flow rate to the actual gas mass flow rate, as is shown in Eq. (13).

$$OR = \frac{m_{g,apparent}}{m_g} \tag{13}$$

Experimental research indicates that the liquid-induced over-reading is influenced by parameters such as X_{LM}, Fr_g, and DR. Once the relationship between the over-reading and the influential parameters is obtained, the over-predicted gas mass flow rate can be corrected using Eq. (14), which is usually call the wet gas correlation.

$$m_g = \frac{m_{g,apparent}}{OR} = \frac{m_{g,apparent}}{f\left(X_{LM}, Fr_g, \frac{\rho_g}{\rho_l}, \cdots\right)} \tag{14}$$

Over the past five decades, many researchers have investigated the response of a DP meter to the wet gas flow and proposed a number of correction correlations. The reported correlations are mainly derived from two basic flow models: the homogeneous flow model and the separated flow model. For instance, the James correlation [14] is based on the homogeneous flow model while the Murdock correlation [15] is developed from the separated flow model. we have summarized the most popular wet gas correlations in Refs. [16-17].

Provided the information of the liquid flow rate or some form of the liquid-to-gas flow rate ratio is obtained from an external source, the over-predicted gas flow rate tends to be correctable by the wet gas correlation. In general, such information can be obtained via an auxiliary correlation, which is either a second wet gas correlation or a semi-empirical correlation that relates the flow rate information of a wet gas flow to a characteristic parameter. The common approach has been stated in section 2. Thus, with the wet gas correlation and the auxiliary correlation incorporated, the gas and liquid flow rates can be predicted simultaneously.

A DP flowmeter’s wet gas correlation uncertainty statement assumes all required fluid properties and the information of the liquid flow rate or the liquid-to-gas flow rate are accurate. However, in many applications the information of the liquid phase may have significant uncertainty. This causes an associated increase in the DP flowmeter’s wet gas flow rates prediction uncertainty. This phenomenon can be explained by error propagation.

Table 1 shows the comparison of prediction errors of three typical DP flowmeters that apply the method of solving simultaneous correlations when they used with wet gas flows. As can be seen, the results exhibit similar error pattern, i.e., the prediction error of gas phase is small while that of the liquid phase is large.

Table 1 - Comparison of prediction errors (P_c is the confidence level)

Throttle device	Relative error (%)			
	x	m_g	m_l	m_{tp}
V-Cone [4]	±7%	±5%	±12%	±10%
Venturi tube [7]	±5%	±2%	±30%	–
Orifice plate [12]	±10% (P_c = 87%)	±5% (P_c = 94%)	±25% (P_c = 74%)	±10% (P_c = 90%)

In the following part, the error propagation rules of metering method based on wet gas correlations are investigated, provided that the gas mass fraction has been supplied in prior via an auxiliary correlation. Note that, although the existed wet gas correlations have different forms, all of them can be regarded as modified forms of the wet gas correlation derived from the separated flow model.

For simplicity, the following error analysis is therefore based on the separated flow model wet gas correlation, as shown in Eq. (15). The equation for predicting the liquid mass flow rate is shown in Eq. (16).

$$m_g = EC_d \varepsilon A\sqrt{2\rho_g \Delta P_{tp}} \cdot \frac{1}{1+X_{LM}} \tag{15}$$

$$m_l = EC_d \varepsilon A\sqrt{2\rho_g \Delta P_{tp}} \cdot \frac{1}{1+X_{LM}} \cdot \frac{1-x}{x} \tag{16}$$

According to error propagation theory, the deviation of indirectly measured parameter y can be estimated by that of the directly measured parameters x_i:

$$\delta y = \sum_{i=1}^{n} \frac{\partial f}{\partial x_i} \delta x_i \tag{17}$$

where $y = f(x_1, x_2, \ldots, x_n)$, δ denotes the deviation.

Substituting the definition of X_{LM} into Eq. (15) gives the equation for the gas mass flow rate:

$$m_g = EC_d \varepsilon A\sqrt{2\rho_g \Delta P_{tp}} \frac{x}{x+(1-x)\sqrt{\rho_g/\rho_l}} \tag{18}$$

Therefore, the relative error of the gas mass flow rate can be estimated by that of the gas mass fraction:

$$\frac{\delta m_g}{m_g} = \frac{\frac{\partial m_g}{\partial x}\delta x}{m_g} = \left(1+\frac{1-x}{x}\sqrt{\rho_g/\rho_l}\right)^{-1} \frac{\sqrt{\rho_g/\rho_l}}{x} \cdot \frac{\delta x}{x} = C_g \frac{\delta x}{x} \tag{19}$$

where C_g is the error transfer coefficient for gas mass flow rate.

$$C_g = \left(1+\frac{1-x}{x}\sqrt{\rho_g/\rho_l}\right)^{-1} \frac{\sqrt{\rho_g/\rho_l}}{x} = \frac{1}{1+X_{LM}} \cdot \frac{\sqrt{\rho_g/\rho_l}}{x} < \frac{\sqrt{\rho_g/\rho_l}}{x} \tag{20}$$

Note that $X_{LM} \leq 0.3$ for wet gas, and

$$X_{LM} = \frac{1-x}{x}\sqrt{\rho_g/\rho_l} \leq 0.3 \Rightarrow \frac{\sqrt{\rho_g/\rho_l}}{x} \leq 0.3+\sqrt{\rho_g/\rho_l} \tag{21}$$

Eq. (20) can then be rearranged to $C_g < 0.3+\sqrt{\rho_g/\rho_l}$.

Taking air-water two-phase flow for instance, C_g is less than 1 as long as the pressure is no more than 37 MPa (where $\sqrt{\rho_g/\rho_l} < 0.7$). As to low pressure laboratory experiments, the operating pressure is usually lower than 3MPa, which gives:

$$C_g < 0.5 \tag{22}$$

In light of the analysis above, it is clear that the relative error of the gas mass flow rate is much smaller than that of the gas mass fraction.

Substituting the definition of X_{LM} into Eq. (16) gives the equation for the liquid mass flow rate:

$$m_l = EC_d \varepsilon A_t\sqrt{2\rho_g \Delta P_{tp}} \frac{1-x}{x+(1-x)\sqrt{\rho_g/\rho_l}} \tag{23}$$

then, the relative error of the liquid mass flow rate can be estimated in the same way:

$$\frac{\delta m_l}{m_l} = \frac{\frac{\partial m_l}{\partial x}\delta x}{m_l} = -\left(1+\frac{1-x}{x}\sqrt{\rho_g/\rho_l}\right)^{-1} \frac{1}{1-x} \cdot \frac{\delta x}{x} = -C_l \frac{\delta x}{x} \tag{24}$$

where C_l is the error transfer coefficient for liquid mass flow rate:

$$C_l = \left(1 + \frac{1-x}{x}\sqrt{\rho_g/\rho_l}\right)^{-1} \frac{1}{1-x} = \frac{1}{1+X_{LM}} \cdot \frac{1}{1-x} \tag{25}$$

Likewise, $X_{LM} \le 0.3$ for wet gas, rearranging Eq. (25) gives

$$C_l \ge \frac{1}{1.3(1-x)} \tag{26}$$

It is worth noting that, for wet gas with $x > 0.23$, C_l is larger than 1, which means that the relative error of liquid mass flow rate is amplified due to error propagation. Moreover, the greater the gas mass fraction, the higher the degree of amplification. When $x = 0.99$, for instance, the relative error of liquid mass flow rate is 77 times larger than that of the gas mass fraction.

To sum up, due to error propagation, the relative error of the gas mass flow rate is much smaller than that of the gas mass fraction, whereas the relative error of the liquid mass flow rate is much larger than that of the gas mass fraction. Besides, the error pattern is a universal phenomenon for wet gas metering method based on differential pressure.

4 CHARACTERISTICS OF PRESSURE DROP

In this section, the basic characteristics of differential pressure signals and the limitation of flow rate metering methods based on differential pressure are studied analytically and experimentally.

4.1 Contribution of each phase to the two-phase differential pressure

As is shown in Table 1, the gas flow rate prediction uncertainty's sensitivity to liquid flow rate input uncertainty is typically relatively low. A liquid flow rate prediction error produces a smaller gas flow rate error. The physical essence of the difference in sensitivity lies in the fact that the gas phase and the liquid phase have exerted different influence on the two-phase differential pressure.

We apply the separated flow model [10] herein: the gas and liquid phases flow separately through the throttling device; both phases are incompressible; the discharge coefficient is the same for both phases; the pressure drop for each phase is the same as that for the two-phase flow. Then, the gas mass flow rate and the liquid mass flow rate can be calculated by Eqs. (27)-(28).

$$m_g = EC_d \varepsilon A\sqrt{2\rho_g \Delta P_{gO}} \tag{27}$$

$$m_l = EC_d \varepsilon A\sqrt{2\rho_l \Delta P_{lO}} \tag{28}$$

where ΔP_{gO} and ΔP_{lO} are the pressure drop if gas or liquid phase flowed alone, respectively.

Rearranging Eqs. (27)-(28) gives the single phase differential pressure ratio:

$$\frac{\Delta P_{lO}}{\Delta P_{gO}} = \left(\frac{m_l}{m_g}\right)^2 \frac{\rho_g}{\rho_l} = X_{LM}^2 \tag{29}$$

Bernoulli's equation states that the the square root of differential pressure is proportional to the flow rate. For simplicity, the following analysis is based on the square root of the differential pressure. Our group's experiments on air-water two-phase flow through horizontally installed orifice plate [12] and V-Cone [19] indicate that the flow pattern is mainly stratified flow or wavy stratified flow for wet gas flow. Assuming that the flow complies with the separated flow model, the relationship between the square root of the differential pressure of wet gas flowing through the throttle device and that of each phase flowing alone can be derived:

$$\sqrt{\Delta P_{tp}} = \sqrt{\Delta P_{gO}} + \sqrt{\Delta P_{lO}} \tag{30}$$

Then, the "contribution" of the gas phase flow and liquid phase flow to the two-phase differential pressure is estimated by the Eqs. (31)-(32).

$$R_g = \frac{\sqrt{\Delta P_{gO}}}{\sqrt{\Delta P_{tp}}} = \frac{1}{1 + X_{LM}} \tag{31}$$

$$R_l = \frac{\sqrt{\Delta P_{lO}}}{\sqrt{\Delta P_{tp}}} = \frac{X_{LM}}{1 + X_{LM}} \tag{32}$$

where R_g and R_l denote the the "contribution".

Considering that X_{LM} is less than 0.3 for wet gas by definition, then R_g is larger than 0.77, which means that the two-phase differential pressure is mainly caused by gas phase and is slightly affected by the liquid phase. For an air-water two-phase flow with a pressure of 0.7 MPa and a gas mass fraction of 0.83 (then, X_{LM} = 0.02), we can derive that R_g = 0.98 and R_l = 0.02, indicating that the effect of the liquid phase on the two-phase differential pressure is negligible compared with the gas phase. Under this condition, the relative error of taking the apparent gas mass flow rate as the prediction value of the gas mass flow rate can be estimated by Eq. (33). We have δr_g=2%, meaning that the gas flow rate prediction uncertainty is small even without correction.

$$\delta r_g = \frac{m_{g,apparent} - m_g}{m_g} \approx \frac{\sqrt{\Delta P_{tp}} - \sqrt{\Delta P_{gO}}}{\sqrt{\Delta P_{gO}}} = X_{LM} \tag{33}$$

4.2 Repeatability of DP signals

Revisiting of the relative errors shown in Table 1 indicates that the measurement accuracy of the orifice plate [12] is lower than that of the V-Cone [4] and the Venturi tube [7]. The three works are all based on wet gas correlations but with different characteristic parameters used for establishing the auxiliary correlation. Ref. [4] adopted the across throttle device pressure drop, while Ref. [7] adopted the permanent pressure loss. These characteristic parameters are both differential pressure in essence, but with different low pressure ports. Refs. [4] and [7] used the mean value of the differential pressure signals, while Ref. [12] used the fluctuation of the differential pressure signals. It is the characteristics of differential pressure fluctuation that bring down the measurement accuracy. In this section, the mean value and the fluctuation of the differential pressure signals are investigated experimentally.

Figure 6 shows that when the pressure is fixed, the differential pressure mean value increases with both the gas and liquid flow rates, which means that the differential pressure mean value can reflect flow rate changes of wet gas. However, as claimed previously, influence of the liquid phase on the differential pressure mean value is small compared to that of the gas phase.

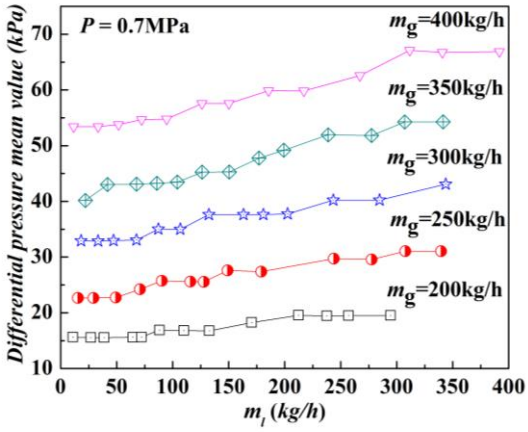


Fig. 6 Relationship between DP mean value and flow rates

Data in Fig. 7 are collected from experiments conducted on different dates with the same pressure and gas mass flow rate. As can be seen, the differential pressure mean values show good consistency, and the relative deviation from the fitted line is less than ±0.46%. Conclusions are then drawn that the differential pressure mean value has good repeatability and can therefore perform as a robust characteristic parameter of the two-phase flow.

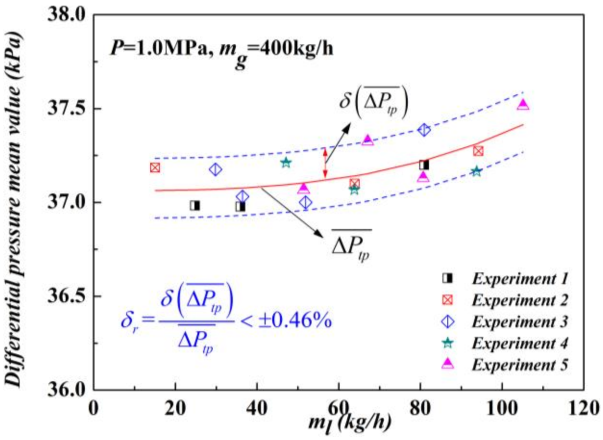


Fig. 7 Variation of DP mean value

As a common practice, the standard deviation is used to quantify the degree of fluctuation. Fig. 8 shows that the differential pressure standard deviation increases with the gas and liquid flow rates for most cases. This tendency indicates that the fluctuation of differential pressure signals can reflect flow rate changes of wet gas, and therefore it is considered as a characteristic parameter of the two-phase flow.

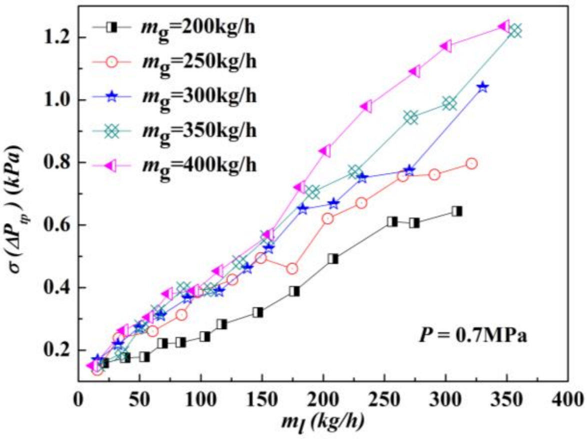


Fig. 8 Relationship between DP standard deviation and flow rates

In the experiment, three sets of differential pressure signals are collected under each experimental condition, for the purpose of evaluating the repeatability of the differential pressure fluctuation. Consequently, three differential pressure standard deviations are calculated for each operating point. As can be seen from Fig. 9(a), the average value of the three differential pressure standard deviations (denoted by circular dots), increases with the liquid mass flow rate, providing that the pressure and the gas mass flow rate remain unchanged. However, the variation of the differential pressure standard deviation from the average value is much wider than that of the differential pressure mean value, with the maximum relative deviation beyond ±10%, as shown in Fig. 9(b). (The error bar in Fig. 9(a) denotes the difference between the maximum and the minimum values of the three differential pressure standard deviations.) The wide variation range means that the repeatability of the differential pressure standard deviation is poor.

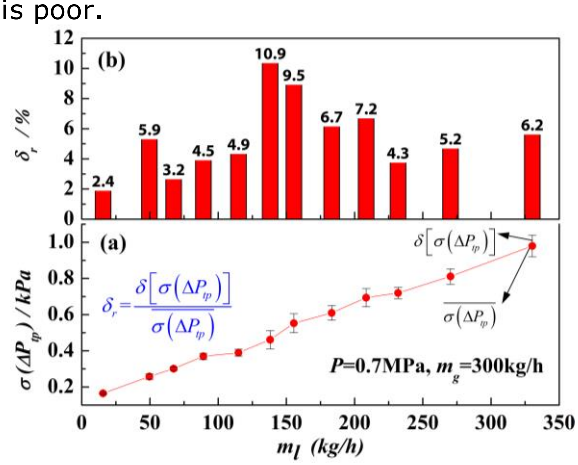


Fig. 9 Variation of DPe standard deviation

Herein, the relative standard uncertainty of the differential pressure standard deviation, defined by Eq. (34), is used to quantify the repeatability:

$$U[\sigma(\Delta P_{tp})] = \frac{u\left[\sigma\left(\Delta P_{tp}\right)\right]}{[\sigma(\Delta P_{tp})]_{ave}} \tag{34}$$

where $[\sigma(\Delta P_{tp})]_{ave}$ is the average value of the three DP standard deviations; $u[\sigma(\Delta P_{tp})]$ is the standard uncertainty of DP standard deviation. Due to the small number of samples, $u[\sigma(\Delta P_{tp})]$ is estimated by Eq. (35):

$$u\left[\sigma\left(\Delta P_{tp}\right)\right]=\frac{\left[\sigma\left(\Delta P_{tp}\right)\right]_{\max}-\left[\sigma\left(\Delta P_{tp}\right)\right]_{\min}}{d_n} \tag{35}$$

where $[\sigma(\Delta P_{tp})]_{max}$ and $[\sigma(\Delta P_{tp})]_{min}$ are the maximum and minimum values of the three DP standard deviations, respectively; d_n is the coefficient (d_3 = 1.693, for n = 3).

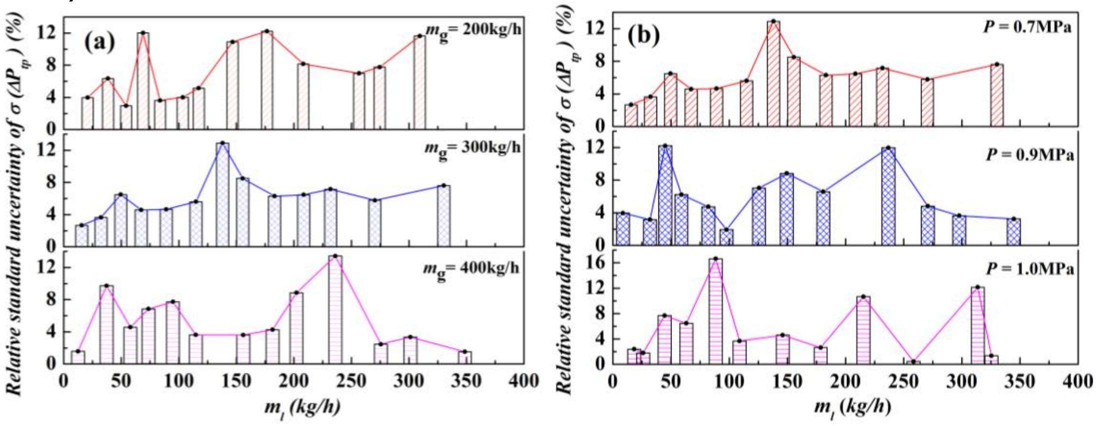


Fig. 10 Variation of $U[\sigma(\Delta P_{tp})]$ under different conditions (a) P = 0.7MPa, (b) mg = 300kg/h

The variation of $U[\sigma(\Delta P_{tp})]$ with the liquid mass flow rate under different pressure and gas mass flow rate is presented in Fig. 13. The results illustrate that $U[\sigma(\Delta P_{tp})]$ varies between 0.3% and 18.5% for all conditions. Besides, $U[\sigma(\Delta P_{tp})]$ shows no rules as the operating condition changes, meaning that the value of $U[\sigma(\Delta P_{tp})]$ is stochastic. The reason for this phenomenon is that gas-liquid two-phase flow is a stochastic flow in nature.

To conclude, both the mean value and the fluctuation of the DP signals can be taken as characteristic parameters. However, these two statistics parameters show different properties. The mean value of the differential pressure signals can reflect flow rate changes in wet gas and has good repeatability. Although the fluctuation of the differential pressure signals increases with the gas and liquid flow rates, the repeatability of the fluctuation is poor.

4.3 Non-monotonicity of the pressure drop

It is generally accepted that liquid in a gas flow causes the differential pressure from the DP flowmeter to be higher than that, which would be indicated if the gas phase of the wet gas flow flowed alone. There is therefore a positive error, often called the "over-reading", associated with DP meters when they are used with wet gas flows. Nevertheless, experiments on orifice plate [20] show that, for very low liquid loading, the liquid causes a negative error in gas flow rate estimation, which means "under-reading" occurring. The under-reading phenomenon, however, hasn't got as much attention as the over-reading.

De Leeuw [21] found that the total pressure loss across a DP flowmeter with wet gas flow contains liquid flow rate information. Applications of this knowledge in wet gas flowmetering have been realized [7, 19]. Generally, the dimensionless parameter, pressure loss ratio (defined as the ratio of pressure loss to differential pressure) is used in practice. The majority of public papers indicate that the pressure loss ratio increases monotonously with increasing liquid loading. However, results of our experiments on orifice plate and V-cone show that, for very low liquid loading, the pressure loss ratio decreases at first and then increases. Negligence of this phenomenon lead to tremendous prediction error for low liquid flow rate [19].

In view of the facts described above, it could be concluded that, for wet gas flow with low liquid loading (hereinafter referred to as 3-L wet gas flow), the differential pressure and pressure loss exhibit different characteristics to that of a general wet gas flow. The following section investigates the non-monotonicity of the pressure drop of 3-L wet gas flow through DP flowmeters, including orifice plate, V-Cone and Venturi tube. The frictional pressure drop, the upstream-throat DP, the throat-downstream DP and the upstream-downstream DP (i.e., the pressure loss) are studied.

Fig. 11 shows the pressure drop of orifice plate, Venturi tube and V-Cone. As can be seen, these three throttle devices exhibit different properties.

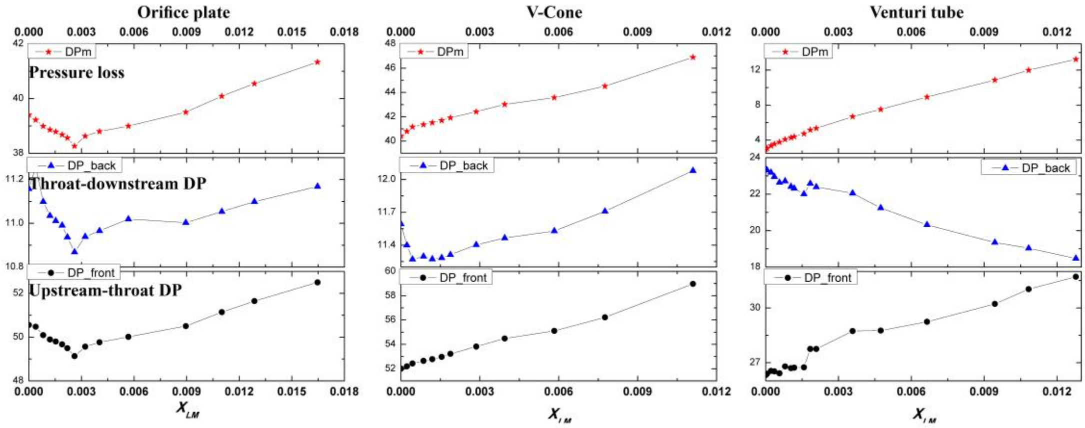


Fig. 11 Pressure drop of orifice plate, Venturi tube and V-Cone

- Upstream-throat DP

The upstream-throat DP of the orifice plate decreases at first and then increases as the liquid loading increases. This trend will result in an under-reading at first and then an over-reading, coinciding with that obtained by Ting [20]. However, the upstream-throat DP of the V-Cone and the Venturi tube increases monotonously as the liquid loading increases. Ref. [22] attributes the under-reading of the orifice plate to the lubrication effect of the trace liquid on the meter tube and orifice plate in which the effective surface roughness has been marginally reduced. To validate this assumption, we measured the frictional pressure drop of a straight pipe (with no throttle device inserted) horizontally installed before the orifice plate. Fig. 12 shows the comparison of the frictional pressure drop and the up-throat DP. In the experiment, the distance between the upstream pressure port and the throat pressure port is about 75mm. As can be seen, the frictional pressure drop dose not decreases with the presence of the trace liquid. Moreover, the frictional pressure drop is negligible compared with the up-throat DP. It is therefore rational to conclude that it is not the lubrication effect of the trace liquid that leads to the under-reading of the orifice plate. Besides, the V-Cone and the Venturi tube should also exhibit under-reading phenomenon as the orifice plate does if the assumption is correct.

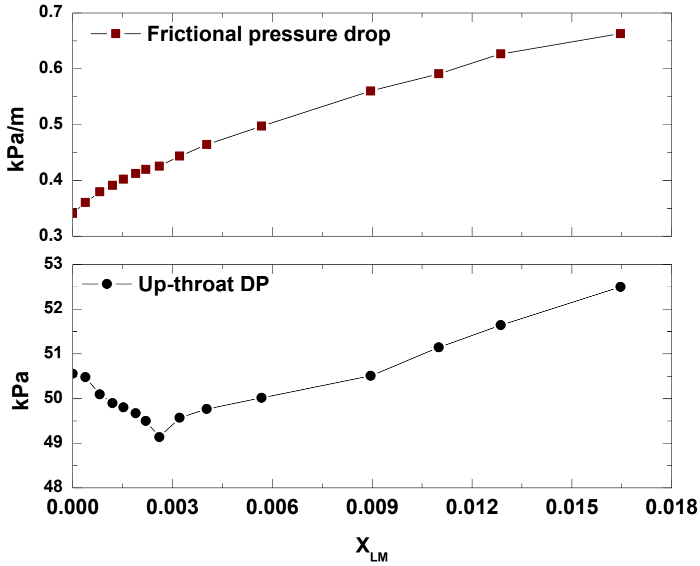


Fig. 12 Comparison of the frictional pressure drop and the up-throat DP (Orifice plate)

A proposed reason for the under-reading may be the flow modulation of the trace liquid on the orifice plate. Unlike with the V-Cone and the Venturi tube, the cross-sectional area of the orifice plate reduces suddenly at the throat, resulting in considerable energy loss. When a trace liquid is present in a gas flow, the liquid will accumulate before the orifice and thus the cross-sectional area reduces gradually. The flow modulation will reduce the energy loss and therefore the under-reading occurs.

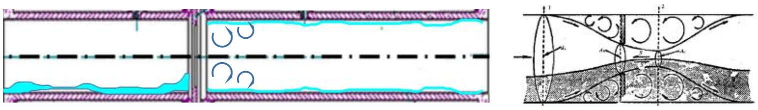


Fig. 13 Flow modulation of the trace liquid

- Throat-downstream DP

Fig. 11 shows that the throat-downstream DP of all the three throttle devices decreases at first and then increases as the liquid loading increases. The non-monotonicity of the throat-downstream DP is adverse if the throat-downstream DP is used to predict the flow rate of a wet gas flow, for it may bring about three types result: correction prediction, incorrect prediction an no prediction. For further details on this issue, see Ref. [23]

- Pressure loss

Fig. 11 shows that the pressure loss of the V-Cone and the Venturi tube increases monotonously as the liquid loading increases, while that of the orifice plate decreases at first and then increases. The non-monotonicity needs to be concerned if the pressure loss is chosen as a characteristic parameter.

5 Development of new measurement model

5.1 Flow Pattern Modulation

For horiaontal wet gas flow, five typical types of flow patterns (i.e., Stratified Flow, Wave-Stratified Flow, Roll-Wave Flow, Pseudo-Slug Flow and Annular Flow) were observed in the experiment, as is shown in Fig. 14. For vertical downward, the flow patterns are all annular flow, as is shown in Fig. 15. Annular flow will facilitate the flow rate measurement.

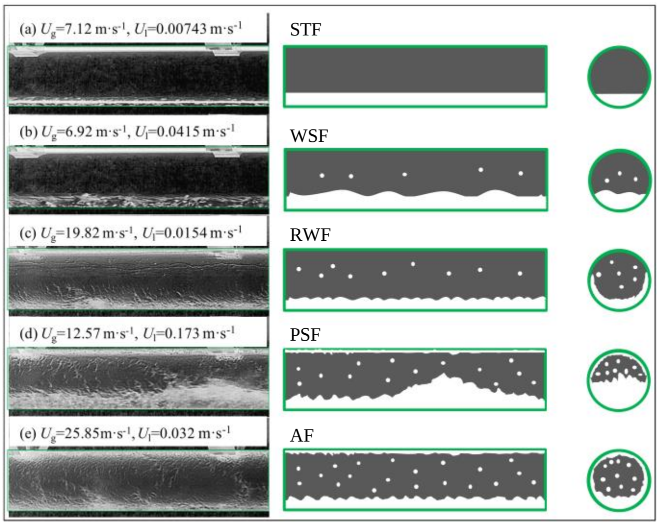


Fig. 14 Typical flow patterns of horizontal wet gas flow [24]
The flow is from the left to the right, the left photos are taken by the high-speed camera, and the right ones are simplified figures of the left photos.

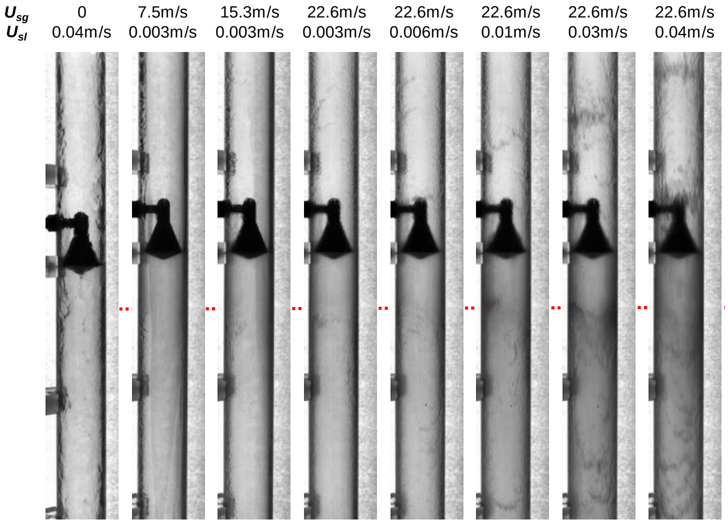


Fig. 15 Typical flow patterns of vertical downward wet gas flow

5.2 New Correction Factor

In our previous work on V-Cone [25] and Venturi tube [17], we proposed a new parameter: the two-phase mass flow coefficient *K*, which is defined as the ratio of the total mass flow rate (the sum of the gas and liquid mass flow rates) to the apparent gas mass flow rate, as shown in Eq. (36). Note that *K* is reduced to 1 when m_l=0, for $m_{g,apparent}$ equals to m_g in this case.

$$K = \frac{m_g + m_l}{m_{g,apparent}} \tag{36}$$

To theoretically analyze the influential parameters of K, we apply the separated flow model. Then, the gas mass flow rate and the liquid mass flow rate can be calculated by Eqs. (37)-(38), where α is the void fraction.

$$m_g = EC_d \varepsilon A \alpha \sqrt{2\rho_g \Delta P_{tp}} \tag{37}$$

$$m_l = EC_d \varepsilon A (1-\alpha) \sqrt{2\rho_l \Delta P_{tp}} \tag{38}$$

Substituting Eqs. (12), (37) and (38) into Eq. (36) gives:

$$K=\alpha+(1-\alpha)\sqrt{\frac{\rho_l}{\rho_g}} \tag{39}$$

Substituting Eqs. (37) and (38) into the ratio of gas mass flow rate to liquid mass flow rate, we get:

$$\frac{m_g}{m_l}=\frac{\alpha}{1-\alpha}\sqrt{\frac{\rho_g}{\rho_l}} \tag{40}$$

Equation (40) can be rewritten as Eq. (41):

$$\alpha=\frac{1}{1+\frac{m_l}{m_g}\sqrt{\frac{\rho_g}{\rho_l}}}=\frac{1}{1+X_{LM}} \tag{41}$$

Substituting Eq. (41) into Eq. (39) gives:

$$K=\frac{1+X_{LM}\sqrt{\frac{\rho_l}{\rho_g}}}{1+X_{LM}} \tag{42}$$

By omitting the terms higher than 2nd order in the Taylor series expansion, Eq. (42) can be rearranged to:

$$K=\left(\frac{1}{\sqrt{\rho_g/\rho_l}}-1\right)X_{LM}+1 \tag{43}$$

Equation (43) indicates that K is equal to 1 when X_{LM}=0 (i.e., m_l=0), which is consistent with the definition of K. It can be concluded from Eq. (43) that K decreases with increasing the gas-to-liquid density ratio ρ_g/ρ_l (namely the pressure), and increases with X_{LM} when the pressure is held constant. Note that Eq. (41) is obtained under the separated flow assumption. In addition, dimensional analysis (not presented here) demonstrates that K is also dependent on the gas densiometric Froude number Fr_g. Consequently, for the sake of making the correlation better correspond to the real case and considering the effect of Fr_g, Eq. (43) is modified to Eq. (44) where the precise nature of the function "*f*" is found by experimental data.

$$K=f\left(Fr_g,\frac{\rho_g}{\rho_l}\right)X_{LM}+1 \tag{44}$$

Combining Eqs. (12), (36) and (44), and after rearranging, the new wet gas correlation based on two-phase mass flow coefficient is obtained, which is

$$m_g=\frac{m_{g,apparent}K}{1+X_{LM}\Big/\sqrt{\rho_g/\rho_l}}=\frac{m_{g,apparent}}{1+X_{LM}\Big/\sqrt{\rho_g/\rho_l}}\left[f\left(Fr_g,\frac{\rho_g}{\rho_l}\right)X_{LM}+1\right] \tag{45}$$

To investigate the difference between the over-reading and the two-phase mass flow coefficient, a diagram describing the variation of OR and K with X_{LM} under the same operating conditions is plotted, as shown in Fig. 16.

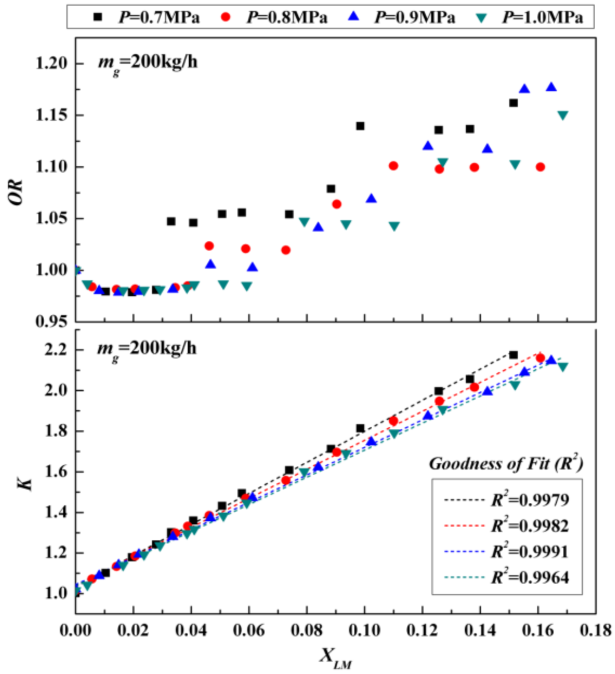


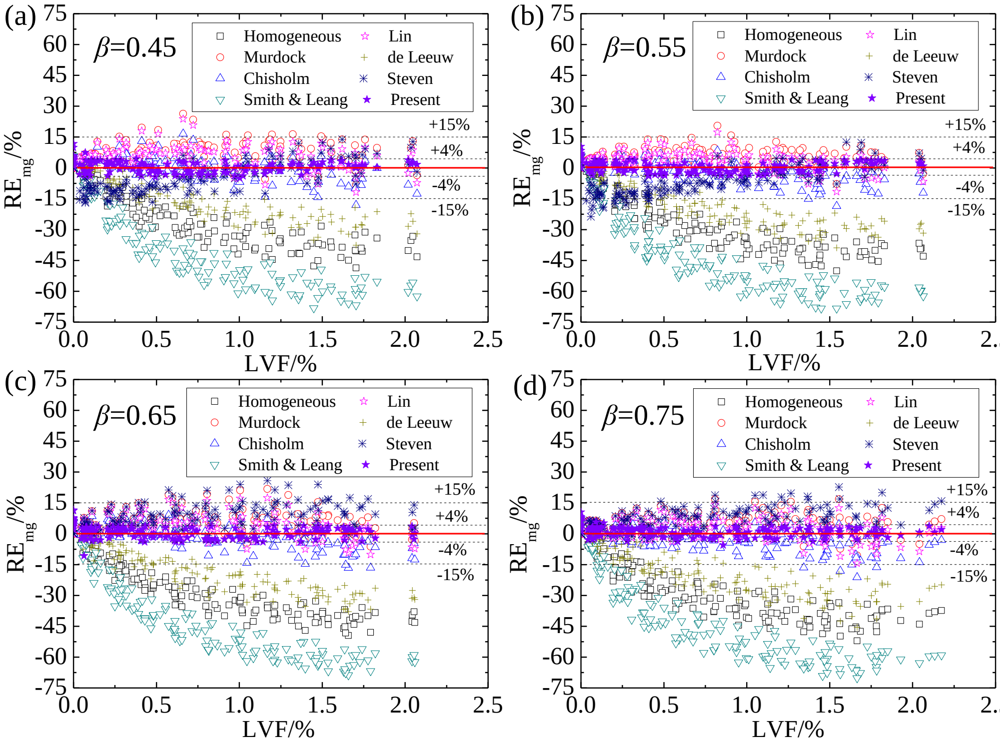
Fig. 16 Comparison between *OR* and *K* under the same operating conditions (Orifice plate)

Fig. 16 shows that even though both *OR* and *K* increase with X_{LM}, the two parameters have different characteristics. *K* exhibits good linearity while *OR* does not. The fact that all the goodness of using linear function to fit the *K* data in Fig. 16 is larger than 0.99 demonstrates the prominent linearity of the K-X_{LM} curve. Besides, in our previous studies on V-cone meters and Venturi meters, the results also show that *K* linearly increases with X_{LM}. Such findings indicate that the character of K increasing linearly with XLM is a universal law for DP meters.

Another important finding regarding Fig. 16 is that the variation range of *K* is nearly six times larger than that of *OR* (1-2.2 versus 0.97-1.17). This difference can be interpreted as follows. When a separated flow is assumed, the over-reading has the simplest expression, as shown in Eq. (46). Therefore, the variation range of *OR* can be estimated by Eq. (46). Likewise, the variation range of *K* can be estimated by Eq. (43). In the experiment, X_{LM} and ρ_g/ρ_l are in the range of 0-0.170 and 0.00961-0.0131, respectively, then *OR* and *K* are approximately in the range of 1-1.17 and 1-2.56 accordingly. This result is in agreement with that in Fig. 16. The great gap between the variation range of *OR* and *K* indicates that *K* is more sensitive to the change of X_{LM}.

$$OR = 1 + X_{LM} \tag{46}$$

Fig. 17 shows the Performance comparison between correlations based on *OR* and *K*. The “present” denotes the correlations based on K, namely Eq. (45). As can be seen, the relative error of the new proposed correlation is less than ± 3.0% at the confidence level of 98.6%. Besides, the points are symmetrically distributed around RE=0. The benefit of the symmetrical distribution is that the prediction error of the cumulative flow rate can be further reduced. These results indicate that the newly developed correlation can predict the gas mass flow rate in high accuracy.



（a）β=0.45（b）β=0.55（c）β=0.65（d）β=0.75

Fig. 17 Performance comparison between correlations based on *OR* and *K*

5.3 Measurement of Liquid Film Based on Wall Shear Stress

As has been stated in section 4.1, for gas-liquid two-phase flow with high gas volume fraction, the influence of the liquid phase on the two-phase differential pressure is negligible, resulting in that the two-phase differential pressure can not reflect the change of liquid flow rate. The metering method of combining two single-phase DP flowmeters in series is theoretically feasible. In practice this can be difficult to achieve. Research into single-phase DP flowmeter responses to wet gas flow have shown that different standard DP flowmeter designs can have too similar wet gas responses for this measurement by difference technique to work well. This can result in relatively large uncertainties in the estimated flow rates, especially for the liquid flow rate. Therefore, direct metering methods are more capable at measuring liquid flow rate than measurement by difference technique.

As can be seen in Fig. 16, for vertical downward wet gas flow, the flow pattern is annular flow. We have proposed a metering method that can directly measure the flow rate of the liquid film in the annular flow by using the wall shear stress between the liquid film and the pipe. The details are not presented here for the reason of intellectual property. Fig. 18 shows the sketch of this method, where DP is a differential pressure transducer.

$$m_l = f\left(\frac{dP}{dZ}, \tau_w\right) \tag{47}$$

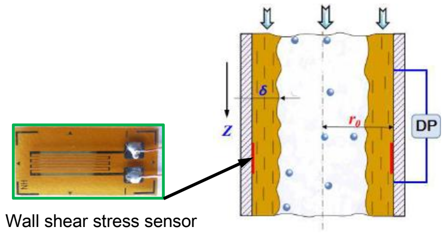


Fig. 18 Measurement of liquid film based on wall shear stress

6 CONCLUSIONS

- Through the investigation into differential pressure signals of orifice plate and V-cone, it is found that the two-phase differential pressure is mainly caused by gas phase and is slightly affected by the liquid phase.
- In the case of low liquid hold up, for orifice plate, the two-phase differential pressure, pressure loss and pressure loss ratio decrease at first and then increase as the liquid hold up increases. A proposed reason for this phenomenon may be the flow modulation of the trace liquid on the orifice plate.
- The fluctuation of the differential pressure is stochastic, causing the fluctuation characteristic parameters, such as the standard deviation, having the properties of poor stability and repeatability. This makes it difficult to be applied to industrial wet gas metering.
- The error propagation analysis demonstrates that the prediction error of liquid phase flow rate is much larger than that of the gas phase, which is a universal phenomenon of metering methods based on over-reading correlations.
- Although both *K* and *OR* increase with the Lockhart-Martinelli parameter, *K* exhibit better linearity and is more sensitive to the change of X_{LM}. Such properties of *K* will greatly benefit the later flow rate measurement, for it can make the fitting equations simple and reduce the fitting errors.
- A new measurement of liquid film based on wall shear stress is proposed.

7 NOTATION

A	Area of the meter inlet	m	Mass flow rate
C_d	Discharge coefficient	x	Gas mass fraction
DR	Gas-to-liquid density ratio	X_{LM}	*Lockhart-Martinelli parameter*
Fr_g	Gas densiometric Froude number	α	*Void fraction*
g	Gravitational acceleration constant	β	*Diameter ratio*
K	Two-phase mass flow coefficient	ΔP	Differential pressure
		ε	Expansibility coefficient
		ρ	Density

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