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A new model for the V-Cone meter in low pressure wet gas metering

Denghui He[1], **Bofeng Bai**[1,4], **Yong Xu**[2,3] **and Xing Li**[1]

[1] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China
[2] Oil and Gas Technology Research Institute, Changqing Oilfield Company of CNPC, Xi'an 710021, People's Republic of China
[3] National Engineering Laboratory for Exploration and Development of Low-Permeability Oil and Gas Field, CNPC, Beijing 100007, People's Republic of China

E-mail: bfbai@mail.xjtu.edu.cn

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Abstract
Wet gas metering with differential pressure (DP) devices (e.g. the orifice plate, the Venturi and the V-Cone) has gained increasing interest in the oil and gas industry. Many investigations have been performed and several models have been proposed. Among the DP devices, the V-Cone flow meter has received increasing attention owing to its remarkable performance characteristics, including high accuracy, excellent repeatability, wide turndowns, shorter straight length and stable signals. In this work, we developed a new method for predicting the gas flow rate in low pressure wet gas flow using a V-Cone flow meter with the diameter ratio of 0.55. The experimental fluid was air and tap water. The test pressure ranged from 0.10 to 0.48 MPa, and the gas and liquid mass flow rates ranged from 100 to 500 N m^3 h^{-1} and from 0.030 to 0.358 m^3 h^{-1}, respectively. Thus, the Lockhart–Martinelli parameter, X_{LM}, was up to 0.158 and the gas volume fraction ranged from 98.94% to 100%. A dimensionless parameter, K, was proposed in this work and defined as the two-phase flow coefficient of the flow meter. The results indicated that the K linearly increased with the Lockhart–Martinelli parameter. In addition, the K increased with the gas densiometric Froude number and decreased with the operating pressure when other parameters were kept constant. On the basis of the two-phase flow coefficient, a new wet gas model was developed and compared with seven popular wet gas models. It was found that with the V-Cone flow meter and under the present experimental conditions the new model produced a more accurate prediction of the wet gas than other models. The research approach to obtaining the model can also be used in the studies on other DP devices and thus will benefit the design of wet gas meters.

Keywords: wet gas, two-phase flow, differential pressure, V-Cone meter, low pressure

(Some figures may appear in colour only in the online journal)

Nomenclature

English symbols

Symbol	Description (units)
A	area of the meter inlet (mm^2)
A_t	minimum cross-sectional area of a differential pressure (DP) meter (mm^2)
a	slope in equation (8) (dimensionless)
b	intercept in equation (8) (dimensionless)
C	gas flow coefficient (dimensionless)
C_d	discharge coefficient of a DP meter (dimensionless)
D	meter inlet pipe diameter (mm)

[4] Author to whom any correspondence should be addressed.

DR	gas-to-liquid density ratio under flowing conditions (dimensionless)
E	velocity of approach of a DP meter (dimensionless)
Fr_g	gas densiometric Froude number (dimensionless)
g	gravitational constant (m s^{-2})
GVF	gas volume fraction under operating conditions (dimensionless)
k	k is a fitting constant in equation (10) (dimensionless)
K	two-phase flow coefficient (dimensionless)
m_{apparent}	apparent wet gas mass flow rate (kg s^{-1})
m_g	gas mass flow rate of the wet gas (kg s^{-1})
$m_{g,\text{apparent}}$	gas flow rate in mass predicted by a DP meter when using ΔP_{tp} (kg s^{-1})
$m_{g,\text{theoretical}}$	theoretical flow rate when the V-Cone meter is used in dry gas flow (kg s^{-1})
m_l	liquid mass flow rate of the wet gas (kg s^{-1})
P	line pressure (Pa)
Q_g	gas volume flow rate of the wet gas (m^3 s^{-1})
Q_l	liquid volume flow rate of the wet gas (m^3 s^{-1})
Re_g	superficial gas Reynolds number (dimensionless)
U_{sg}	superficial gas velocity (m s^{-1})
U_{sl}	superficial liquid velocity (m s^{-1})
X_{LM}	Lockhart–Martinelli parameter (dimensionless)

Greek symbols

Symbol	Description (units)
ΔP_g	DP produced by the V-Cone meter as it is used to meter the dry gas flow (Pa)
ΔP_{tp}	actual wet gas DP (Pa)
α	front cone angle of the V-Cone meter (°)
β	'Beta' ratio, i.e. the square root of the ratio of minimum cross-sectional area to inlet area of a DP meter (dimensionless)
γ	back cone angle of the V-Cone meter (°)
ε	expansibility coefficient for a DP meter (dimensionless)
κ	isentropic exponent (dimensionless)
ρ_g	gas density (kg m^{-3})
ρ_l	liquid density (kg m^{-3})

1. Introduction

Wet gas flow exists in a variety of industrial processes, such as the petroleum industry, chemical industry, nuclear industry, metallurgical industry, so the measurement of wet gas flow is increasingly important [1–4]. According to the American Petroleum Institute (API), wet gas flow is defined as any gas and liquid two-phase flow with the Lockhart–Martinelli parameter (denoted as X_{LM}) less than or equal to 0.3. The Lockhart–Martinelli parameter, a dimensionless number which is commonly used in the investigation on wet gas, is defined as the square root of the ratio of the liquid inertia if the liquid flowed alone in the conduit to the gas inertia if the gas flowed alone in the conduit (see equation (1)). The gas densiometric Froude number, Fr_g, is another important parameter in the wet gas metering. The definition of Fr_g is the square root of the ratio of the gas inertia force to the liquid gravitational force (see equation (2)). In equation (2) the term U_{sg} is the superficial gas velocity, i.e. the average velocity of the gas in the pipe if that phase flowed alone. U_{sg} is calculated using equation (3).

$$X_{\text{LM}} = \frac{m_l}{m_g}\sqrt{\frac{\rho_g}{\rho_l}}, \tag{1}$$

$$Fr_g = \frac{U_{\text{sg}}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}}, \tag{2}$$

$$U_{\text{sg}} = \frac{4m_g}{\pi D^2 \rho_g}, \tag{3}$$

where m_g, m_l are the gas and liquid mass flow rate, respectively, ρ_g and ρ_l are the gas and liquid density, respectively, g is the gravitational constant and D is the internal diameter of the pipe.

Although many methods (e.g. partial separation, isokinetic sampling, vortex meters and ultrasonic meters) are available to meter the wet gas, the majority of wet gas meter designs employ the differential pressure (DP) meter technology including the orifice plate, the Venturi and V-Cone meter [5]. Many investigators such as Murdock [6], Chisholm [7, 8], Smith and Leang [9, 10], Lin [11], de Leeuw [12], Steven and Stewart [13–16] and Dong [17, 18] have explored the DP devices in wet gas (in fact, some of their testing conditions were beyond the range of wet gas flow). They found that DP-based flow meters shared many performance characteristics in wet gas applications. For instance, when used in wet gas flows, all these DP meters produced a higher DP than when used in single-phase gas, i.e. an over-reading. This uncorrected gas mass flow rate prediction is generally referred to as the 'apparent' gas mass flow, $m_{g,\text{apparent}}$, and it is determined in terms of ΔP_{tp} (shown in equation (4)):

$$m_{g,\text{apparent}} = EA_tC_d\varepsilon\sqrt{2\rho_g\Delta P_{\text{tp}}}, \tag{4}$$

where $E = 1/\sqrt{1-\beta^4}$ is the velocity of approach of the DP meter (a geometric constant), $\beta = \sqrt{A_t/A}$ is the square root of the ratio of the minimum cross-sectional area to the inlet area of the DP meter, A_t and A are the minimum cross-sectional area and the pipe cross area, respectively, C_d is the discharge coefficient, ε the expansibility coefficient for the DP meter and ΔP_{tp} is the actual wet gas DP.

Studies have also shown that there are significant differences among the correlations considering over-reading and liquid content for the different types of DP meters. The seven most popular models in wet gas flow metering are tabulated in table 1. Note that for all the correlations in table 1, the gas mass flow rate is predictable only when the information about the liquid mass flow rate or the liquid-to-gas flow rate ratio is initially known. Then the gas mass flow rate is derived by iteration. However, in previous studies on wet

Table 1. Wet gas correlations based on DP devices.

Model	Correlation	Primary element and materials	Test conditions
Homogeneous [5]	$m_g = \frac{m_{g,\text{apparent}}}{\sqrt{1+\left(\sqrt{\rho_g/\rho_l}+\sqrt{\rho_l/\rho_g}\right)X_{\text{LM}}+X_{\text{LM}}^2}}$	–	–
Murdock [6] (1962)	$m_g = \frac{m_{g,\text{apparent}}}{1+1.26X_{\text{LM}}}$	Orifice plate; wet steam, air/water, gas/salt water, gas/liquid hydrocarbon	P: 0.101–6.3 MPa X_{LM}: 0.041–0.25 Re_{sg}: 13 000–1270 000 β: 0.2602–0.5
Chisholm [7, 8] (1967, 1977)	$m_g = \frac{m_{g,\text{apparent}}}{\sqrt{1+CX_{\text{LM}}+X_{\text{LM}}^2}}$, $C = \left(\rho_l/\rho_g\right)^{\frac{1}{4}} + \left(\rho_g/\rho_l\right)^{\frac{1}{4}}$	Orifice plate; steam/water mixtures	P: 1.0–7.0 MPa X_{LM}: 0.5–5.0 β: 0.186–0.498 D: 51 mm
Smith and Leang[a] [9] (1975), Smith *et al* [10] (1977)	$m_g = (\text{BF})\, m_{g,\text{apparent}}$, $\text{BF} = 0.637 + 0.4211x - 0.001\,83/x^2$	Orifice plate; steam/water	P: 0.0827–4.03 MPa x: 0.0061–0.9672 β: 0.1875–0.8303 D: 6.35–168.021 mm
Lin [11] (1982)	$m_g = \frac{EA_tC_d\sqrt{2\rho_g \Delta P_{\text{tp}}}}{1+\theta X_{\text{LM}}}$, $\theta = 1.486\,25 - 9.265\,41\left(\frac{\rho_g}{\rho_l}\right) + 44.6954\left(\frac{\rho_g}{\rho_l}\right)^2 - 60.615\left(\frac{\rho_g}{\rho_l}\right)^3 - 5.129\,66\left(\frac{\rho_g}{\rho_l}\right)^4 + 26.5743\left(\frac{\rho_g}{\rho_l}\right)^5$	Orifice plate; saturated steam; R-113	P: 1.961–2.863 MPa DR: 0.004 55–0.328 x: 0–1.0 β: 0.312, 0.439, 0.625
de Leeuw [12] (1997)	$m_g = m_{g,\text{apparent}} \Big/ \sqrt{1+CX_{\text{LM}}+X_{\text{LM}}^2}$, $C = \left(\rho_l/\rho_g\right)^n + \left(\rho_g/\rho_l\right)^n$ $\begin{cases} n = 0.41, & 0.5 \leqslant Fr_g \leqslant 1.5 \\ n = 0.606\left(1 - e^{-0.746Fr_g}\right), & Fr_g \geqslant 1.5 \end{cases}$	Venturi meter; natural gas/water; nitrogen/diesel oil	P: 1.5–9.8 MPa X_{LM}: 0–0.34 Fr_g: 0.5–4.8 $\beta = 0.401$ D: 101.6 mm
Steven *et al* [14] (2002)	$m_g = \frac{m_{g,\text{apparent}}}{\left(\frac{1+AX+BFr_g}{1+CX+BFr_g}\right)}$, $A = 1.224 + \frac{0.141}{\rho_g/\rho_l}$, $B = -0.0334 - \frac{0.001\,39}{\rho_g/\rho_l}$, $C = \sqrt{0.0805 + \left(\frac{0.0109}{\left(\rho_g/\rho_l\right)^2}\right)}$	V-Cone meter; kerosene/nitrogen; natural gas/water	P: 1.5–6.0 MPa X_{LM}: 0–0.3 $\beta = 0.55$ Fr_g: 0.4–4.0 D: 101.6 mm

[a] The Smith and Leang correlation is created from a collection of orifice plate meter wet saturated steam data sets [9, 10].

gas correlations, the researchers focused mainly on the orifice plate and the Venturi meter, and comparatively less work on the V-Cone meter was published [14, 16, 19–22], though the V-Cone meter had remarkable performance characteristics, including high accuracy, excellent repeatability, wide turndowns, shorter straight length and stable signals [19, 23–27].

The objective of this paper is to develop a new wet gas model for the V-Cone flow meter. We first proposed a new model by defining the two-phase flow coefficient, K, of the meter, and then investigated the effects of the Lockhart–Martinelli parameter (X_{LM}), the operating pressure (P) and the gas densiometric Froude number (Fr_g) on K. Then the exact model for the V-Cone meter in low pressure wet gas flow was obtained. Finally, we compared the new model with other wet gas models.

2. Experimental apparatus

2.1. V-Cone flow meter

Figure 1 shows the sketch of the V-Cone meter used in this study. The pipe diameter, D, is 50 mm, and the diameter ratio, β, is 0.55. The primary element of the V-Cone DP meter is a cone held by a supporting bar downstream of the high pressure port. The cone apex is attached to this supporting bar and points into the flow (with a front cone angle, α). The second cone of

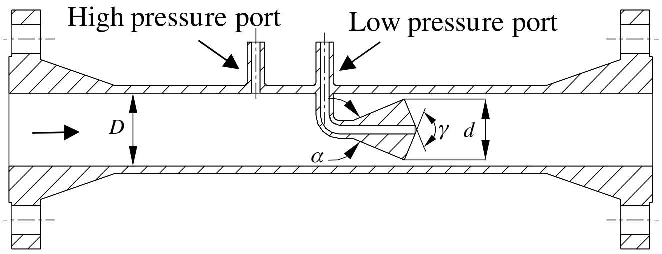

Figure 1. Sketch of the V-Cone DP meter.

shorter length extends from the base of the first upstream cone, hence with the apex pointing downstream (with a back cone angle, γ). The low pressure port extends through the cones and up through the supporting bar. The central line of the cone is aligned with the central line of the pipe. Figure 2 shows a sketch of the V-Cone meter with the primary element exposed.

2.2. Flow loop

The wet gas flow loop in the experiment is shown in figure 3. The compressed air was supplied by the screw compressor and flowed through the cooling and drying unit and then into the air storage tank. Two pin valves were used to regulate the air flow rate. This system could supply clean air with constant pressure and temperature in the test. The Yokogawa vortex flow meter with an uncertainty of 1.0% was employed to meter the gas flow rate. The vortex flow meter was brand new and officially calibrated. Moreover, the pressure and temperature sensors near the flow meter allowed for the correction of flow meter readings to compensate for variations in air density. The measurement uncertainties of the pressure and temperature sensors are 0.1% and 0.2%, respectively. The tap water was supplied from a liquid storage tank by a centrifugal pump. The water flow rate was measured with the Yokogawa electromagnetic flow meter with an uncertainty of 0.1%. The electromagnetic flow meter was calibrated with the weighting method.

The air and liquid mixer was used approximately 50 pipe diameters upstream of the test section. The Rosemount 3051 DP transmitter set for a full scale reading of 12 kPa directly measured the pressure difference of the V-Cone meter. The measurement uncertainty of the DP transmitter is lower than 0.075%. The pressure of the test section was measured using a

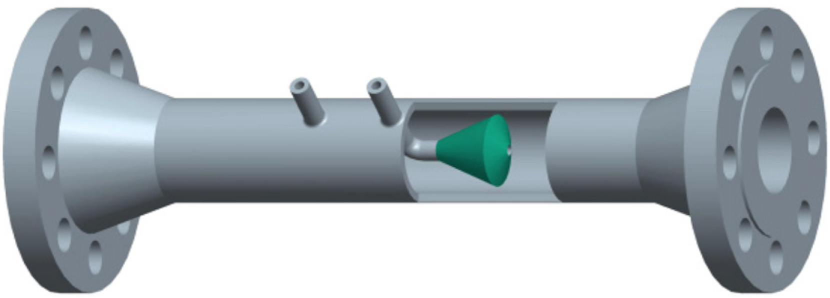

Figure 2. Structure of the V-Cone flow meter.

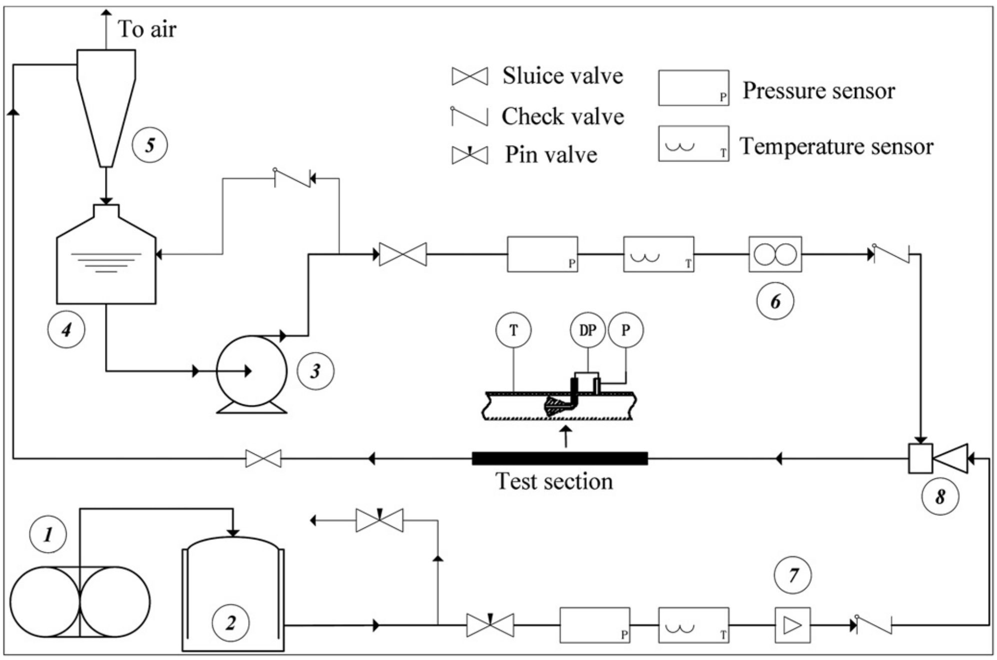

Figure 3. Schematic diagram of the experimental setup: 1—screw compressor, 2—air storage tank, 3—centrifugal pump, 4—liquid storage tank, 5—gas–liquid separator, 6—electromagnetic flow meter, 7—vortex flow meter, 8—gas–liquid mixer.

Table 2. Experimental parameters in present tests.

D (mm)	β	Pressure (MPa)	DR	Fr_g	X_{LM}	GVF (%)
50	0.55	0.10	0.002 31	0.516–1.800	0.003 58–0.142	99.32–100
		0.20	0.003 45	0.423–1.697	0.003 72–0.154	99.11–100
		0.30	0.004 61	0.374–1.478	0.003 81–0.158	98.94–100
		0.40	0.005 75	0.661–1.641	0.003 95–0.0720	99.46–100
		0.48	0.006 66	0.606–1.529	0.004 40–0.0768	99.38–100

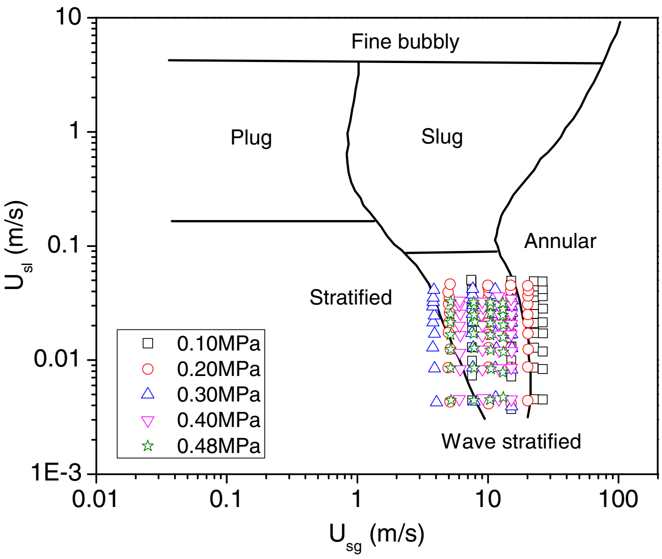

Figure 4. Experimental wet gas flow distribution in the Mandhane flow pattern map [28].

Keller pressure transmitter with a full scale reading of 1.0 MPa and the measurement uncertainty is lower than 0.1%. All the transmitters were brand new and officially calibrated. At the outlet of the experimental pipe a sluice valve regulating the test pressure was installed. Then the gas–liquid mixtures flowed into the gas–liquid separator, and the water returned to the liquid storage tank for recycling while the gas was directly discharged. The data acquisition system is based on the NI USB-6229 data acquisition module and LabVIEW. The experimental parameters are tabulated in table 2. DR is the ratio of the gas density ρ_g to the liquid density ρ_l; GVF is the gas volume fraction under the operating conditions and defined as the ratio of the gas volume flow rate to the total volume flow rate.

The test matrixes distributed in the Mandhane flow pattern map [28] are shown in figure 4. U_{sg} and U_{sl} are the superficial gas and liquid velocity, respectively. The experimental conditions were such as to include stratified flow, wave stratified flow and annular flow, the wave stratified flow being present in most cases.

3. Results and discussions

3.1. K-XLM model

Unlike the orifice plate and the Venturi meter, the V-cone meter is a nonstandard DP meter, so both C_d and ε are not tabulated. Equation (4) is thus reduced to equation (5), and m_{apparent} is the apparent wet gas mass flow rate:

$$m_{\text{apparent}} = EA_t\sqrt{2\rho_g \Delta P_{\text{tp}}}. \tag{5}$$

We define a dimensionless parameter as the two-phase flow coefficient, K, which is the ratio of the total mass flow rate (the sum of the gas and liquid mass flow rates) to the apparent wet gas mass flow rate (see equation (5)). K is calculated using equation (6):

$$K=\frac{m_g + m_l}{m_{\text{apparent}}}. \tag{6}$$

Substituting equations (1) and (5) into (6), we obtain the new correlation as shown in equation (7) based on the two-phase flow coefficient:

$$m_g = \frac{m_{\text{apparent}}K}{1 + X_{\text{LM}}/\sqrt{\rho_g/\rho_l}}. \tag{7}$$

We term this model the K-XLM model. m_{apparent} is calculated from the measured wet gas DP ΔP_{tp} and K is corrected by the experiment.

In the next section, we will discuss the factors influencing K and finally propose the exact correlation to calculate the gas flow rate of the wet gas flow.

3.2. Effects of parameters

Many studies have shown that when the V-Cone meter is used to measure wet gas, the deviation is dependent on the Lockhart–Martinelli parameter (X_{LM}), the operating pressure (P) and the gas densiometric Froude number (Fr_g) [14, 16, 20]. Therefore, we focus our study on the effects of these three parameters.

Figure 5 shows the effect of the Lockhart–Martinelli parameter X_{LM} on the two-phase flow coefficient, K. We can see that K linearly increases with X_{LM}. The relationship between K and X_{LM} has the form given in equation (8), where a is the slope and b is the intercept. The coefficient a is affected by the DR and Fr_g. b equates the dry gas flow coefficient, C, as shown in equation (9).

$$K = aX_{\text{LM}} + b. \tag{8}$$

$$b = C = C_d\varepsilon = \frac{m_g}{m_{g,\text{theoretical}}} = \frac{m_g}{EA_t\sqrt{2\rho_g\Delta P_g}}, \tag{9}$$

where m_g is the gas mass flow rate, $m_{g,\text{theoretical}}$ is obtained from the mass continuity equation and the energy conservation equation and denotes the theoretical gas mass flow rate when the V-Cone meter is used in the gas flow, and ΔP_g is the DP produced by the V-Cone meter.

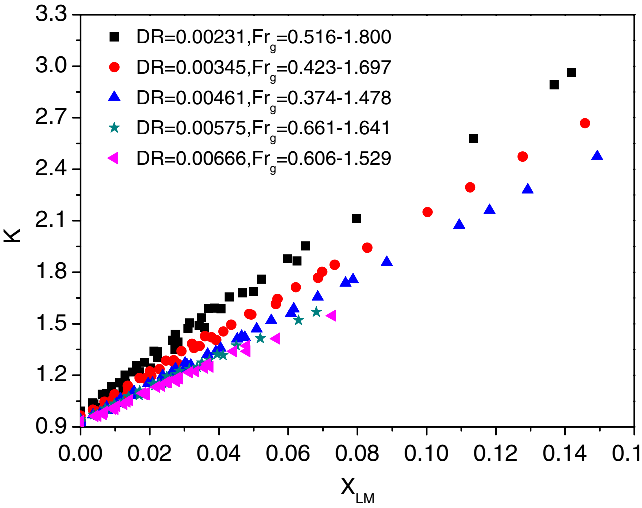

Figure 5. Two-phase flow coefficients for all test data.

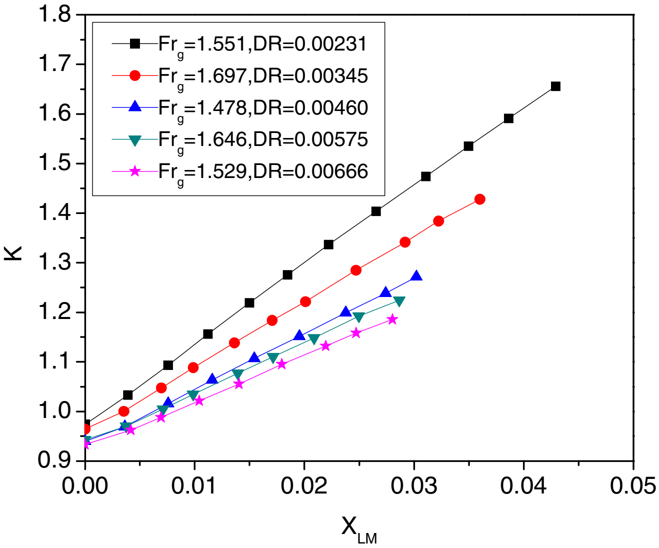

Figure 6. Effects of the ratio of gas density to liquid density on the two-phase flow coefficient.

The effect of the ratio of the gas density to the liquid density (DR) on K is shown in figure 6. K decreases with an increase in the pressure. Hence, the slope a increases as the pressure decreases with other parameters held constant. Figure 7 shows the influence of the gas densiometric Froude number on K at the pressure of 0.40 MPa (DR = 0.005 75). K tends to increase with the gas densiometric Froude number. So the slope a increases with Fr_g at the same pressure.

As shown in equation (9), for the V-Cone flow meter with a constant β, b consists of the discharge coefficient (C_d) and the expansibility coefficient (ε). Stewart *et al* [25, 26] reported that the ε of a V-Cone meter with the constant β is independent of Re and dependent on the DP (ΔP), the operating pressure (P) and the isentropic exponent (κ). ε has the form given in equation (10). Moreover, studies also show that C_d slightly increases with Re with other parameters kept constant [29]. As shown in figure 8, the results in this study agree well with

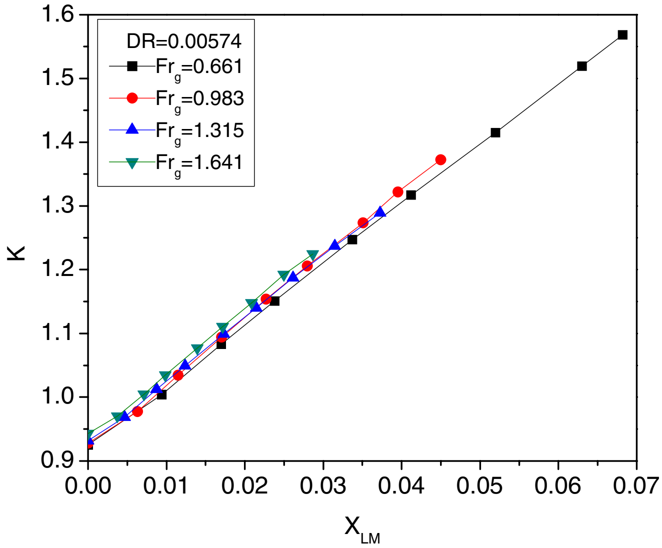

Figure 7. Effects of the gas densiometric Froude number on the two-phase flow coefficient for DR = 0.005 75.

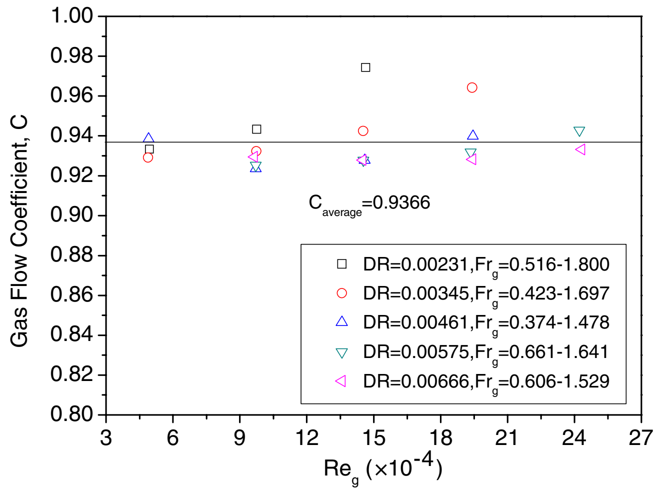

Figure 8. Relationship between gas flow coefficient (C) and gas Reynolds number (Re_g) for different gas-to-liquid density ratios (DR).

those of the previous studies.

$$\varepsilon = 1 + \frac{k}{C_d}\frac{\Delta P}{\kappa P}, \tag{10}$$

where k is the fitting constant. The exact equation forms of ε and the value of C_d are also related to the structure of the V-Cone (which is normally held confidential by the manufacturers and researchers). Given that the scatter of C is not so big in this study, we use the mean value of C (C_{average} = 0.9366) for simplicity. The relative deviation of C ranges from −1.40% to 3.88%, which is also acceptable.

3.3. Fitting coefficient a of the K-XLM model

As shown in figures 5–7, K varies linearly with the Lockhart–Martinelli parameter X_{LM}. The coefficient a is dependent on the gas-to-liquid density ratio (DR) and the gas densiometric Froude number (Fr_g). Figure 9 shows the coefficient a for

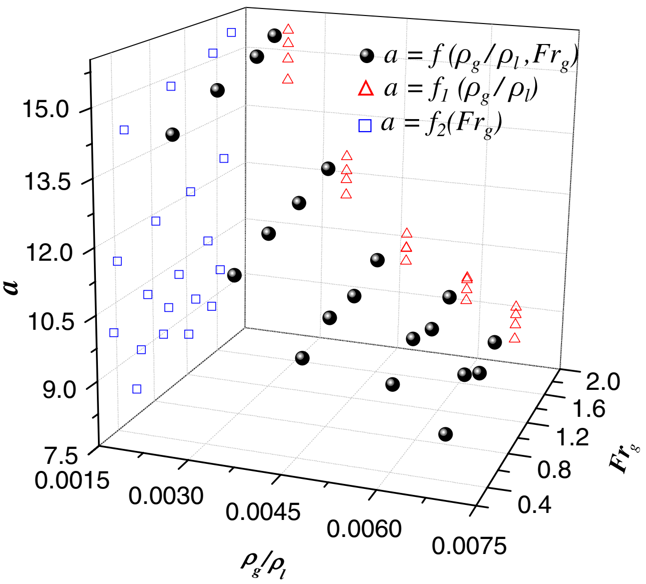

Figure 9. Coefficient a for different DR and Fr_g.

different DR and Fr_g. a is determined in terms of DR and Fr_g as follows:

$$a = -1.066 + \frac{0.723}{\sqrt{\rho_g/\rho_l}} + 0.720 Fr_g. \quad (11)$$

Therefore, the two-phase flow coefficient K is expressed as follows:

$$K = \left(-1.066 + \frac{0.723}{\sqrt{\rho_g/\rho_l}} + 0.720 Fr_g\right) X_{\mathrm{LM}} + 0.9366. \quad (12)$$

Substitute equation (12) into (7), and we obtain the K-XLM wet gas correlation shown in equation (13). The gas mass flow rate is derived by iteration for a known liquid mass flow rate. Note that when the flow is dry gas, i.e. $X_{\mathrm{LM}} = 0$, the K-XLM model is the single-phase gas mass flow rate measurement correlation.

$$m_g = \frac{m_{\mathrm{apparent}}}{1 + X_{\mathrm{LM}}/\sqrt{\rho_g/\rho_l}} \times \left\{\left(-1.066 + \frac{0.723}{\sqrt{\rho_g/\rho_l}} + 0.720 Fr_g\right) X_{\mathrm{LM}} + 0.9366\right\}. \quad (13)$$

3.4. Comparisons of the K-XLM model with other models

Among the models in table 1, the homogeneous model is based on several assumptions and theories and no experimental data are involved, and thus it is applicable for all DP meters; the Murdock, Chisholm, Smith and Leang, Lin and de Leeuw models are developed for the orifice plate meter or the Venturi meter, so these models are non-cone models, and only the Steven model is dedicated to the V-Cone meter.

Comparisons of the K-XLM model with the homogeneous model, five non-cone models and the Steven 0.55 V-Cone model are made under the conditions of the pressure P ranging from 0.10 to 0.48 MPa (the ratio of the gas density to the liquid

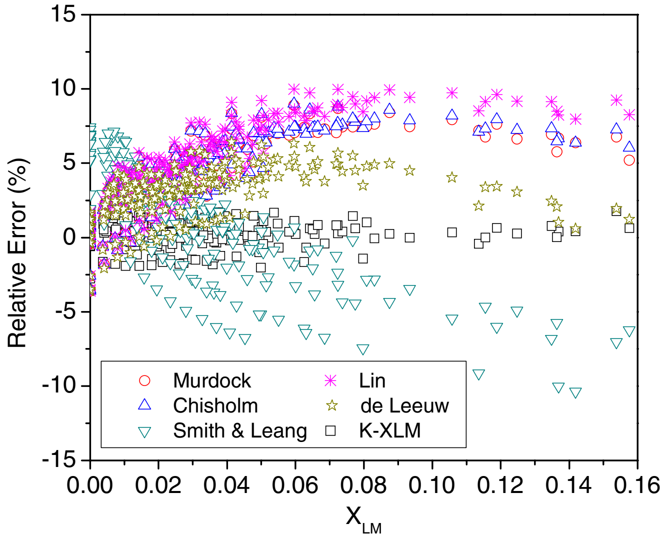

Figure 10. Gas mass flow rate relative error of five non-cone models and K-XLM model.

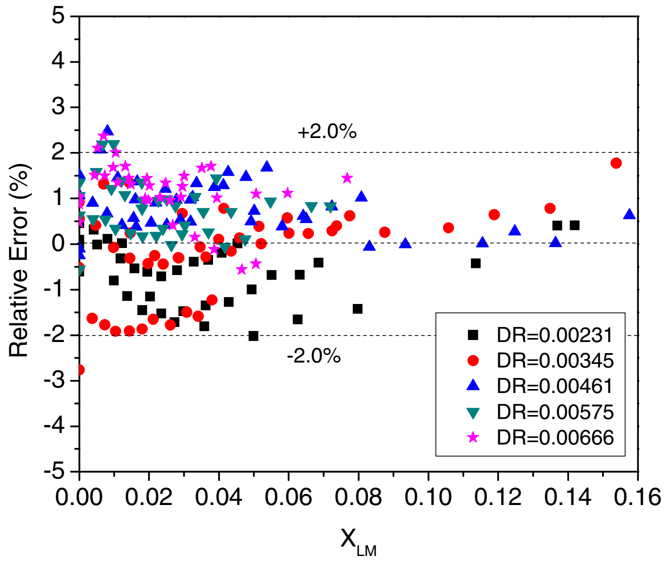

Figure 11. Gas mass flow rate relative error of the K-XLM model.

density DR ranging from 0.0023 to 0.0067), Fr_g from 0.42 to 1.80 and X_{LM} from 0 to 0.16 (see figure 10).

Figure 10 shows the gas mass flow rate relative error predicted by the non-cone models and the K-XLM model. It can be seen that the K-XLM model can accurately predict the gas mass flow rate. As shown in figure 11, the relative error is less than $\pm 2.0\%$ at the confidence level of 95.5%. The K-XLM model proves to be superior to the de Leeuw model, followed by the Smith and Leang model, the Murdock model, the Chisholm model and lastly by the Lin model. The results demonstrate that the wet gas models developed based on orifice plate meters or Venturi meters cannot be reliably applied to V-Cone meters.

The relative errors of the homogeneous model and the Steven 0.55 β V-Cone model are shown in figure 12. Neither of these two models can predict the gas flow rate accurately, and the maximum relative error is as high as 40%. The Steven

Table 3. RMSE of eight models.

Models	K-XLM	de Leeuw	Smith and Leang	Murdock	Chisholm	Lin	Steven	Homogeneous
RMSE	0.0106	0.0344	0.0410	0.0489	0.0501	0.0569	0.1043	0.1313

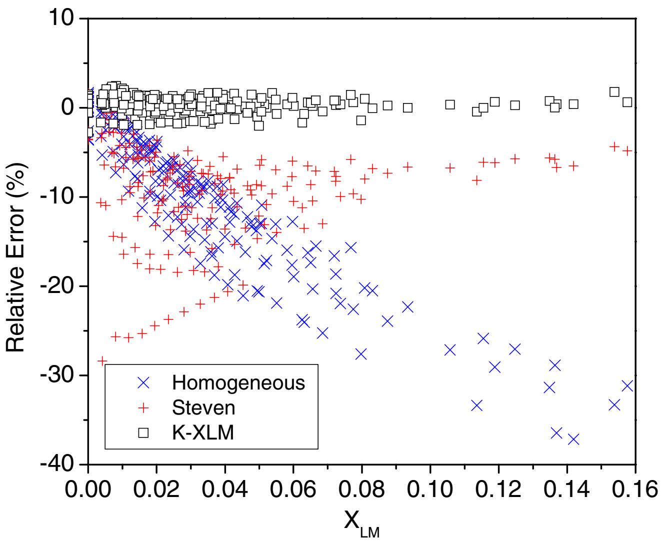

Figure 12. Gas mass flow rate relative error comparisons of three cone models.

model under-predicts the gas flow rate and the maximum relative error is up to –30%. The reason may be that the Steven correlation is a blind data fitted equation at the pressure of 1.5–6.0 MPa [14] and cannot be extrapolated to the low pressure conditions as described in this study. Furthermore, investigations also show that the over-reading of the V-Cone meter is higher under low pressure conditions than that under high pressure conditions [5]; hence it provides a lower prediction in the low pressure tests. In the homogeneous model, the gas and liquid phases are assumed to perfectly mix [5] and thus it is limited to be applied in homogeneous flow. The flow pattern in the present test is not the homogeneous flow pattern (see figure 4), so unsurprisingly, the relative error of the homogeneous model is the maximum among all the models.

The root mean square error (RMSE) of eight models shown in table 3 also clearly indicates the performance of these wet gas models. The RMSE of the gas flow rate is defined as

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{m_{g,\mathrm{predicted}}(i) - m_{g,\mathrm{reference}}(i)}{m_{g,\mathrm{reference}}(i)}\right)^2}, \quad (14)$$

where N is the total number of test data, $m_{g,\mathrm{predicted}}$ is the gas mass flow rate predicted by the wet gas model and $m_{g,\mathrm{reference}}$ is the real gas mass flow rate provided by the gas flow meter.

4. Conclusions

In this paper, we have proposed a two-phase flow coefficient in wet gas flow. The experiments indicate that the two-phase flow coefficient is affected by the Lockhart–Martinelli parameter, the operating pressure and the gas densiometric Froude number. The results show that the two-phase flow coefficient linearly increases with X_{LM} and decreases with an increase in the pressure with other parameters kept constant. In addition, the two-phase flow coefficient also increases with the gas densiometric Froude number at the same pressure. On the basis of the two-phase flow coefficient, the new wet gas correlation for the 0.55 β V-Cone flow meter in low pressure wet gas flow is developed. The new correlation produces more accurate prediction of the wet gas flow than other correlations for the case analyzed. The relative error of the new correlation is within $\pm 2.0\%$ at the confidence level of 95.5%. To further improve the applicability of the proposed model, more investigations on the relationship of the two-phase flow coefficient with different parameters under other conditions, such as high pressure and high X_{LM} ($0.15 \leqslant X_{\mathrm{LM}} \leqslant 0.30$) and different β ratio V-Cone meters, are required. The method for proposing the new correlation can also be applied in the studies on other DP flow meters.

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