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

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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\textsuperscript{3} h\textsuperscript{-1} and from 0.030 to 0.358 m\textsuperscript{3} h\textsuperscript{-1}, respectively. Thus, the Lockhart–Martinelli parameter, $X_{\text{LM,w}}$, 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)

\textbf{Nomenclature}

\textbf{English symbols}

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description (units)</th>
<th>$A_t$</th>
<th>$a$</th>
<th>$b$</th>
<th>$C$</th>
<th>$C_d$</th>
<th>$D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>area of the meter inlet (mm\textsuperscript{2})</td>
<td>minimum cross-sectional area of a differential pressure (DP) meter (mm\textsuperscript{2})</td>
<td>slope in equation (8) (dimensionless)</td>
<td>intercept in equation (8) (dimensionless)</td>
<td>gas flow coefficient (dimensionless)</td>
<td>discharge coefficient of a DP meter (dimensionless)</td>
<td>meter inlet pipe diameter (mm)</td>
</tr>
</tbody>
</table>
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 force to the gas 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).

\[
X_{LM} = \frac{m_l}{m_g} \sqrt{\frac{\rho_g}{\rho_l}},
\]

\[
Fr_g = \frac{U_{sg}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}},
\]

\[
U_{sg} = \frac{4m_{tg}}{\pi D^2 \rho_g},
\]

where \( m_g, m_l \) are the gas and liquid mass flow rate, respectively, \( \rho_g \) and \( \rho_l \) 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, \( m_{g, apparent} \), and it is determined in terms of \( \Delta P_p \) (shown in equation (4)):

\[
m_{g, apparent} = E A C_d \sqrt{2 \rho_g \Delta P_p},
\]

where \( E = 1/\sqrt{1 - \beta^4} \) is the velocity of approach of the DP meter (a geometric constant), \( \beta = \sqrt{A_0/A} \) is the square root of the ratio of the minimum cross-sectional area to the inlet area of the DP meter, \( A_0 \) and \( A \) are the minimum cross-sectional area and the pipe cross area, respectively, \( C_d \) is the discharge coefficient, \( \varepsilon \) is the expansibility coefficient for the DP meter and \( \Delta P_p \) 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
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, \( \beta \), 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, \( \alpha \)). The second cone of...
shorter length extends from the base of the first upstream cone, hence with the apex pointing downstream (with a back cone angle, $\gamma$). 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...
Unlike the orifice plate and the Venturi meter, the V-Cone meter is used in the gas flow, and the measurement uncertainty is lower than 0.1%. All the transmitters were brand new and officially calibrated. At 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. 

<table>
<thead>
<tr>
<th>$D$ (mm)</th>
<th>$\beta$</th>
<th>Pressure (MPa)</th>
<th>DR</th>
<th>$Fr_g$</th>
<th>$X_{LM}$</th>
<th>GVF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.55</td>
<td>0.10</td>
<td>0.00231</td>
<td>0.516–1.800</td>
<td>0.00358–0.142</td>
<td>99.32–100</td>
</tr>
<tr>
<td>0.20</td>
<td>0.00345</td>
<td>0.423–1.697</td>
<td>0.00372–0.154</td>
<td>99.11–100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>0.00461</td>
<td>0.374–1.478</td>
<td>0.00381–0.158</td>
<td>98.94–100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>0.00575</td>
<td>0.661–1.641</td>
<td>0.00395–0.0720</td>
<td>99.46–100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.48</td>
<td>0.00666</td>
<td>0.606–1.529</td>
<td>0.00440–0.0768</td>
<td>99.38–100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.** Experimental parameters in present tests.

Equation (4) is thus reduced to equation (5), and $m_{\text{apparent}}$ is the apparent wet gas mass flow rate:

$$m_{\text{apparent}} = EA_t \sqrt{2 \rho_g \Delta P_g}.$$  \hspace{1cm} (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):

$$K = \frac{m_g + m_l}{m_{\text{apparent}}}.$$ \hspace{1cm} (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:

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

We term this model the K-XLM model. $m_{\text{apparent}}$ is calculated from the measured wet gas DP $\Delta P_g$ 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).

$$K = aX_{LM} + b.$$ \hspace{1cm} (8)

$$b = C = C_X = \frac{m_g}{m_{g,\text{theoretical}}} = \frac{m_g}{EA_t \sqrt{2 \rho_g \Delta P_g}}.$$ \hspace{1cm} (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 $\Delta P_g$ is the DP produced by the V-Cone meter.
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 = 0.00575). $K$ 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 $\beta$, $b$ consists of the discharge coefficient ($C_d$) and the expansibility coefficient ($\varepsilon$). Stewart et al [25, 26] reported that the $\varepsilon$ of a V-Cone meter with the constant $\beta$ is independent of $Re$ and dependent on the DP ($\Delta P$), the operating pressure ($P$) and the isentropic exponent ($\kappa$). $\varepsilon$ 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 those of the previous studies.

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

where $k$ is the fitting constant. The exact equation forms of $\varepsilon$ 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 $C$ ($C_{\text{average}} = 0.9366$) 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...
different DR and Fr_g, a is determined in terms of DR and Fr_g as follows:

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

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

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

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. $X_{LM} = 0$, the K-XLM model is the single-phase gas mass flow rate measurement correlation.

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

### 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 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 $\beta$ 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 model...
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

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{m_{g,\text{predicted}}(i) - m_{g,\text{reference}}(i)}{m_{g,\text{reference}}(i)} \right)^2},
\]

where \(N\) is the total number of test data, \(m_{g,\text{predicted}}\) is the gas mass flow rate predicted by the wet gas model and \(m_{g,\text{reference}}\) 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 \(\beta\) 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 ±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 \(X_{LM} (0.15 < X_{LM} < 0.30)\) and different \(\beta\) 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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