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Error analysis of gas and liquid flow rates metering method based on differential pressure in wet gas

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ABSTRACT

Online measurement of gas and liquid flow rates in wet gas is of great significance in industry. When the differential pressure meter is used to measure the gas and liquid flow rates, an over-reading correlation is needed to correct the liquid-induced overestimation of the gas flow rate and an auxiliary correlation is needed to obtain the liquid fraction or flow rate. With the two correlations incorporated, the gas and liquid flow rates can be calculated. In the present study, error analysis of this metering method is conducted. The results demonstrate that metering methods based on differential pressure exhibit similar error pattern, i.e., the prediction error of gas phase is small while that of the liquid phase is large. This phenomenon can be interpreted by error propagation and the underlying physics is that the two-phase differential pressure is mainly dependent on the gas phase but insensitive to the liquid phase. It is found that both the mean value and the fluctuation of the differential pressure signals are able to reflect flow rate changes of wet gas flow. However, metering methods based on the differential pressure fluctuation present larger prediction errors than that based on the differential pressure mean value. The reason is that the differential pressure fluctuation has much poorer repeatability compared with the differential pressure mean value.

1. Introduction

Wet gas is a subset of gas-liquid two-phase flow, which widely exists in industrial processes, such as oil and gas industry, nuclear industry, and chemistry industry. According to the technical report released by ASME, wet gas refers to gas-liquid two-phase flow with the Lockhart-Martinelli parameter less than or equal to 0.3 [1]. Accurate online measurement of wet gas flow rate is important for engineering and science.

As the most robust and repeatable type of flow meters, differential pressure meters have been widely applied and researched in wet gas flows [2]. However, a problem with differential pressure meters is that the presence of liquid in the gas flow results in a phenomenon termed "over-reading" [1], which is a positive error of gas flow rate prediction. In order to acquire the actual gas flow rate, one common method is to use an over-reading correlation to correct the liquid-induced error. This approach is feasible on condition that the liquid flow rate or some form of liquid fraction information (e.g. the gas mass fraction) is supplied. In general, the liquid fraction is obtained via an auxiliary correlation, which relates the flow rate information of wet gas with a characteristic parameter of the flow. Thus, with the over-reading correlation and the auxiliary correlation incorporated, the gas and liquid flow rates can be predicted simultaneously.

Over the past few decades, many typical over-reading correlations with regard to different throttle devices have been developed, such as Murdock correlation [3], Bizon correlation [4], Chisholm correlation [5], de Leeuw correlation [6], Lin correlation [7] and others, and an enormous amount of researches have been conducted worldwide to improve the performance of these typical correlations [8–13]. As to the auxiliary correlation, the key is to extract characteristic parameters of the flow.

The across throttle device pressure drop, usually termed differential pressure, is a widely used characteristic parameter. Throttle devices with specific geometries produce distinct differential pressure and hence generate distinct over-reading correlations. Therefore, by installing two different throttle devices in series and solving the two combined over-reading correlations, the auxiliary correlation can be obtained. For example, in the work done by Zhang [14], gas and liquid flow rates measurement was achieved in this way. Sometimes, however, distinction between the two over-reading correlations is very small, making the two correlations almost identical. As a consequence, there may be no

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Nomenclature

English symbols

A	area of the meter inlet (m^2)
A_t	cross-sectional area at the throat (m^2)
B	dimensionless parameter in Eq. (13) (–)
C	error transfer coefficient (–)
C_d	discharge coefficient (–)
d_n	coefficient in Eq. (31) (–)
E	velocity of approach, $E = \frac{1}{\sqrt{1-\beta^4}}$ (–)
Fr_g	gas densiometric Froude number (–)
m	mass flow rate (kg/s)
OR	over-reading (–)
P	pressure (Pa)
P_c	confidence level (%)
u	standard uncertainty (–)
U	relative standard uncertainty (–)
U_{sg}	superficial gas velocity (m/s)
x	gas mass fraction (–)
X_{LM}	Lockhart-Martinelli parameter (–)

Greek symbols

β	equivalent diameter ratio, $\beta = \sqrt{\frac{A_t}{A}}$ (–)
δ	deviation
δ_r	relative deviation (%)
ΔP	differential pressure (Pa)
ε	expansibility coefficient (–)
ρ	density (kg/m^3)
σ	standard deviation

Subscripts

app	apparent
ave	average value
g	gas phase
l	liquid phase
max	maximum value
min	minimum value
tp	two-phase/wet gas

solution or more than one solution within a reasonable range [15]. Moreover, this method needs two throttle devices and two differential pressure sensors, thus increasing flow resistance and making the metering system more complicated and costly.

The permanent pressure loss, which has contributed to on-line detection of wet gas [16,17], can also be used as a characteristic parameter to establish the auxiliary correlation. A recent study carried out by Monni [18] applied the permanent pressure loss in Venturi meter to derive flow rates of the gas and liquid phases. However, a drawback of this method is that the permanent pressure loss or pressure loss ratio (the ratio of pressure loss to differential pressure) may not vary monotonously with flow rates in the whole wet gas range [17]. Besides, although only one throttle device is needed when using permanent pressure loss as the characteristic parameter, the metering system still consists of two differential pressure sensors, thus increasing the investment.

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 [19]. In-depth study reveals that the fluctuation contains a wealth of information relevant to the flow, and whereupon the fluctuation can be considered as a characteristic parameter. The differential pressure fluctuation has been applied in flow regime identification [20,21] and aiding wet gas metering [15]. Shaban [22] attempted to measure the gas and liquid flow rates by the application of machine learning techniques to differential pressure signals. Shen [23] managed to measure the gas mass fraction and the total mass flow rate of air-water two-phase flow. Theoretically, once the gas mass fraction and the total mass flow rate were acquired by using differential pressure fluctuation [23], the gas and liquid flow rates could be computed afterwards. Thus, flow rate measurement of the two phases can be implemented by using only one throttle device and one differential pressure sensor, making the metering system simplified and cost-effective.

Electrical parameters, such as the capacitance and the conductance, can act as characteristic parameters as well. Huang [24] used a single-wire capacitance probe to measure the equivalent water layer height in gas-liquid flow. Abbas [25] used a conductance multiphase Venturi meter to measure the gas volume fraction at the inlet and the throat of the Venturi. However, electrical parameters are easily affected by component, salinity and temperature.

When using differential pressure meters to measure the gas and liquid flow rates in wet gas, a widely existed phenomenon is that the prediction error of the gas phase is small while that of the liquid phase is large. Most researchers attempted to improve the measurement accuracy by proposing new correlations [16,17,26]. However, there is no published work conducting error analysis on differential pressure meters to explain this prediction error pattern.

In this study, laboratory experiments are carried out to investigate the application of differential pressure fluctuation in wet gas flow rate measurement. Afterwards, error analysis of metering method based on differential pressure is concluded, aiming at interpreting the prediction error pattern. Finally, characteristics of the differential pressure signals are analyzed and their influences on the gas and liquid flow rates measurement are discussed.

2. Metering method based on differential pressure

When a differential pressure meter is used with wet gas flow, the two-phase differential pressure from the meter is higher than that, which would be read if the gas phase of the wet gas flowed alone [1]. Consequently, the gas mass flow rate prediction due to the two-phase differential pressure, which is generally termed the apparent gas mass flow rate ($m_{g,app}$) (indicated by Eq. (1)), is larger than the actual gas mass flow rate (m_g). Therefore, there is a positive prediction error, usually called the “over-reading (OR)”, as is shown in Eq. (2).

$$m_{g,app} = EC_d\varepsilon A_t\sqrt{2\rho_g\Delta P_{tp}} \tag{1}$$

$$OR = \frac{m_{g,app}}{m_g} \tag{2}$$

where E is the velocity of approach; A_t is the minimum cross-sectional area of a differential pressure meter, sometimes called the “throat”; C_d is the discharge coefficient; ε is the expansibility coefficient; ρ_g is the gas density; ΔP_{tp} is the two-phase (wet gas) differential pressure.

The over-reading denotes influences induced by the liquid phase on the gas phase. Provided that the liquid flow rate or some