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Online measurement of gas and liquid flow rate in wet gas through one V-Cone throttle device

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ABSTRACT

In the present study, an accurate cost-effective online system for metering both the gas flow rate and the liquid flow rate in wet gas with only one V-Cone throttle device is developed. The two-phase mass flow coefficient is employed to correct the measurement deviation of the V-Cone throttle device. The effects of the liquid densiometric Froude number, the gas densiometric Froude number and the ratio of gas density to liquid density on the two-phase mass flow coefficient are experimentally investigated. The equivalent diameter ratio of the V-Cone throttle device is 0.55. The experimental fluids are air and tap water. The operating pressure, the superficial gas velocity and superficial liquid velocity range from 0.1 MPa to 0.3 MPa, 4.87 m/s to 25.26 m/s and 0 to 0.38 m/s, respectively. The results show that the two-phase mass flow coefficient linearly increases with the liquid densiometric Froude number and is affected by the gas densiometric Froude number and the ratio of gas density to liquid density. On the basis of the two-phase mass flow coefficient, the correlation for measuring the gas flow rate of the wet gas is developed. To reflect the influences of the liquid on the measurement, the pressure loss ratio of the V-Cone throttle is proposed. By incorporating the gas measurement correlation of the wet gas, the wet gas correlations to simultaneously meter the gas and liquid flow rate are concluded. In the present cases, the relative error of the gas mass flow rate predicted by the correlations is within ±5.0% and the mean absolute percentage error is 2.52%; the full scale relative error of the liquid mass flow rate is within ±5.0% and the mean absolute percentage error is 7.03%. The method proposed in this study creates a simple inexpensive wet gas metering system that can operate well in a significant range of industrial applications.

1. Introduction

As a distinctive gas-liquid two-phase flow, wet gas is defined as a gas–liquid mixture with the Gas Volume Fraction (GVF) of no less than 95% [1]. It widely exists in industrial processes, particularly in the natural gas industry [2]. The gas flow rate and liquid flow rate of the wet gas are important parameters reflecting the output of a single well and they are also of great significance for accurately measuring the amount of liquid in gas reservoirs, rationally prorating the production and efficiently designing the techniques for increasing production. The development of an accurate and cost-effective online device for measuring the gas and liquid flow rate of wet gas has thereby drawn increasing attention in researches [3].

At present, the commonly-used wet gas meter is the so-called "combined type wet gas meter", which consists of two or more single phase meters (or sensors) combined in series. The majority of these wet gas meters are made up of differential pressure meters (e.g., orifice plate, Venturi meter and V-Cone meter) and other measurement sensors, such as velocity flowmeter, volumetric flowmeter, mass flowmeter, γ ray sensor, microwave sensor, and infrared sensor [3]. Since the 1950 s, researchers have been engaged with the exploration of an online wet gas measurement technology, and many companies and research institutes have developed a variety of devices. The Dualstream II wet gas meter developed by Solartron ISA [4], TTWGF wet gas meter by Tianjin University [5], WGFM wet gas flow meter by Elster-Instromet Ultrasonics [6], MPFM-50 flowmeter by Agar [7], Roxar flow meter by Emerson [8], Haimo wet gas flow meter by Lanzhou Haimo Technologies Co. [9] and Alpha VS/R flow meter by Weatherford [10] are some examples. These existing measurement devices can predict the wet gas accurately, but they are practically limited by

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Nomenclature

English symbols

A	Area of throttle device, $A = \pi D^2/4$ (m^2)
a	Coefficient in Eq. (10) (–)
b	Coefficient in Eq. (10) (–)
C	Coefficient in Eq. (10) (–)
D	Inlet diameter of DP device (m)
d	Maximum diameter of V-Cone (m)
DP	Differential pressure (Pa)
DR	Gas-to-liquid density ratio (–)
FSRE	Full-scale relative error (%)
f	Some function (–)
Fr_g	Gas densiometric Froude number, $Fr_g = \frac{U_{sg}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l-\rho_g}}$ (–)
Fr_l	Liquid densiometric Froude number, $Fr_l = \frac{U_{sl}}{\sqrt{gD}}\sqrt{\frac{\rho_l}{\rho_l-\rho_g}}$ (–)
g	Gravitational constant (m/s^2)
K	Two-phase mass flow coefficient (–)
k	Slope in Eq. (10) (–)
l	Intercept in Eq. (10) (–)
MAPE	Mean absolute percentage error (%)
MRE	Mean relative error (%)
m	Mass flow rate (kg/s)
N	Total number of test data (–)
P	Pressure (Pa)
RE	Relative error (%)
T	Temperature (°C)
U_{sg}	Superficial gas velocity, $U_{sg} = \frac{4m_g}{\pi D^2 \rho_g}$(m/s)
U_{sl}	Superficial liquid velocity, $U_{sl} = \frac{4m_l}{\pi D^2 \rho_l}$ (m/s)

Greek symbols

β	Equivalent diameter ratio, $\beta = \sqrt{\frac{D^2-d^2}{D^2}}$ (–)
δ	Pressure loss ratio (–)
θ	Back-cone angle (°)
ρ	Density (kg/m^3)
φ	Font-cone angle (°)

Subscripts

1, 2 apparent	Different coefficient apparent
g	Gas
l	Liquid
sg	Superficial gas
sl	Superficial liquid
wg	Wet gas

Abbreviation

AF	Annular Flow
GMF	Gas Mass Fraction
GVF	Gas Volume Fraction
LVF	Liquid Volume Fraction
PSF	Pseudo-Slug Flow
RWF	Roll-Wave Flow
STF	Smooth Stratified Flow
WSF	Wave Stratified Flow

their innate disadvantages including complex structure and large size. In addition, some of them contain radiation-emitting devices which render their operation rather difficult. Most importantly, owing to their high price, they are not applicable for such natural gas wells with low production as Sulige gas field which is the largest land gas field in China. To economically exploit this type of oil-gas reservoirs, the inter-well concatenation technology is employed [11]. The lack of an accurate cost-effective online measurement of liquid flow rate and gas flow rate has limited the development of this technology.

The V-Cone throttle device has been widely used in the measurement of single phase gas and liquid flow owing to its high accuracy, wide turndowns, short straight length, excellent repeatability and stable signals [12–15]. In recent years, much research work has been devoted to the measurement of multiphase flow with the V-Cone throttle device [13,16–20]. Deviation was found when the measurement correlation of the single phase flow was used to measure the multiphase flow. Steven et al. [13,19] and He et al. [17] reported that the gas flow rate in wet gas predicted with the gas measurement equation was higher than the actual gas flow rate. The corresponding corrected measurement correlations have been proposed to correct the deviation. But the gas flow rate is predictable only when the information about the liquid flow rate or the liquid phase fraction is initially known with the ray method, the microwave method and the isokinetic sampling method [3], for example. It is still difficult to online measure both the gas flow rate and liquid flow rate by using only one V-Cone throttle device. When the differential pressure (DP) devices (e.g., the orifice plate, the Venturi tube and the V-Cone) are used to measure the wet gas flow, their pressure loss reflects much of the wet gas flow information and it is affected by many flow parameters, including the gas and liquid flow rate, the phase fraction and the gas-to-liquid density ratio [21]. Pressure loss has been used by the Venturi meter to measure the gas flow rate of wet gas [1,21,22], but the liquid flow rate of wet gas is not be metered simultaneously. Steven [23] once pointed out that gas flow rate and liquid flow rate can be measured through appropriate mathematical analysis with the V-Cone meter. When the relationship between pressure loss and liquid flow rate or liquid phase fraction is known, the online measurement of gas flow rate and liquid flow rate can be realized by combining the established corrected measurement correlation [17].

When the V-Cone throttle device is used to measure the single phase flow, the flow rate can be obtained by measuring DP of the V-Cone. In the measurement of the gas-liquid two-phase flow, the V-Cone throttle device will "over-read" the actual gas flow rate. In our previous work [15,24], we proposed a dimensionless parameter called two-phase mass flow coefficient to correct this "over-reading". The results demonstrated that the introduction of the two-phase mass flow coefficient of the V-Cone throttle device made a simple and accurate wet gas measurement correlation feasible. The objective of this paper is to develop an online measurement of gas flow rate and liquid flow rate through only one V-Cone throttle device. A wet gas correlation based on the two-phase mass flow coefficient is developed. Then pressure loss ratio of the V-Cone throttle device is analyzed and a liquid measurement correlation in wet gas is concluded. Finally, the implementation of the measurement is described.

2. Experimental set-up and test section

2.1. V-Cone test section

The sketch of the V-Cone throttle device in this study is shown in Fig. 1(a). The inside diameter of its inlet, D, is 50 mm. The