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An investigation of wet gas over-reading in orifice plates under ultra-low liquid fraction conditions using dimensional analysis

Wuxiao Chen [a, b], Ying Xu [a, b, *], Chao Yuan [a, b], Haitao Wu [a, b], Tao Zhang [a, b]

[a] School of Electrical Engineering and Automation, Tianjin University, Tianjin, China
[b] Key Laboratory for Process Measurement and Control, Tianjin, China

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ABSTRACT

Wet gas represents a special gas-liquid two-phase flow case which is often encountered in the oil and gas industry, such as wet natural gas extraction from a condensate field. The on-line, non-separation measurement of wet gas under ultra-low liquid fraction conditions is an important research area that presents significant technical challenges. In this paper, a method based on dimensional analysis is investigated that may enable predictions of the over-reading parameter in wet gas with liquid fractions less than 0.5% using non-separation measurement. A standard orifice plate with a diameter of 50 mm and a beta ratio of 0.55 was used as the flow measurement device. The dimensional analysis method was used to investigate the flow characteristics of a wet gas flowing through an orifice plate for Lockhart-Martinelli parameters ranging from 0 to 0.08, gas Froude numbers ranging from 0.5 to 2.4 and liquid gas density ratios ranging from 75 to 170. A measurement-based correlation of the wet gas over-reading parameter in an orifice plate is derived using dimensionless parameters combined with physical analysis. The experimental data shows that the relative deviation of this correlation is less than ±2% in experimental verification. The results of this study show that this method can be applied to the non-separation measurement of wet natural gas from the ultra-low liquid fraction of an oil and gas field in the future.

1. Introduction

Wet gas represents a special gas-liquid two phase flow case and is widely encountered in both nature and industry. There is currently no unique, internationally accepted definition of a wet gas. The American Society of Mechanical Engineers (ASME) uses Lockhart-Martinelli parameter of less than 0.3 to define wet gas ISO/TR11583 defines wet gas as a gas-liquid two phase flow in which the gas volume fraction is 95% or greater (ISO, 2012).

Wet natural gas is a typical type of wet gas from oil and gas fields. At present, wet gas flow is commonly measured by the separation method in the oil and gas industry and is expensive as well as inconvenient. Therefore, there is a need to develop on-line and non-separation measurement technologies to determine wet gas flow (ASME, 2008). In general, the liquid volume fraction in wet natural gas is more than 1%. Therefore, some research has been carried out to perform the non-separation measurement (Steven and Hall, 2009). However, with further development technology to exploit petroleum and natural gas, wet natural gas is generally found with a liquid volume fraction lower than 0.5%, such as in the Kela gas field of Tarim Basin. This increases the difficulty of generating accurate measurements because there is such a small amount of liquid. To date, there has been little research regarding the measurement method under these conditions.

An orifice plate is a common throttle flowmeter, which is most frequently used to measure the gas flowrate in the oil and gas industry. When wet gas flows through the orifice plate, the differential pressure induced by the orifice plate is larger than that in an equivalent amount of dry gas. This phenomenon is called over reading (Xu et al., 2013). Since the 1960s, a large amount of research has been carried out on over reading in orifice plates. Murdock (1962) used a large amount of experimental data to fit a semi-empirical correlation for the wet gas measurement in an orifice plate based on the modified separated flow model. A correlation for the wet gas measurement in an orifice plate was given by Chisholm (1977) based on separated flow theory in gas-liquid two-phase flow. In the 1980s, Lin (1982) developed the Z. H. Lin correlation by analyzing gas-liquid two-phase flow experimental data in an orifice

* Corresponding author. School of Electrical Engineering and Automation, Tianjin University, Tianjin, China.
E-mail address: xuying@tju.edu.cn (Y. Xu).

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Nomenclature

English symbols

d	diameter of orifice (m)
D	diameter of pipeline (m)
DP	differential pressure (KPa)
Fr_g	gas Froude number
g	Gravitational acceleration (m/s^2)
K_1	ratio defined in Table 2 (−)
K_2	ratio defined in Table 2 (−)
LMF	liquid mass fraction (%)
LVF	liquid volume fraction (%)
m_g	gas mass flow rate (kg/s)
m_l	liquid mass flow rate (kg/s)
OR	Over-reading defined in Table 2 (−)
P	system pressure (MPa)
Re_{sg}	superficial gas Reynolds number (−)
U_{sg}	superficial gas flow velocity (m/s)
X_{LM}	Lockhart-Martinelli parameter (−)
ΔP_1	DP of orifice plate under wet gas (KPa)
ΔP_2	total pressure loss of orifice plate under wet gas (KPa)
ΔP_g	DP of orifice plate under equal dry gas (KPa)

Greek symbols

α	definite value in Table 2 (−)
β	beta ratio of orifice plate (−)
σ_l	liquid surface tension (N/m)
ρ_g	gas density (kg/m^3)
ρ_l	liquid density (kg/m^3)
μ_g	kinetic viscosity of gas (Pa-s)
μ_l	kinetic viscosity of liquid (Pa-s)

plate. In ISO/TR11583, a correlation for wet gas over reading in an orifice plate was proposed under the given working conditions, namely, a modified Chisholm correlation (ISO, 2012). Steven (2008) introduced dimensional analysis for a throttle flowmeter. In 2014, He and Bai (2014) used dimensional analysis to establish the correlation for the wet gas measurement in a V-cone flowmeter.

A large number of studies on wet gas measurements have been conducted by Tianjin University in recent years. A wet gas measurement method based on differential pressure was proposed by Zhang et al. (2012). The same research team developed a method for making wet gas measurement based on the H correction factor in Venturi (Xu et al., 2014). Tan (2013) presented a correlation for wet gas measurements based on using both an orifice plate and an ultrasonic flowmeter. Yuan et al. (2015) established a wet gas measurement correlation in Venturi meters based on dimensional analysis, which has been successfully applied to the measurement of wet natural gas in the Tarim oilfield.

Although researchers have put forward some measurement correlations, the form of the correlations are similar as most of the coefficients were established by data fitting, leading to a narrow scope of application. Using dimensional analysis for the wet gas measurement is a new attempt. So it requires further analysis and application to be proved feasible. On the basis of previous studies, the method of dimensional analysis is used to investigate the flow characteristics of wet gas flowing through an orifice plate with a liquid fraction lower than 0.5%, combing mechanism analysis with a real flow experiment. The measurement correlation of wet gas over reading in the orifice plate is established based on the dimensionless parameters and is experimentally verified. The prediction errors of the new correlation are compared, providing the foundation for industrial applications, which will allow for the non-separation measurement of wet gas in the ultra-low liquid fraction in the oil and gas field in the future.

2. Theory of dimensional analysis

In this paper, a standard orifice plate is used as the research object. The structure for pressure of this prototype is shown in Fig. 1. Flange taps were designed. According to ISO/TR11583, the first and second pressure tappings that are located in the upstream and downstream of orifice plate, respectively, and the third pressure tapping, which is 6D away from the downstream of orifice plate, are designed (ISO, 2012). The aim was to collect the two-stage differential pressure to measure the wet gas flowrate.

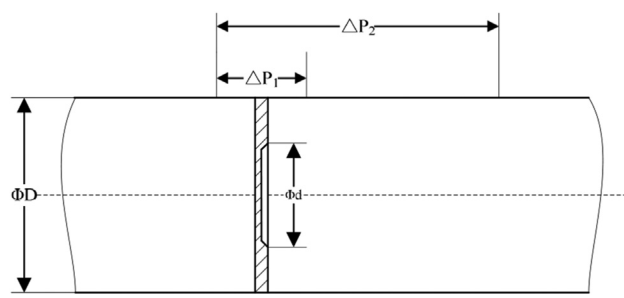

Fig. 1. Structure for pressure of orifice plate.

Complex fluid mechanisms are involved in wet gas measurements. In dimensional analysis, dimensionless parameters are used to establish the correlation that will predict these complex flows. The Buckingham Pi theorem, proposed by Buckingham (1914), is the core of dimensional analysis. It determines the relationship among the physical flow quantities, basic dimensional and dimensionless parameters found in nature. For any given phenomenon, the number of dimensionless parameters related to that phenomenon is equal to the number of physical quantities that affect the phenomenon minus the number of basic dimensional parameters required for the expression of the physical quantities (Tan, 2005).

The physical quantities related to the dimensional analysis of wet gas flowing through an orifice plate are given in Table 1. They are expressed in terms of three basic dimensional parameters: mass (m), length (l) and time (t).

The total number of physical quantities is 13, and the number of dimensionless parameters is $13-3=10$. Selecting D, m_g and ρ_g as the three basic physical quantities, the dimensionless parameters can be derived by the method of undetermined coefficients. According to the Buckingham Pi theorem, any of the dimensionless parameters Π_i ($i=1, 2, \ldots, 10$) can be replaced by combining them with other dimensionless parameters Π_j ($j \neq i$) (Tan, 2005). Therefore, some of these parameters can be recast in terms of commonly used parameters, such as the over-reading parameter, the gas Froude number and the Lockhart-Martinelli parameter. The dimensionless parameters Π_i before and after making these substitutions are shown in Table 2.

According to the Buckingham Pi theorem, we have