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Experimental investigation of wet gas over reading in Venturi

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ABSTRACT

In the present age, wet gas measurement is playing an increasingly significant role in the oil and gas industry. Venturi, a classic single-phase flow meter, proved to be a reliable and accurate wet gas flow meter, but it requires correction. Finding a simple wet gas model of Venturi for all possible applications is a common target of researchers and engineers. In this paper, a double differential pressure Venturi is used to reveal the flow characteristics of wet gas and establish a more accurate correlation that performs well in laboratory and on-site tests. Based on a dimensionless analysis and the experimental data, the essential dimensionless groups in wet gas including the differential pressure ratio, gas liquid density ratio, gas Froude number and Lockhart–Martinelli parameter are studied. By using these crucial parameters, the wet gas correlation is established. The results of the laboratory experiment in the Tianjin University wet gas test loop indicate that the relative deviations of this correlation are better than ±1% and that the standard deviation is 0.34%. Despite the different working conditions of a laboratory and the Tarim oilfield, the usage of the wet gas correlation exhibits a system deviation of 18% and a small dispersion. Thus, after the modification, the relative deviations of cumulative flow are all less than ±1%. There is no denying that this wet gas correlation promotes the development of a widely used correlation to a certain extent and benefits other researchers in wet gas measurement.

1. Introduction

Wet gas flow metering is an important flow measurand in many industries. If a relatively small volume of liquid is present in a gas, it is generally said to be "wet" [1]. The American Petroleum Institute (API) released a report [2] where wet gas flow was defined and characterized. Three different ranges of the Lockhart–Martinelli parameter were identified with regard to wet gas metering systems by the API [2]. They are $X_{LM} \leqslant 0.02$, $0.02 < X_{LM} \leqslant 0.3$, and $X_{LM} > 0.3$. The "Handbook of Multiphase Metering" [3] of the Norwegian Society for Oil and Gas Measurement states that "generally wet gas is defined as gas/liquid systems with a Lockhart–Martinelli parameter smaller than approximately 0.3". In ISO/TR 11583 [4], wet gas is defined as a two-phase flow of gas and liquid in which the flowing fluid mixture consists of gas in the region of 95% volume fraction or more.

Wet gas measurement is becoming more prevalent in the modern oil and gas marketplace. The effect of entrained liquid in gas and its impact on measurement systems is being researched worldwide by various laboratories and joint industry project working groups [5]. To date, the most common method to use in wet gas metering is the gas–liquid separator. Gas and liquid phases are measured in the downstream of the separator by using single-phase flow meters. Despite that, in consideration of the expensive cost of installation and maintenance, the availability of a system for estimating real-time oil, gas and water standard flow rates coming from each well is of primary importance for field operators [6].

Wet gas can be measured by single-phase flow meters such as a Venturi or a V-cone meter. Nevertheless, when single-phase meters such as these are used for wet gas flow measurements, one must correct the standard single-phase measurement models using various models and correction factors to compensate for the presence of liquid in the gas [7]. Due to the presence of a liquid phase, Venturi will give a higher reading than it would for the gas phase flowing alone while metering wet gas; this is what is termed "over reading" of the gas mass flow rate. From the 1960s, many experts investigated the over reading correlations of orifice plates [8–11], V-cones [12–14] and Venturi [15–18]. In recent years, Venturi has become a hotspot in two-phase flow measurement [19], especially in wet gas measurement [20–23].

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Nomenclature

English symbols

A	cross-sectional area of pipeline (m^2)
C	discharge coefficient of Venturi (–)
d	diameter of throat (m)
D	diameter of pipeline (m)
DR	gas liquid density ratio (–)
Fr_g	gas Froude number (–)
GMF	gas mass fraction (%)
GVF	gas volume fraction (%)
g	acceleration of gravity (m/s^2)
H	defined in Table 2 (–)
K_1	ratio defined in Table 2 (–)
K_2	ratio defined in Table 2 (–)
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 (–)
OR_0	initial value of OR (–)
P	system pressure (Pa)
Re_{sg}	superficial gas Reynolds number (–)
RMSD	root-mean-square deviation (–)
U_{sg}	superficial gas flow velocity (m/s)
X_{LM}	Lockhart–Martinelli parameter (–)
ΔP	differential pressure (Pa)
ΔP_1	DP of convergent section (Pa)
ΔP_2	DP of divergent section (Pa)

Greek symbols

β	beta ratio of Venturi (–)
ε	expansion factor (–)
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)

Making a comprehensive survey of these investigations for over reading, it is concluded that researchers attempt to study the vital factors that affect over reading and to make the physical essence of this complex phenomenon clear. Actually, dimensional analysis is a useful tool that can help us determine the important parameters in the process of wet gas measurement. He [24] employed dimensional analysis in the process of wet gas flowing through a V-cone meter and proposed a wet gas metering correlation by using the Lockhart–Martinelli parameter (X_{LM}), gas liquid density ratio (DR), gas Froude number (Fr_g) and beta ratio (β) as the key factors. Steven [25] performed a dimensional analysis of two-phase flow through a horizontally mounted Venturi meter and then derived some important dimensional groups and compared some existing correlations such as Murdock [8], Chisholm [9] and de Leeuw [15] correlations. The use of suitably chosen dimensionless groups is very important in understanding these phenomena and in developing useable two-phase/wet gas flow correlations for differential pressure meters.

This research aims at wet gas flow in a horizontally double differential pressure Venturi tube. Dimensional analysis provides an important way to solve complex problems when there is no available mathematical model. To determine the suitably dimensionless groups and to establish wet gas correlation, a dimensional analysis of this process is presented first. Next, an over reading correlation using the experimental data from the Tianjin University flow laboratory is proposed. Finally, after modification, this correlation is applied in the Tarim oilfield in Xinjiang with a good performance.

2. Dimensional analysis

As a matter of fact, the investigations of some phenomena can be characterized by existing physical and mathematical models or formulas. Meanwhile, a number of complex problems such as wet gas flow cannot be described clearly, making it more necessary than ever to apply dimensional analysis and to design appropriate experimentation to expose cruxes and clarify causality. Revealing the fundamental physical characteristics of problems requires a dimensional analysis and a physical analysis. The dimensional analysis shows a list of dimensionless groups that have an influence on a Venturi meter wet gas flow response. It will be shown that these dimensionless groups can be re-arranged to give a set of dimensionless numbers that include all of the dimensionless numbers currently used by wet gas flow metering researchers. Dimensional analysis is important because it fundamentally proves the validity of using several dimensionless numbers that have been in common use for many years [25]. As mentioned above, the Buckingham Pi theorem [26], the core of dimensional analysis, can help us describe the relationship between all variables and dimensionless parameters in a complicated problem.

In this study, the double differential pressure Venturi tube is applied to collect more efficient parameters in wet gas flow to establish an accurate correlation. The structure of this prototype is shown in Fig. 1. The convergent and divergent angles of the Venturi are 21° and 7.5° respectively. The throat length is d. This Venturi tube has three pressure tappings; hence, the differential pressures of convergent and divergent sections are measured. The first tapping is placed around 0.5D upstream of the beginning of the convergent section. The second one is mounted around 0.5d downstream of the beginning of the throat. The third one is fixed around 6D downstream of the end of the divergent section. Generally speaking, more measurable parameters lead to more options for parameters in correlation and the in-depth understanding of wet gas flow.

As demonstrated in the theory of dimensional analysis, the first step is to list all parameters and state their dimensions. Assume that the surface roughness of this Venturi tube is ignored and that the possible variables listed in Table 1 are expressed by three basic dimensions: mass M, length L and time T.

The number of quantities is $n = 13$, and the number of basic dimensions is $m = 3$. Select three basic quantities $\rho_g(m/l^3), m_g(m/t), D(l)$.

The number of dimensionless groups equals $13 - 3 = 10$. It should be noted that variables $\Pi_1, \Pi_2, \ldots, \Pi_{10}$ are mutually

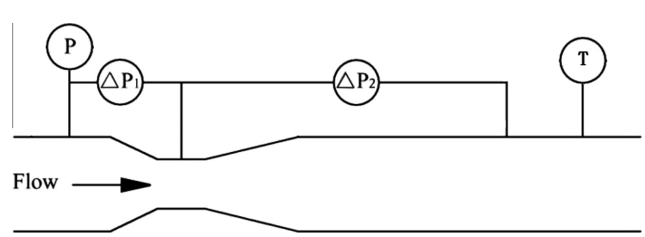

Fig. 1. Structure of the Venturi tube.