Journal of Natural Gas Science and Engineering 24 (2015) 330–336

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Dual-iterative model for gas condensate measurement based on void fraction

Chao Yuan [a, b], Ying Xu [a, b, *], Tao Zhang [a, b], Xili Ba [c], Huaxiang Wang [a, b]

[a] Tianjin Key Laboratory of Process Measurement and Control, Tianjin, China
[b] Academy of Electrical Engineering & Automation, Tianjin University, Tianjin, China
[c] PetroChina Planning & Engineering Institute, Beijing, China

A R T I C L E I N F O

Article history:
Received 17 December 2014
Received in revised form
3 March 2015
Accepted 27 March 2015
Available online 8 April 2015

Keywords:
Gas condensate
Dual-iterative model
Void fraction
Over reading
Venturi

A B S T R A C T

Gas condensate frequently appears in the production of natural gas, and the accurate measurement of this gas–liquid flow, known as wet gas, plays an increasingly significant role in the present age. This study proposed a novel model to measure wet gas based on the void fraction and the Lockhart–Martinelli (L–M) parameter. A vital parameter in two phase flow, the void fraction is not often used in wet gas models because it is difficult to measure. The proposed dual-iterative model attempts to ease this calculation by using an iterative algorithm to obtain the gas phase flow rate. Another complication of existing wet gas correlations is that they require the liquid flow rate to measure the gas flow rate, but this approach is impractical in industrial environments. The proposed dual-iterative model, however, only requires differential pressure ratios and two phase densities, which can be measured accurately and easily. Laboratory results indicate that the relative deviations of the dual-iterative model range from −5.92% to 5.36% with a standard deviation of 1.56%. An on-site test to verify the applicability of the model was conducted at the Petro China's Tarim Oilfield Company and resulted in relative deviations from the cumulative predicted gas flow rate below 5.2% for every well tested.

1. Introduction

Gas/liquid pipe flow with low liquid loading is often encountered in natural gas production wells and transmission pipelines (Zhang and Sarica, 2011). Although natural gas is normally dried by passing through wellhead equipment, the variations of pressure and temperature through transmission pipelines may eventually result in the formation of liquid phase due to retrograde condensation behavior (Talaie and Deilamani, 2014). This results in wet gas, in which the gas phase is continuous and the liquid phase is dispersed. In ISO TR 11583 (ISO, 2012), 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 exists in such industrial process as natural gas, chemical, metallurgy, nuclear energy, aerospace and other fields. With the rapid development of traditional and emerging industries in recent decades, people have increasing demands to measure wet gas accurately.

Researches about Venturi (De Leeuw, 1997; Steven, 2002; Lide et al., 2007; Xu et al., 2011), orifice plate (Murdock, 1962; James, 1965; Lin, 1982; Geng et al., 2007) and V-cone (Stewart et al., 2002; Steven, 2009; He et al., 2012) have proved that differential pressure (DP) meters are convenient and reliable in wet gas measurement. Among these throttle devices, Venturi has minimum permanent pressure loss and no movable part but it gives higher readings to wet gas than to gas alone, which is termed as "over reading" of the gas mass flow rate, due to the presence of liquid phase. Domestic and foreign researchers have carried out a large number of theoretical and experimental studies about over reading since the 1960s. Chisholm (1977) developed the orifice over reading model, which assumes that the phases are distributed separately and gas phase exerts a drag force on liquid phase, by examining flow through a sharp-edged orifice. Steven (2002) applied the NEL data to establish a wet gas correlation. Reader-Harris and Graham (2009) considered that the discharge coefficient in wet gas is not equal to its dry gas value and they established a function between C and L–M parameter, modified the "n" parameter in De Leeuw correlation (De Leeuw, 1997) and derived a new over reading correlation. Xu et al. (2015) studied the effects of flow condition and geometry structure parameter on wet gas performance on Venturi

* Corresponding author. Tianjin Key Laboratory of Process Measurement and Control, Tianjin, China.
E-mail address: xuying@tju.edu.cn (Y. Xu).

http://dx.doi.org/10.1016/j.jngse.2015.03.040
1875-5100/

Nomenclature

English symbols

A	cross sectional area of pipeline (m^2)
a	coefficient in Eq. (11) (−)
b	coefficient in Eq. (11) (−)
C	discharge coefficient (−)
C_{ch}	coefficient in Eq. (1) (−)
c	coefficient in Eq. (11) (−)
D	diameter of pipeline (m)
d	coefficient in Eq. (11) (−)
Fr_g	gas Froude number defined in Eq. (10) (−)
GMF	gas mass fraction (%)
GVF	gas volume fraction (%)
g	acceleration of gravity (m/s^2)
K	ratio defined in Eq. (9) (−)
n	coefficient in Eq. (4) (−)
OR	over reading defined in Eq. (1) (−)
P	system pressure (Pa)
S	slip ratio (−)
U_g	gas flow velocity (m/s)
U_l	liquid flow velocity (m/s)
U_{sg}	superficial gas flow velocity (m/s)
U_{sl}	superficial liquid flow velocity (m/s)
W_g	gas mass flow rate (kg/s)
W_l	liquid mass flow rate (kg/s)
W_m	mass flow rate of two phase mixture (kg/s)
X	Lockhart–Martinelli parameter (−)
x	dryness fraction (−)
ΔP_1	DP of convergent section (Pa)
ΔP_2	DP of divergent section (Pa)
ΔP_3	permanent pressure loss of Venturi (Pa)
ΔP_g	DP of gas phase flow alone (Pa)
ΔP_{tp}	DP of two phase flow (Pa)

Greek symbols

α	void fraction (−)
α_H	void fraction in homogenous flow (−)
β	beta ratio of Venturi (−)
ε	expansion factor (−)
ρ_g	gas density (kg/m^3)
ρ_l	liquid density (kg/m^3)
ρ_m	density of two phase mixture (kg/m^3)

tube, then proposed the “*H*” correction factor for Venturi over reading.

Even though the applied models for Venturi have been studied for a long time, there are still problems that need to be solved. It is generally acknowledged that widely-used correlations such as De Leeuw correlation, can be used to measure the actual gas flow rate in wet gas streams, provided the liquid content is known (De Leeuw, 1997). Nevertheless, in most cases, liquid flow rates cannot be obtained directly.

This study aimed at establishing a wet gas model for industrial application without the use of liquid flow rate. Firstly, Chisholm correlation was analyzed and a new correlation is derived by using void fraction and L–M parameter. Secondly, L–M parameter was correlated through experimental data and the dual-iterative model was established. Finally the dual-iterative model was tested in laboratory and industrial fields.

2. New correlation

In wet gas measurement, Chisholm correlation (Chisholm, 1977) should never be forgotten. Chisholm considered the slip ratio S and established the over reading correlation (Eq. (1)) through the fluid momentum conservation equation based on the separated flow theory.

$$OR = \sqrt{\frac{\Delta P_{tp}}{\Delta P_g}} = \sqrt{1 + C_{ch}X + X^2}$$
$$C_{ch} = \frac{1}{S}\left(\frac{\rho_l}{\rho_g}\right)^{0.5} + S\left(\frac{\rho_g}{\rho_l}\right)^{0.5} \tag{1}$$
$$X = \frac{1-x}{x}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}$$

Chisholm and Rooney (1974) correlated the experimental data from steam/water mixture over the pressure range from 1 to 7 MPa and gave the equation (Eq. (2)) of slip ratio for dryness fraction x up to 0.1.

$$S = \left(\frac{\rho_l}{\rho_{Hom}}\right)^{0.5} = \left[1 + x\left(\frac{\rho_l}{\rho_g} - 1\right)\right]^{0.5} \tag{2}$$

Chisholm pointed out that where $X \le 1$, S was independent of x; where $X > 1$, S was a function of x and was given satisfactorily by Eq. (2). Suppose that S was continuous at $X = 1$, combining $X = 1$ and Eq. (2) gave Eq. (3).

$$S = \left(\frac{\rho_l}{\rho_g}\right)^{0.25} \tag{3}$$

Therefore either when $X \le 1$ (higher x values) or $X > 1$ (lower x values),

$$C_{ch} = \left(\frac{\rho_l}{\rho_g}\right)^{0.25} + \left(\frac{\rho_g}{\rho_l}\right)^{0.25} = \left(\frac{\rho_l}{\rho_g}\right)^{n} + \left(\frac{\rho_g}{\rho_l}\right)^{n}. \tag{4}$$

It is the origin of C_{ch} in the Chisholm over reading correlation.

Chisholm correlation has been extensively studied and developed by many researchers. De Leeuw (1997) first applied it in Venturi tubes, he believed that gas Froude number was another important parameter that affects over reading significantly but not included in the Chisholm correlation. De Leeuw found that the Chisholm correlation can be used to predict wet gas data in Venturi by modifying the C_{ch} appropriately. Reader-Harris and Graham (2009) did a similar work to modify the Chisholm correlation.

However, in the origin Chisholm correlation, Eq. (4) was established based on the empirical equation of slip ratio and the assumptions mentioned above. Therefore we did not correlate “n” but used the origin C_{ch} formula and the definition of S in this study. Assume that the void fraction α was constant, the S and C_{ch} were calculated by Eqs. (5) and (6). And then, the Chisholm correlation was transformed to Eq. (7).

$$S = \frac{U_g}{U_l} = \frac{U_{sg}}{U_{sl}}\frac{1-\alpha}{\alpha} = \frac{W_g}{W_l}\frac{\rho_l}{\rho_g}\frac{1-\alpha}{\alpha} = \frac{x}{1-x}\frac{\rho_l}{\rho_g}\frac{1-\alpha}{\alpha} \tag{5}$$