

Research on the Two-phase Flow Measurement of Condensate Natural Gas

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Abstract: This research is on the implementation of online non-separation flow measurement of gas-liquid two-phase condensate natural gas. The V-cone throttle device, which has the shrinkage characteristics of fluid-flux sectional area along the outside surface of its core and the inside surface of its pipe wall, and the venturi throttle device, which has the shrinkage characteristics of fluid-flux sectional area along the center of its tube, are assembled. Then the two overreading measurement models are built up according to the different characteristics of the two overreading measurement values and their inherent law respectively. Using the iterative correction method repeatedly, the flowrates of the gas-liquid two-phase can be implemented respectively. Taking a prototype with DN80 diameter designed and made for example, with the experimental devices of the wet gas flow measurement, the experimental research and the performance verification of the prototype is carried out in the flow laboratory of TianJin University. The results indicate that the error limits of gas flowrate and liquid flowrate are less than $\pm 2\%$ and less than $\pm 10\%$ respectively. Meantime, a series of experimental research and performance verification are carried out in industrial fields of Southwest oil and gas fields of Petro-China. The results showed that the accumulated flow error of both the gas and the liquid is less than 1% respectively.

Keyword: Condensate Natural Gas; Double Flow Throttle Device; V-Cone; Venturi; Overreading

1. The Definition of Condensation Natural Gas and the Difficulty of Flow Measurement

The Condensation Natural Gas which is also called wet gas, is a particular subset of gas-liquid two phase flow, widespread in natural gas industrial field. This term is used to denote a natural gas flow containing a relative small amount of free liquid (viz. water and hydrocarbon), usually this exceeds the standards of pipe-line transportation. These liquid components are formed due to the reduction of temperature and pressure of the product system, sometimes there may even be sands, slag and the chemical agent that instilled to prevent the hydrate formation in the natural gas well outputs. The behavior of gas and liquid in a flowing pipe exhibit various and complex characteristics depending on the pressure, velocity, and some other parameters, the wet gas may behave as “mist flow”, “annular flow”, “stratified flow” or “slug flow”^[1]. Therefore the metering of wet gas flow is a particular case of multiphase flow measurement. However, the accurate measurement of each phase of a multiphase flow is an arduous work. Currently, the existing measuring techniques generally simplify it as gas-liquid two phase measurement issues, and put emphasis on the measurement of the natural gas well outputs whose GVF usually higher than 90% .

In 2008, Tianjin University developed a condensate natural gas two-phase flow meter called the TTWGF, a new dual differential pressure wet gas metering technique based on the combination of cone and venturi meter was actualized. In this design, peripheral shrinking characteristic of

cone and central shrinking characteristic of venturi are considered, and the two differential pressure devices are mounted in series, applying the difference of the wet gas metering performance of the two meters, the gas and liquid flow rates are solved accurately^[2].

2. The Basic Metering Principle Based on Dual Differential Pressures

In wet gas metering, the lockhart-martinelli parameter is used to indicate the liquid fraction of a wet gas stream, and it is defined as the square root of the ratio of the liquid inertia force if it flowed alone in the conduit to the gas inertia force if it flowed alone in the conduit^[3]. It is denoted here by X and expressed in equation (1) as follows

$$X = \frac{W_l}{W_g} \sqrt{\frac{\rho_g}{\rho_l}} \quad (1)$$

where W_l and W_g are the liquid and gas mass flowrates respectively, ρ_g and ρ_l are gas and liquid densities respectively

The gas densimetric Froude number is defined as the square root of the ratio of the superficial gas inertia force to the liquid gravity force, and is calculated by equation (2), U_{sg} is the superficial gas velocity calculated by equation (3), g is the gravitational constant.

$$F_{rg} = \frac{U_{sg}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} \quad (2)$$

$$U_{sg} = \frac{4W_g}{\rho_g \pi D^2} \quad (3)$$

The uncorrected gas mass flowrate is called apparent gas flowrate. The over-reading is the ratio of the apparent gas flowrate to the actual gas flowrate and is denoted by Φ_g . Equation (4) is the definition of over-reading

$$\Phi_g = \frac{W_p}{W_g} \quad (4)$$

To illustrate the issues in a simple way, the over-reading correlation model of differential pressure meter is expressed in Bizon correlation model^[4] as equation (5)

$$\Phi_{gs} = A + B \cdot X \quad (5)$$

In equation (4) and (5), Φ_g is the actual over-reading and Φ_{gs} is the over-reading calculated by a correlation model respectively, A and B are constant parameter.

By applying placing two different differential pressure flow meters in series, two different apparent gas mass flow rates can be get as equation (6) and equation (7)

$$W_{p1} = \frac{C_1 \cdot \varepsilon_1}{\sqrt{1 - \beta_1^4}} \times \frac{\pi}{4} \beta_1^2 D^2 \times \sqrt{2\Delta P_{p1} \rho_g} \quad (6)$$

$$W_{p2} = \frac{C_2 \cdot \varepsilon_2}{\sqrt{1 - \beta_2^4}} \times \frac{\pi}{4} \beta_2^2 D^2 \times \sqrt{2\Delta P_{p2} \rho_g} \quad (7)$$

For the two meters are closely placed, the slight difference of the lockhart-martinelli parameter due to the pressure changes at the two meters can be neglected. The ratio of two different over-readings can be get as equation (8)

$$K = \frac{W_{tp1}/W_g}{W_{tp2}/W_g} = \frac{\Phi_{g1}}{\Phi_{g2}} \approx \frac{\Phi_{gs1}}{\Phi_{gs2}} = \frac{A_1 + B_1 \cdot X}{A_2 + B_2 \cdot X} \quad (8)$$

By the combination of two correlation models, the lockhart-martinelli parameter can be solved as equation (9)

$$X \approx \frac{A_1 - K \cdot A_2}{K \cdot B_2 - B_1} \quad (9)$$

Finally, the gas flow rate can be solved by applying the correlation as follow

$$W_g \approx \frac{W_{tp1}}{\Phi_{gs1}} = \frac{W_{tp1}}{A_1 + B_1 \cdot X} \quad (10)$$

3. The Dual Differential Pressures Over-reading Characteristic

In order to investigate the over-reading characteristic of cone and venturi, four prototypes with different diameters (DN50/DN65/DN80/DN100) were made. Taking the prototype of DN50 for example, it is comprised of a 0.75 beta ratio wafer cone and a 0.4 beta ratio venturi. Figure 2 shows the over-reading of this prototype at the working condition of 0.2MPa, Froude number from 0.8 to 1.4, lockhart-martinelli parameter from 0 to 0.1. It is shown in this figure that as the lockhart-martinelli increases the over-reading of wafer cone and venturi increase, however, as the Froude number increases the over-reading of venturi increases and inversely the over-reading of cone decreases^[2].

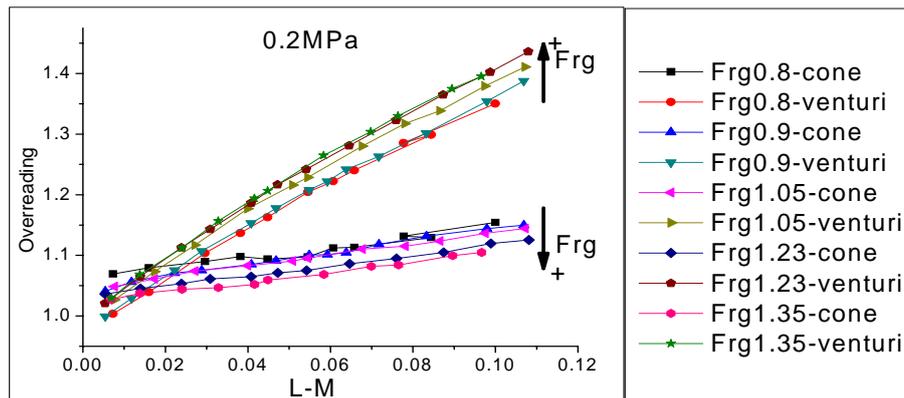


Fig.2 Overreading performance of Wafer-Cone and Venturi device with the beta ratio of 0.75 and 0.4 respectively

Therefore, the correlations of cone and venturi can be well predicted by the data fitting of the lockhart-martinelli parameter, Froude number, and the gas to liquid density ratio. The venturi correlation is based on the de Leeuw style equation^[4] as follow

$$\Phi_{g-venturi} = \sqrt{1 + CX + X^2} \quad (11)$$

where

$$C = \left(\frac{\rho_l}{\rho_g}\right)^n + \left(\frac{\rho_g}{\rho_l}\right)^n$$

$$n = a \cdot Fr_g + b \cdot \sqrt{Fr_g} + c \dots \dots \dots 0.5 \leq Fr_g \leq 1.5$$

The correlation of cone use a linear form for the over-reading of cone has a good linear relationship with the lockhart-martinelli parameter and Froude number. The cone correlation form is as follow

$$\Phi_g = a_2 + b_2 \cdot X + c_2 \cdot X \cdot Fr_g + d_2 \cdot Fr_g + e_2 \left(\frac{\rho_l}{\rho_g}\right) \tag{12}$$

The over-reading prediction errors of wafer cone and venturi devices are shown in figure 3 and 4 respectively. The relative errors of gas flow rates predicted by cone and venturi correlations are within $\pm 2\%$. On the other hand, the Froude number effect is neglected and the over-reading correlations are simplified in the form of equation (5)

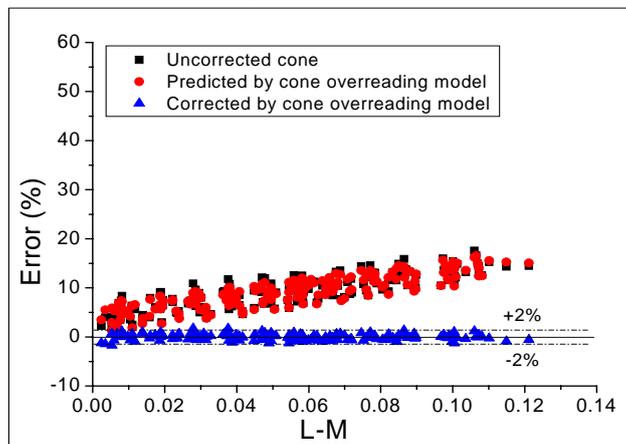


Fig.3 Overreading Prediction error for Wafer-Cone device

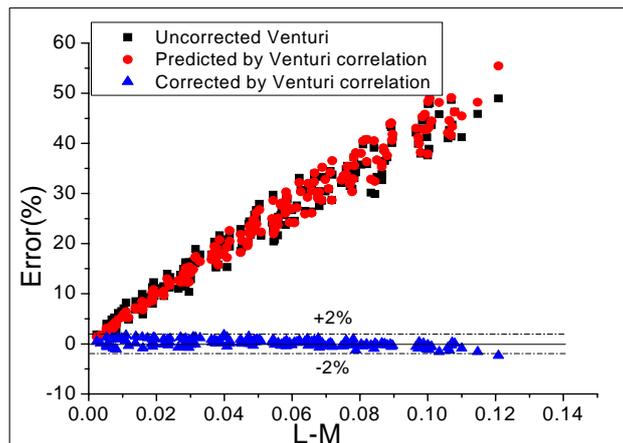


Fig.4 Overreading Prediction error for Venturi device

4. Iteration Correlations Based Metering Algorithm

By the combination of equation (6), (7) and the simplified correlations of cone and venturi, the initial value of gas and liquid flow rates can be solved. Figure 5 shows the relative error of gas initial value

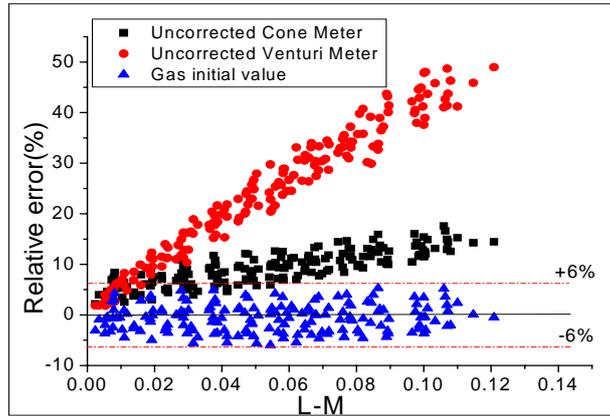


Fig.5 Air phase flow metering relative error of initial value

Then, applying the iterating of the high accuracy correlations of cone and venturi, the initial value of gas and liquid flow rates can be corrected repeatedly until the relative change within 0.1 %. Figure 6 shows the relative error of converged gas flow rate after four steps iterations and figure 7 shows the full scale error of liquid flow rate.

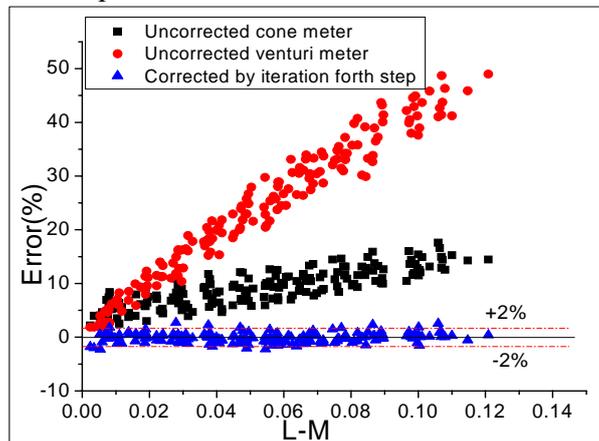


Fig.6 Air phase flow metering relative error after the fourth iteration

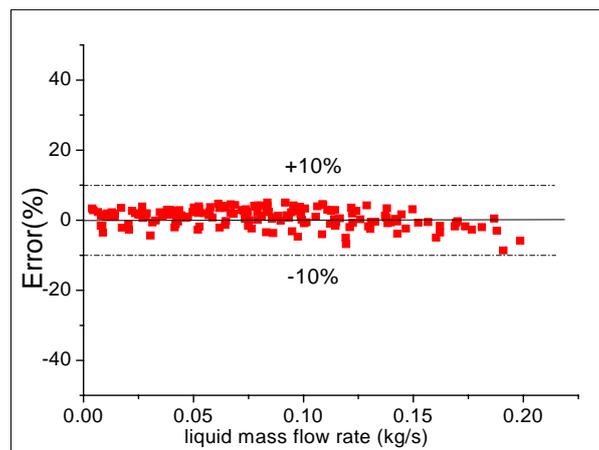


Fig.7 Liquid flow metering error (FS.)

The data result shows that the metering of the gas phase flow rate of the wet gas can be solved accurately by the dual differential pressure device comprised with cone and venturi, the test data is well converged after four steps iterations with a few outliers, the gas flow rate applying this

technique is predicted to within 2% relatively, and the mean relative error of the gas phase flow rate is within 1%. The measurement of liquid flow rate is better than 10% judged by full scale error applying this device and method, which is also with high accuracy.

5. Verification of the Dual Differential Pressure Device Performance

5.1. Laboratory Test

The wet gas measurement performance of this dual differential pressure device has been verified at the laboratory and gas industrial field respectively. Taking the DN80 prototype for example to illustrate as follow

5.1.1. Wet Gas Test Facility of Tianjin University

The laboratory test was carried out at Tianjin University wet gas test loop. The research loop was designed for two-phase flow studies consisting of water and air. Figure 5 is a simplified block diagram that shows the major components of the wet gas research loop. The air used in the test loop is pressurized by two air compressors to nearly 0.8 MPa. The operating pressure range in the test loop is between 0.1 to 0.4 MPa. A vortex gas flow meter measures the mass flow rate of the air before mixing. The water is injected into to the test loop and the pressure of the water is maintained by a water tower. An electromagnetic flow meter measures the mass flow rate of the water. The gas drives the liquid through the test loop by the application of gas dynamic force. The water returned via the separator to the water tank and circulated. The gas is exhausted into the ambient.

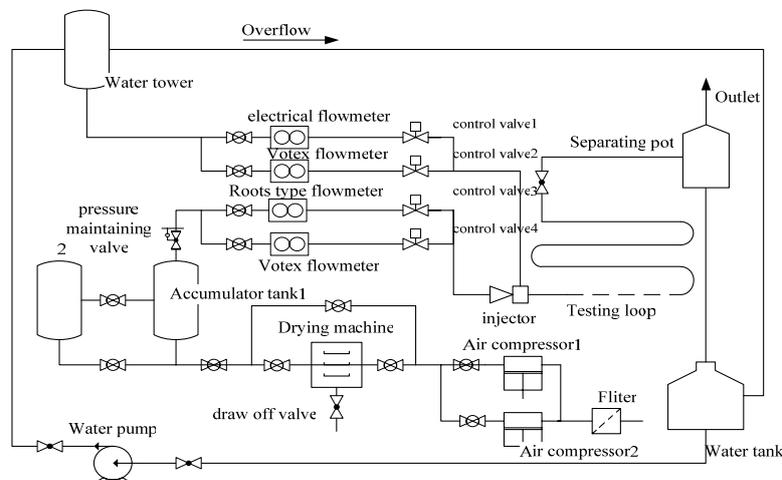


Figure 5 Schematic Diagram of Tianjin University Wet Gas Research Loop

5.1.2. The Laboratory Test Results

The test results show that gas phase flow rate is measured to within 2% relatively for GMF (gas mass fraction) between 60% and 100%, and the liquid phase flow rate is measured to within 10% (full scale error), as it shown in figure 11 and 12 respectively.

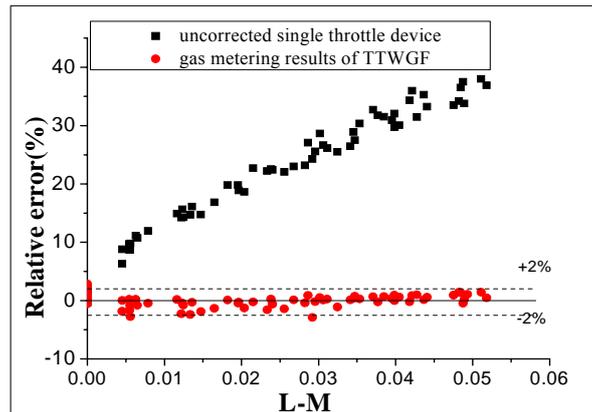


Fig.11 Air phase flow metering relative error for the prototype of DN80

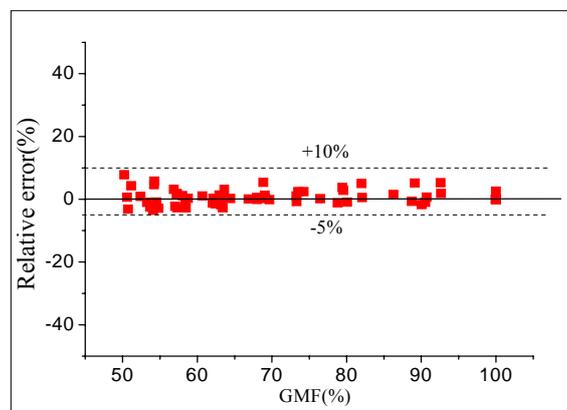


Fig.12 Liquid phase flow metering full scale error for the prototype of DN80

5.2. Natural Gas Industrial Field Test for the Dual Differential Pressure Device

5.2.1. Installation at the Industrial Field and the Comparison Method

From November 2008 to August 2009, Tianjin University tested this prototype of DN80 in real condensate natural gas conditions at a gas-gathering station of Southwest Subsidiary Company of oil and gas field of PetroChina, Sichuan, China. This prototype was positioned at the upstream of a separator, as it shown in figure 13. At the downstream of the separator, an identical dry gas flow Orifice Plate meter was installed according to ISO5167^[5] as a reference meter. There are several gas pipe lines gathered in this gas-gathering station, each of which transports the outputs of one or several gas wells. By the control of the group of switch valves, the fluid of each pipe or the combination of several gas pipes can be controlled to flow through the prototype and the separator. The gas flow rate of the fluid that flows through the prototype was approximately varying from 20000Nm³/d to 100000Nm³/d and the pressure was approximately 3MPa.

The gas metering result of the prototype was compared with that of the dry gas Orifice Plate meter, the uncertainty for Orifice Plate meters with dry gas is 0.5%, and the reference of liquid phase was realized by the volume calculation of the fluid reservoir tank of the separator which is located at the low part of the separator.



Fig.13 Prototype installation in situ.

5.2.2. The Error Calculation Method

The error of cumulate gas flow rate is calculated by equation (13) as follow

$$E_{Q_g} = \frac{\sum_{i=1}^{n=259} q_{gc}(i) - \sum_{i=1}^{n=259} q_{gk}(i)}{\sum_{i=1}^{259} q_{gk}(i)} \times 100\% \quad (13)$$

where $q_{gc}(i)$ is for the gas flow rate measured by the prototype at the order of “i” hour, and $q_{gk}(i)$ is for the gas flow rate measured by the dry gas Orifice Plate meter at the order of “i” hour. The constant “259” is the cumulative hours of comparison.

The error of cumulate liquid flow rate is calculated by equation (14) as follow

$$E_{Q_l} = \frac{\sum_{j=1}^{n=79} q_{lc}(j) - 504 \times 79}{504 \times 79} \times 100\% \quad (14)$$

where the constant “504” is the calculated volume of fluid reservoir tank of the separator, and the constant “79” is the cumulative total number of times the fluid reservoir tank was fully filled.

5.2.3. The Comparison Result of Industrial Field Test

It is listed in table 1 that the gas and liquid flow rates measured by the prototype and the dry gas flow rate measured by the Orifice Plate meter in the hundreds hours of continuous industrial field test. The range of this industrial field test is well expanded by the metering of different wells and the combination of them, and the wet gas metering performance of the prototype is well tested across the full range of wet gas conditions. The test result shows that the cumulate gas metering error is 0.31%, and the cumulate liquid metering error is 0.38%.

Table 1 comparison result

Gas metering Comparison	Orifice Plate (Nm ³)	DN80 prototype	Cumulate error(%)
	515691	517286	0.31%
Liquid metering comparison	Liquid reference	DN80 prototype	Cumulate error(%)
	38067.19Kg	38212.59	0.38%

6. Conclusion

The dual throttling wet gas metering devices comprised of cone with the fluid peripheral shrinking characteristic and venturi with the fluid central shrinking characteristic have significant different responses to wet gas flow. Then the two overreading correlations are built up according to the difference characteristic of the two overreading measurement values and their inherent law respectively

Taking the DN50 prototype for example, this prototype comprised of a 0.75 beta ratio wafer cone and a 0.4 beta ratio venturi, has a high accuracy of gas metering in wet gas flow. Most of the test data is converged after four steps iterations. The gas flow rate is measured to within $\pm 2\%$ and the mean relative error is within 1%.

Taking the DN80 prototype for example, the laboratory test at Tianjin University wet gas test loop shows that the gas flow rate is measured to within $\pm 2\%$, and the full scale error of liquid measurement is less than $\pm 10\%$.

The wet gas performance of this dual throttle wet gas metering device has been confirmed in the industrial field test. The cumulate gas and liquid flow rates is measured to within $\pm 1\%$. The short time slug flow has no significant influence on the metering.

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