

Research on the Flow Characteristics of Low Liquid holdup Gas Liquid Two Phase

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Abstract: With the continuous growth of natural gas demand, the low liquid content gas-liquid two-phase flow characteristics of wet natural gas during pipeline transportation have become a research hotspot. Accurate prediction of pressure drop gradient is crucial for pipeline design, operational safety, and economic benefits. This article summarizes the flow characteristics of gas-liquid two-phase flow with low liquid content in wet natural gas pipelines, and focuses on analyzing the applicability and predictive performance of three typical theoretical models (FLAT model, ARS model, and double circle model). The FLAT model is based on the assumption of a horizontal interface, which is computationally simple but ignores interface fluctuations; The ARS model considers the gas-liquid shear effect and is suitable for low liquid content conditions; The double circle model assumes a more realistic flow through a double arc interface, but the calculation is complex. Research has shown that existing models still have limitations in predicting complex conditions such as inclined pipelines, high flow rates, and droplet entrainment. Future research needs to combine multi-scale simulation, intelligent algorithms, and high-precision experiments to further enhance the universality and engineering applicability of the model. This article provides a systematic reference for the theoretical research and engineering practice of the flow characteristics of wet natural gas pipelines.

Keywords: Wet natural gas; Gas-liquid two-phase flow; Flow characteristics.

1. Introduction

With the rapid development of our country's economy, the demand for energy in our country is also increasing. At the same time, due to the increasingly tight and scarce non renewable resources such as oil and natural gas, the extraction and transportation of natural gas have received more and more attention. After natural gas is extracted from gas wells, it is often accompanied by components such as free water, water vapor, and liquid hydrocarbons. This type of natural gas is called wet natural gas.

At present, the exploration and development of oil and gas resources in China are gradually shifting towards unmanned areas such as deserts and oceans, and many large-scale oil and gas reservoirs have been detected. In order to transport the extracted oil and gas resources to downstream users, the following two transportation methods are generally adopted: the first is to establish a gas processing plant around the well site to separate the wet natural gas (also known as condensate gas) extracted from the gas well into condensate oil and dry natural gas, and then transport it in a single-phase manner. The second method is to not separate the wet natural gas extracted from the gas well first, and use the pressure at the wellhead to transport the wet natural gas through a long-distance pipeline to a gas treatment plant near downstream users for processing.

The first wet natural gas processing method requires the construction of corresponding natural gas processing equipment and related operators near the oil and gas field. As natural gas extraction gradually shifts to areas with harsh natural environments such as deserts and oceans, adopting the first treatment method will undoubtedly increase the cost of natural gas extraction and reduce its economic benefits. Therefore, in order to reduce the extraction cost of enterprises,

the second treatment method is generally adopted, which first transports wet natural gas to downstream users for processing.

Long distance pipeline transportation of wet natural gas reduces extraction costs, but during the natural gas transportation process, with changes in temperature, pressure, and other parameters along the pipeline, liquids such as condensate may precipitate inside the pipeline. [1-3] The precipitated liquid deposits in the low-lying areas of the pipeline, forming a liquid accumulation that can affect the efficiency of natural gas pipeline transportation, corrode the pipeline, and even cause ice blockage and accidents in severe cases. Even single-phase natural gas will precipitate liquid in the pipeline during transportation when the temperature inside the pipeline is lower than the saturation temperature of water vapor or the dew point of heavy hydrocarbons.

During the transportation of wet natural gas, the released liquid can affect the safe and stable operation of the entire pipeline, and even cause corresponding economic losses. Natural gas transmission pipelines often pass through areas with undulating terrain, causing downward and upward tilting of the pipeline. When the gas velocity is lower than the critical liquid carrying velocity of the pipeline, it will accumulate in low-lying areas of the pipeline, forming liquid accumulation and causing a series of problems [4,5].

When the transportation speed of natural gas is higher than the critical liquid carrying velocity of natural gas, the liquid deposited in the low-lying area of the pipeline will be carried by the natural gas and transported along the pipeline with the gas, forming a gas-liquid two-phase flow. Therefore, natural gas pipeline flow belongs to the category of multiphase flow, and its flow state is relatively complex, which is an urgent issue in contemporary oil and gas industry production. Therefore, countries with relatively developed petroleum industries have invested a large amount of material and

human resources in recent decades to study the characteristics of gas-liquid two-phase flow in natural gas transmission pipelines.

The hydraulic characteristics such as pressure drop and liquid holdup play a very important role in the design and safe operation of condensate natural gas pipelines. Studies have shown that the presence of a small amount of liquid can have a significant impact on the flow of gas phase in pipelines. Hart et al. [6] pointed out that the pressure drop of natural gas containing 0.5% condensate is 30% higher than that of single-phase natural gas. Therefore, the low content of liquid in pipelines has a significant impact on the transport capacity and efficiency of natural gas transportation systems. Accurate prediction of liquid holdup and pressure drop in gas-liquid two-phase flow under operating conditions is of great significance for pipeline size design and selection of compression equipment. At the same time, the liquid holdup rate is also an important parameter that determines the frequency of natural gas pipeline cleaning and the design of downstream equipment. It has significant reference value for analyzing pipeline corrosion, wear, paraffin deposition, and hydrate formation.

Therefore, it is of great significance to conduct in-depth research on the flow characteristics of liquid accumulation in low-lying areas of wet natural gas pipelines during transportation, accurately predict the critical liquid carrying velocity, pipeline pressure drop gradient, and liquid holdup characteristics of pipeline liquid accumulation [7-9]. It can not only reduce costs for enterprises, but also reduce resource waste for the country, which has significant economic and social significance.

2. Low Liquid Content Gas Liquid Two Phase Flow Model

The shape of the gas-liquid interface is an important factor in studying the flow characteristics of low liquid content gas-liquid two-phase flow in wet natural gas pipelines, and is crucial for predicting critical liquid carrying velocity, pressure drop, and holdup. When the gas phase flow rate is high, the gas-liquid interface will bend, and the interface shape is therefore very different from the flat interface assumption of the basic two fluid model. Researchers have not yet reached a consensus on how to determine the interface shape. [10] Due to the shear effect of high-speed airflow, a large number of small droplets appear in the wavy stratified flow. The mechanism of droplet carrying and deposition makes the interface rougher. Therefore, how to better predict the basic flow parameters after determining the interface shape requires comprehensive consideration of various factors such as interface friction and droplet entrainment in theoretical calculations. And different phase interfaces correspond to different wet wall fractions, interface perimeters, and friction coefficients. And the closed form relationships of these parameters are essential for predicting pressure drop and holdup. Domestic and foreign scholars have successively established different interface shape models (Figure 2-1) to study the flow characteristics of gas-liquid two-phase stratification.

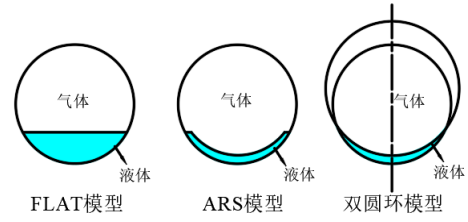


Figure 2-1. Schematic diagram of different gas-liquid interface shapes

2.1. FLAT Model

In 1976, Taitel and Dukler first proposed the FLAT model, an interface shape model for gas-liquid two-phase laminar flow, which assumes that the gas-liquid interface shape during the flow process is horizontal, as shown in the above figure.

Liquid phase channel area:

$$A_L = 0.25d^2 \left[\pi - \cos^{-1} \left(2 \frac{h_L}{d} - 1 \right) + \left(2 \frac{h_L}{d} - 1 \right) \sqrt{1 - \left(2 \frac{h_L}{d} - 1 \right)^2} \right] \quad (1)$$

Gas phase flow channel area:

$$A_G = A - \left\{ 0.25d^2 \left[\pi - \cos^{-1} \left(2 \frac{h_L}{d} - 1 \right) + \left(2 \frac{h_L}{d} - 1 \right) \sqrt{1 - \left(2 \frac{h_L}{d} - 1 \right)^2} \right] \right\} \quad (2)$$

Pipeline cross-sectional area:

$$A = \frac{1}{4} \pi d^2 \quad (3)$$

Liquid phase wetting circumference:

$$S_L = d \left[\pi - \cos^{-1} \left(2 \frac{h_L}{d} - 1 \right) \right] \quad (4)$$

Gas phase wetting circumference:

$$S_G = S - \left\{ d \left[\pi - \cos^{-1} \left(2 \frac{h_L}{d} - 1 \right) \right] \right\} \quad (5)$$

Pipeline cross-sectional circumference:

$$S = \pi d \quad (6)$$

Wetting circumference at gas-liquid interface:

$$S_i = d \sqrt{1 - \left(2 \frac{h_L}{d} - 1 \right)^2} \quad (7)$$

In the formula, represents the height of the bottom liquid film, m.

2.2. ARS Model

In 1989, Hart proposed a new interface shape model called ARS (Apparel Rough Surface) model for low liquid holdup ($H_L < 0.06$), and established a correlation between frictional pressure drop and liquid holdup in horizontal gas-liquid pipe flow based on this model.

Liquid phase wet wall fraction: Hart pointed out that when the gas phase flow rate is low, the liquid phase wet wall fraction can be calculated by the following formula

$$\Theta = 0.52H_L^{0.374} + 0.26Fr_L^{0.58} \quad (8)$$

In the formula, Θ represents the wet wall fraction of the liquid phase, dimensionless, and Fr_L represents the Froude number of the liquid phase, dimensionless.

Liquid phase Froude number:

$$Fr_L = \frac{\rho_L u_L^2}{(\rho_L - \rho_G)gd} \quad (9)$$

In the formula, d represents the inner diameter of the pipeline, m; g represents the acceleration due to gravity, m^2/s .

Liquid phase channel area:

$$A_L = H_L \frac{\pi}{4} d^2 \quad (10)$$

Gas phase flow channel area:

$$A_G = (1.0 - H_L) \frac{\pi}{4} D^2 \quad (11)$$

Liquid phase wetting circumference:

$$S_L = \Theta \pi d \quad (12)$$

Wetting circumference at gas-liquid interface: Hart pointed out that in the ARS model, the thickness of the liquid film at the pipe wall is much smaller than the inner diameter of the pipeline, so the wetting circumference at the gas-liquid interface in the ARS model can be approximately equal to the wetting circumference of the liquid phase;

$$S_i = S_L \quad (13)$$

Liquid phase wetting circumference:

$$S_G = (1.0 - \Theta) \pi d \quad (14)$$

Friction factor at the gas wall:

$$f_G = \frac{0.07725}{\left[\log_{10} \left(\frac{Re_G}{7} \right) \right]^2} \quad (15)$$

In the equation, represents the gas phase Reynolds number, which is dimensionless.

Gas phase Reynolds number:

$$Re_G = \frac{dV_{SG}\rho_G}{(1.0 - H_L)\mu_G} \quad (16)$$

In the formula, μ_G represents the gas-phase dynamic viscosity, Pa•s

Friction factor at gas-liquid interface:

$$f_i = \frac{0.0625}{\left[\log_{10} \left(\frac{15}{Re_G} + \frac{k}{3.715d} \right) \right]^2} \quad (17)$$

In the formula, k/d represents the relative roughness of the pipeline, which is dimensionless.

Pipeline roughness:

$$k = \delta_{MAX} - \delta_{MIN} \approx 2.3\delta \quad (18)$$

δ represents the average thickness of the liquid film at the pipe wall, m.

Average thickness of liquid film:

$$\delta = \frac{H_L d}{4\Theta} \quad (19)$$

Friction factor at the liquid wall:

$$f_L = f_i \cdot 108 Re_{SL}^{-0.726} \quad (20)$$

In the equation, represents the apparent Reynolds number in the liquid phase,

$$Re_{SL} = \frac{\rho_L V_{SL} d}{\mu_L} \quad (21)$$

2.3. Double circle model

In 1997, Chen et al. proposed the Double Circle model and theoretically studied the liquid holdup and pressure drop of gas-liquid two-phase stratified wavy flow in horizontal pipes under low liquid holdup. The model suggests that the interface shape of gas-liquid two-phase flow is a double circle.

According to the empirical relationship proposed by Hart et al. [27] (1989) based on experimental data, the wet wall fraction of the pipeline can be calculated based on the liquid holdup H_L :

$$\Theta = 0.52H_L^{0.374} + 0.26Fr_L^{0.58} \quad (22)$$

Liquid phase Froude number:

$$Fr_L = \frac{\rho_L u_L^2}{(\rho_L - \rho_G)gd} \quad (23)$$

Liquid holding capacity;

$$H_L = \frac{A_L}{A} \quad (24)$$

According to the geometric relationship in the double ring, the liquid phase flow channel area can be obtained:

$$A_L = \frac{\pi D_1^2}{4} \frac{2\theta_1}{2\pi} - \left(\frac{\pi D_2^2}{4} \frac{2\theta_2}{2\pi} - \frac{1}{4} D_1 D_2 (\theta_1 - \theta_2) \right) \quad (25)$$

According to the definition of liquid holding capacity:

$$A_L = H_L \frac{\pi D_1^2}{4} \quad (26)$$

Based on the geometric relationship of double circular rings, the relationship between pipeline diameter, circular ring diameter, and central angle can be obtained:

$$\frac{D_1}{2} \sin \theta_1 = \frac{D_2}{2} \sin \theta_2 \quad (27)$$

From the above equation, we can obtain:

$$\theta_2 = \left(\frac{\sin \theta_2}{\sin \theta_1} \right)^2 \left(\theta_1 + \frac{\sin^2 \theta_1}{\tan \theta_2} - \frac{1}{2} \sin(2\theta_1) - \pi H_L \right) \quad (28)$$

Gas phase flow channel area:

$$A_G = (1.0 - H_L) \frac{\pi D_1^2}{4} \quad (29)$$

Liquid phase wetting circumference:

$$S_L = \Theta \pi D_1 \quad (30)$$

Gas phase wetting circumference:

$$S_G = (1.0 - \Theta) \pi D_1 \quad (31)$$

Diameter of the circular ring:

$$D_2 = D_1 \frac{\sin \theta_1}{\sin \theta_2} \quad (32)$$

Wetting circumference at gas-liquid interface:

$$S_i = D_2 \theta_2 \quad (33)$$

Thickness of liquid film at the bottom of the pipeline:

$$h_L = \frac{D_1}{2} (1 - \cos \theta_1) - \frac{D_2}{2} (1 - \cos \theta_2) \quad (34)$$

Friction factor at the liquid wall:

$$f_L = \frac{16}{Re_L} \quad Re_L \leq 2000 \quad (35)$$

$$f_L = 0.046 Re_L^{-0.2} \quad Re_L > 2000 \quad (36)$$

In the equation, Re_L represents the liquid phase Reynolds number, which is dimensionless.

$$Re_L = \frac{\rho_L V_{SL} d_L}{\mu_L H_L} \quad (37)$$

In the formula, d_L represents the diameter of the liquid phase water, dimensionless.

$$d_L = \frac{4A_L}{S_L} \quad (38)$$

Friction factor at the gas wall:

In the equation, Re_G represents the gas phase apparent Reynolds number

$$Re_G = \frac{\rho_L V_{SG} d_G}{\mu_G (1.0 - H_L)} \quad (39)$$

In the formula, d_G represents the gas phase hydraulic diameter, dimensionless.

Gas phase hydraulic diameter:

$$d_G = \frac{4A_G}{S_G + S_i} \quad (40)$$

Friction factor at gas-liquid interface:

$$\frac{f_i}{f_G} = 1.0 + 3.75 \left(\frac{H_L}{\Theta} \right)^{0.2} \left(\frac{V_{SG}}{V_{SG,t}} - 1 \right)^{0.08} \quad (41)$$

3. Results and Discussion

This article studies the flow characteristics of gas-liquid two-phase flow with low liquid content in wet natural gas pipelines, with a focus on analyzing the performance of FLAT model, ARS model, and Double Circle model in predicting pressure gradients. This article uses experimental data from Mantilla et al. for analysis^[11].

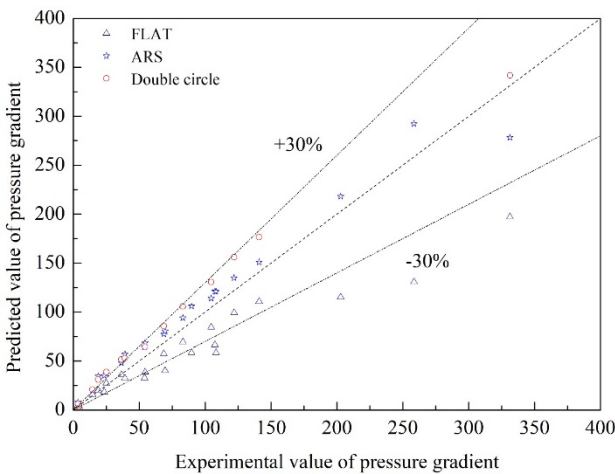


Figure 2-1. Comparison of Model Prediction Results

The FLAT model assumes that the gas-liquid interface is a horizontal plane, simplifying the calculation of geometric parameters such as wetted perimeter and flow area, and is suitable for gas-liquid two-phase flow under low velocity and

laminar conditions. It has high computational efficiency and a clear theoretical foundation. However, it ignores interface fluctuations and has significant prediction errors under turbulent or high gas velocity conditions.

The ARS model more accurately describes the effect of gas-liquid shear on pressure gradient. However, its application is limited and only suitable for low liquid content conditions, without considering droplet entrainment.

The double circle model assumes that the gas-liquid interface is a double circular arc shape, which is closer to the geometric characteristics of actual flow. It can calculate the liquid holdup and wetted perimeter more accurately. The interface shape parameters can be dynamically adjusted. However, its computational complexity is high and lacks universality.

As shown in Figure 2-1, the prediction of pressure gradient in horizontal pipelines must take into account the accurate prediction of shear stress, which has a significant impact on model prediction.

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