



# Study On Gas-Liquid Two-Phase Flow Characteristics of Low Liquid Holding Capacity In Micro-Inclined Pipelines

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## ABSTRACT

With the expansion of oil and gas resource development to complex terrain areas, the problem of gas-liquid two-phase flow in long-distance pipeline transportation of wet natural gas has become a core concern in the industry. This article systematically reviews the research progress on the flow characteristics, critical liquid carrying velocity, pressure drop, and holdup prediction models of gas-liquid two-phase flow in response to the decrease in transportation efficiency and safety risks caused by liquid accumulation in low-lying areas of wet natural gas pipelines. Research has shown that existing achievements have preliminarily revealed the dynamic mechanism of fluid accumulation and airflow carrying, but there is still a lack of systematic research on the non-uniformity of flow in complex terrains, the universality of models for high-pressure conditions with large pipe diameters, and droplet entrainment effects. Domestic and foreign experimental and theoretical models (such as laminar flow model and ARS interface model) provide a basis for parameter prediction, but the limitations of experimental conditions and the closure problem of interface parameters restrict engineering applications. Future research needs to integrate fractal theory, high-speed measurement technology, and deep learning algorithms to construct a cross scale gas-liquid interface dynamic model, strengthen the coupling mechanism of multiple physical processes, and verify actual pipeline data to improve the accuracy of pipeline design and operation optimization. This review provides direction references for theoretical breakthroughs and technological innovations in the safe and efficient transportation of wet natural gas pipelines

## KEYWORDS

Micro-Inclined Pipelines; Low Liquid; Two-Phase.

## 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. 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.

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. 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. It can not only reduce costs for enterprises, but also reduce resource waste for the country, which has significant economic and social significance.

## 2. CURRENT RESEARCH STATUS OF TWO-PHASE FLOW

### 2.1. Study on Liquid Accumulation and Critical Liquid Carrying Velocity in Wet Natural Gas Pipelines

The flow characteristics of liquid accumulation in wet natural pipelines are a very complex and special flow phenomenon in gas-liquid two-phase flow. The most important features of the system are the non-uniformity and non-equilibrium of the gas-liquid two-phase structure and distribution, as well as the existence of deformable phase interfaces between the gas-liquid phases. The gas-liquid two-phase interface and its induced characteristics are closely related to various factors such as flow rate, physical properties, flow parameters, pipeline geometry, and geometric position of each phase, which brings many difficulties to researchers' in-depth research.

So far, in China, the research has mainly focused on the overall pipeline, exploring the calculation methods and treatment methods of fluid accumulation inside the pipeline. However, there has been no systematic study on the flow characteristics of fluid accumulation in wet gas transmission pipelines under complex terrain conditions, especially in low-lying bends. Liang Fachun et al. Provided a calculation process for calculating the amount of liquid accumulation in pipelines. It first divides the pipeline into several calculation units, calculates the temperature and pressure of each unit section from the inlet, and determines whether there is condensate precipitation based on the phase equilibrium equation.

In foreign countries, researchers have studied the flow of liquid accumulation at low-lying bends in wet gas pipelines through experimental or mechanistic modeling methods. The experimental studies involve placing a certain amount (adjustable) of liquid in the low-lying bends of the pipeline in advance, and then adjusting the gas velocity to observe the distribution of the liquid phase and record relevant data. Based on the experimental observations, reasonable mechanistic models are used for analysis. However, due to the narrow range of experimental conditions, further expansion and in-depth research are needed. Among them, Gregory et al. simulated the flow of liquid accumulation through experiments. When the pipeline was filled with water, the gas velocity was gradually introduced and increased to observe the changes in the flow pattern of the liquid accumulation during the process of being carried away. At the same time, the liquid holdup and pressure gradient were recorded. Although they did not establish a relevant and appropriate theoretical model, they provided valuable experimental data for further research in the future. Bibergm proposed a calculation method for the shear stress of liquid/wall at the critical state, where the apparent flow velocity of the liquid phase is zero.

The Koakal&Stanislaw model is based on the experimental research data of Gregory et al., and uses a standard steady-state stratified flow model to establish a separated flow model. They further divide the liquid layer into two sub layers and use the model to predict the pressure drop value. However, due to the fact that the application of the model not only needs to consider the closure relationship of interlayer shear stress, but also needs to determine the position of interface disturbance, the degree of use of the model is limited to a certain extent. In addition, there is no specific analysis on the liquid holdup.

Amaravadi et al. also conducted an experiment similar to that of Gregory et al., and used a slug flow model to calculate the blowing velocity of liquid accumulation. They then compared their calculated results with experimental data. Wood experiment also pre filled the pipeline with liquid, observed different flow combinations by changing the gas velocity, and finally established a flow combination diagram, and recorded parameters such as the frequency of slug flow. The drawback is that there was no research on the relationship between pre placed liquid volume and flow pattern, and no flow mechanism model was established. Birvalski et al. Conducted liquid accumulation flow experiments in a pipeline elbow with an inner diameter of 50.8mm and a length of 18m, using air-water and air-60% glycerol/water mixture as experimental media, under the premise that the liquid phase never

filled the pipeline. By gradually increasing the gas phase velocity, the experimental process and data were observed and recorded, and a theoretical mechanism model of liquid accumulation flow in inclined pipeline sections was established. The predicted results of the model were compared and verified with experimental values, providing valuable experimental data for studying the critical liquid carrying velocity of liquid accumulation in low-lying areas of pipelines. Barnea pointed out that the momentum balance equation of gas-liquid two-phase flow in critical state is an implicit function of liquid content, so it is necessary to iteratively solve the momentum balance equation to obtain the critical liquid carrying velocity of the gas.

## **2.2. Study on pressure drop and holdup of gas-liquid two-phase stratified flow**

When the gas transportation speed of a natural gas pipeline is higher than its critical liquid carrying velocity, the gas begins to carry away the accumulated liquid that has settled in the low-lying areas of the pipeline. The accumulated liquid then moves forward along the pipeline with the gas under the action of the gas, forming a gas-liquid two-phase flow with low liquid holdup. At present, research on gas-liquid two-phase flow in wet natural gas pipelines with low liquid content mainly involves experimental and theoretical studies. Theoretical research has mainly gone through the process from empirical relationships to mechanistic models. Lockhart&Martinelli(1949) was the first to conduct research on gas-liquid two-phase laminar flow in horizontal pipelines abroad. They proposed an empirical formula for calculating the relationship between liquid holdup and pressure gradient. Their relationship is presented in the form of a double logarithmic coordinate graph containing the parameters X (Lockhart&Martinelli parameters). It is also pointed out that in turbulent gas-liquid two-phase flow, the roughness of the gas-liquid interface has a certain impact on the holdup and pressure gradient, and it is necessary to conduct further research on this effect. In 1973, Beggs and Brill studied the pressure drop characteristics of gas-liquid two-phase flow in inclined pipelines by introducing a correlation between liquid content and pressure gradient.

Li Yuhao et al. summarized the existing calculation methods for gas-liquid two-phase pipelines and proposed the use of Beggs&Brill correlation equation for upward inclined pipeline section, Eaton correlation equation for horizontal pipeline section, and Xiao&Drill correlation equation for downward inclined pipeline section to calculate the liquid accumulation volume of undulating pipelines under low liquid holdup. Through comparative analysis with on-site data from Puguang gas field, the Beggs&Brill correlation equation calculated the pressure drop value well, which can be used for predicting the pressure drop value of multi undulating low liquid holdup pipelines. Zhou Liangsheng(2009) used pipePhase software to simulate the factors affecting liquid holdup and pressure drop, and then gridded the pipeline. The Brill flow pattern discrimination method was used to distinguish the flow pattern, and the liquid holdup and pressure drop were calculated based on different flow patterns. The average liquid holdup of the pipeline was calculated to determine the amount of liquid accumulation in each section and summed up.

Subsequently, foreign scholars conducted research on low liquid content gas-liquid two-phase flow and established some theoretical calculation models or empirical relationships, including Minami (1983) and Minami&Burr (1987), who studied the holdup of gas-liquid two-phase flow in horizontal pipes; Andritsos&Hanratty (1987) proposed an empirical relationship to predict the gas-liquid interface friction factor of stratified wave flow.

There is relatively little research on low liquid content gas-liquid two-phase flow in China. Xu et al. conducted a mechanistic model study on the cleaning process of low liquid content gas condensate horizontal pipelines; Wang Yan et al. conducted simulation experiments in a vertical pipe with a diameter of 65mm to study the liquid holding characteristics and emission reduction laws of gas wells under low liquid flow rates; Deng et al. conducted unsteady state computational simulations on the flow characteristics of rich natural gas gathering and transportation pipelines, and used the model proposed by Ottens et al. to calculate the pressure drop of low liquid content rich natural gas in their

research. When conducting research on gas-liquid two-phase flow with low liquid content, domestic studies evaluate models or relationships proposed by foreign researchers, or use computational models and empirical relationships proposed by foreign researchers to predict the actual situation in China, or establish computational models using traditional numerical calculation methods. Most of these researchers have borrowed theoretical calculation models from abroad, but have not proposed specialized theoretical systems or empirical relationships. Zhang Weimin et al. studied the three-phase interface model of gas oil water in wet gas pipelines, considering that the selection of the interface model has a certain impact on the accuracy of pipeline pressure drop and average liquid holdup calculation. The ARS model proposed by Hart et al. and the double ring model proposed by Chen et al. were selected to compare the computational performance of the two interface models on experimental data, analyze the applicable conditions of each interface model, and provide theoretical basis for establishing a comprehensive hydraulic calculation model for wet gas pipelines.

There are many experimental studies on low holdup gas-liquid two-phase flow, but it has been observed that the experimental phenomena differ significantly from the theoretical predictions, and the conclusions obtained are not universal. In many cases, the proposed models are only applicable to the current experimental conditions and may not be applicable to gas-liquid two-phase flow systems in other situations. On the other hand, due to the lack of experimental conditions, there is no reliable piping system to study gas-liquid two-phase flows with large diameters, high pressures, and low holdup (with and without chemical additives). Research has shown that droplet entrainment is commonly present in gas-liquid two-phase flow. When droplet entrainment occurs, some liquid is distributed in the gas phase in the form of droplets, which can have a significant impact on the flow characteristics of gas-liquid two-phase flow. However, the above studies did not consider the influence of droplet entrainment

In the past 60 years, many scholars abroad have conducted extensive theoretical analysis and experimental research on the problem of gas-liquid two-phase flow, and proposed many predictive equations. However, so far, research in this area is far from mature, and an empirical relationship that can be universally applicable to identified flow patterns and provide accurate and reliable prediction results has not been proposed. Low liquid content gas-liquid two-phase flow is one of the weakest areas in multiphase flow research. At present, there is a lack of systematic research on gas-liquid two-phase flow during natural gas pipeline transportation.

### **3. RESEARCH ON FLUID ACCUMULATION MODEL IN WET GAS PIPELINE**

The structure of the liquid spreading towards the downstream pipeline of the elbow is actually a complex three-dimensional structure, with its boundary composed of curved pipeline walls and gas-liquid interfaces. When gas passes over the liquid accumulated in the elbow, interface waves are formed, causing the upper part of the liquid layer to move downstream of the elbow under the action of interface shear stress. On the other hand, under the influence of the gravity of the liquid layer itself, it will flow back, forming a special low liquid content gas-liquid two-phase flow, namely ZNLF flow, in the inclined upward pipe section. To simplify the analysis, this article cites a two-phase stable stratified flow model. This model is based on the momentum balance of the gas-liquid phase, and different geometric equations and friction coefficient closure equations are selected according to the shape of the gas-liquid interface.

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. 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.

Taitel and Dukler first proposed a horizontal interface shape model (FLAT model) for gas-liquid two-phase laminar flow in 1976, Hart et al. (1989) proposed an equivalent rough surface model (ARS model), and in 1989, Hart proposed a new interface shape model for low liquid holdup - the Apparel Rough Surface model, ARS model. In 1997, Chen et al. proposed the Double Circle model, abbreviated as the Double Circular Ring model. Grolman and Fortin revised the ARS model in 1997 and proposed the Modified Apparel Rough Surface model, abbreviated as the MARS model. Banafi and Talaie proposed a new interface shape model for gas-liquid two-phase stratified flow through experimental research in 2014.

#### **4. DEVELOPMENT TREND**

In terms of theoretical construction, fractal theory and chaotic dynamics are applied to deeply analyze the complex changes of boundary wave breaking and merging in different flow patterns such as annular flow and bubbly flow, establish a unified theoretical framework, refine the description of the dynamic process of gas-liquid interface, and provide a more solid theoretical basis for the model. In terms of experiments, non-invasive measurement techniques such as high-speed photography and particle image velocimetry (PIV) are used to capture the spatiotemporal changes of interface waves with high resolution. For example, high frame rate PIV is used to record the velocity field at the moment of interface wave breaking, providing a large amount of accurate data for model parameter calibration. Finally, deep learning algorithms are introduced to analyze massive experimental data, explore the complex relationship between interface wave morphology, frequency, and flow field parameters, construct a data-driven model, and couple it with traditional mechanism models to quickly and accurately predict the gas-liquid two-phase flow characteristics under different operating conditions, thereby significantly improving the overall prediction accuracy of the model.

#### **5. SUMMARIZE**

The research on gas-liquid two-phase flow in wet natural gas pipelines has achieved phased results in predicting critical liquid carrying velocity, pressure drop, and liquid holdup. However, the flow characteristics of liquid accumulation in complex terrains, the universality of models for large diameter and high-pressure scenarios, and the influence of droplet entrainment still need to be further studied. In the future, it is necessary to establish more accurate and universal theoretical and computational models through interdisciplinary and technological integration to support safe and efficient transportation in the oil and gas industry.

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