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Prediction Model of Critical Liquid-Carrying Flow Velocity of Micro-tilt Pipeline under Droplet Entrainment in X Gas Field

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Abstract

A prediction model of critical liquid-carrying flow rate of gas-liquid two-phase flow considering the influence of droplet carrying was established. Combined with the dynamic equilibrium and the Banafi-Talaie boundary equation, the calculation method of gas/liquid/wall shear stress was improved. Compared with the four classical fully enclosed models, namely FLAT, ARS, Double rings and MARS, the experimental test data of the air-water and air-60% glycerol liquid systems show that the critical liquid-carrying flow rate obtained by the model established in this paper deviates from the experimental data by ≤1%. For highly viscous liquids, the model established in this paper can obtain the highest critical liquid holding ratio. It can help to make up for the shortcomings of the original model that cannot deal with high-viscosity liquids, and can provide a theoretical basis for the safety of long-distance natural gas pipelines.

Keywords

Liquid Hold-up; Two-phase Flow; Droplet; Shear Stress; Critical Liquid-carrying Flow Rate.

1. Preface

During the extraction and transportation of natural gas, the issue of liquid accumulation inside pipelines has always been a critical challenge affecting flow protection and system safety. As service time increases, pipeline systems at gas collection stations and processing facilities gradually show signs of aging, urgently requiring reliable predictive models to guide safe operation. Traditionally, predictions of the critical liquid-carrying velocity for gas-liquid two-phase flow have been based on simplified assumptions, which have significant limitations, especially when dealing with high-viscosity liquids, and cannot accurately reflect the effects of complex phenomena such as droplet entrainment. To overcome this challenge, this study aims to establish a predictive model for the critical liquid-carrying velocity in slightly inclined pipelines, taking droplet entrainment into account. The significance of this study lies in providing theoretical support for the flow safety assurance of long-distance natural gas pipelines, particularly applicable to practical engineering environments such as the X gas field. By deepening the understanding of the mechanism of droplet entrainment, the model offers new ideas for preventing pipeline liquid accumulation and optimizing design, helping to improve the reliability and economic efficiency of the natural gas industry. [1-2]

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2. Critical Carrying Liquid Flow Rate Prediction Model

Based on the descriptive equations of four types of gas-liquid interface forms, this paper successfully establishes an evaluation model for critical liquid-carrying velocity and liquid holdup, covering droplet entrainment phenomena, relying on the principle of momentum conservation in gas-liquid two-phase flow. This study selects the interface equation from the Banafi-Talaie theory as the core model.

2.1. Liquid Droplet Entrainment Rate

Droplet entrainment rate:

$$F_E = \frac{W_E}{W_L} = \frac{W_L - W_F}{W_L} \tag{1}$$

In the formula, WL represents the mass flow rate of the liquid; WE represents the amount of droplets carried in the liquid; WF represents the mass flow rate of the liquid film.

In the field of studying droplet entrainment phenomena, Pan and Hanratty developed a method for calculating entrainment rate in 2002, which is based on the theoretical principles of droplet atomization and deposition mechanisms. This article quantitatively evaluates the droplet entrainment rate using specific formulas:

$$\left(F_E/F_{E,max}\right)/\left(1 - F_E/F_{E,max}\right) = 6 \times 10^{-5}\left[\left(V_G - V_{G,cr}\right)^2 d\sqrt{\rho_L \rho_G}/\sigma\right] \tag{2}$$

$$V_{G,cr} = 40\sqrt{\sigma/d\sqrt{\rho_L \rho_G}} \tag{3}$$

In the formula,F_E represents the droplet entrainment rate, dimensionless; $F_{E.\,max}$ represent the maximum droplet entrainment rate, dimensionless. In this article, F_E and max are taken as 1.0;$V_{G,\,cr}$ represents the critical gas velocity at which entrainment begins, m/s; d represents the diameter of the pipeline, m;σ represents the surface tension of the liquid phase, N/m. [3-4]

2.2. Gas/Wall Shear Stress

In conventional understanding, shear stress is regarded as the product of fluid kinetic energy (calculated per unit volume) and interfacial friction coefficient, expressed as:

$$\tau_{wG} = f_G \frac{\rho_{GFE} V_{sg}^2}{2(1 - H_L)^2} \tag{4}$$

In this study, the researchers adopted the strategy jointly developed by Gregory and Fogarasi to estimate the friction coefficient between gas and wall.

$$\frac{1}{\sqrt{f_G}} = -4\, log\left[\frac{k}{3.7d} - 5.02\, log\, A_6\right] \tag{5}$$

$$A_6 = \frac{k}{3.7d} - \frac{5.02}{Re_G} log\, A_5 \tag{6}$$

$$A_5 = \frac{k}{3.7d} + \frac{13}{Re_G} \tag{7}$$

In the provided mathematical expression, the symbol k/d represents the relative roughness of the pipeline, which is dimensionless; Re_G represents the Reynolds number of the gas phase, which is also a dimensionless quantity; A_5 and A_6 respectively refer to two different empirical coefficients, both of which belong to the dimensionless category.

The gas phase Reynolds number is:

$$Re_G = \frac{\rho_{GFE} V_{sg} d}{\mu_G (1 - \theta + s_i)} \tag{8}$$

In the formula, μ_G represents the dynamic viscosity of the gas phase, Pa·s; θ represents the wet wall fraction of the liquid phase, dimensionless; s_i represents the wet wall fraction at the gas/liquid interface, dimensionless.

The wet wall fraction of liquid phase is:

$$\theta = \frac{S_L}{\pi d} \tag{9}$$

The wet wall fraction at the gas/liquid interface is:

$$s_i = \frac{S_i}{\pi d} \tag{10}$$

2.3. Shear Stress At Gas/Liquid Interface

The shear stress at the gas/liquid interface is:

$$\tau_i = f_i \frac{\rho_{GFE} V_{sg}^2}{2(1 - H_L)^2} \tag{11}$$

This study adopted the computational model proposed by Banafi and Talaie to estimate the friction coefficient f_i in the gas/liquid interface region.

$$f_i = \frac{0.02066}{\left(\log\left(\frac{15}{Re_G} + \frac{k}{3.71d}\right)\right)^2} \tag{12}$$

This study adopted the calculation strategy proposed by Grolman and Fortin to estimate the relative roughness of pipelines, which is the ratio of parameter k to diameter d.

$$F_n = \frac{f_1}{(0.05 + f_1)(1 - H_L)^2} \left(\frac{V_{sg}}{\sqrt{gd}}\right) \left(\frac{\sigma}{\mu_L}\sqrt{gd}\right)^{0.04} \left(\frac{\rho_L g d^2}{\sigma}\right)^{0.22} \tag{13}$$

$$\frac{k}{d} = 0.5145 H_L s_i^{-1.5} \{tan\, h[0.05762(F_n - 33.74)] + 0.9450\} \tag{14}$$

$$f_2 \frac{0.0625}{\left\{\log_{10}\left[\frac{15}{Re_G + \frac{k}{3.715d}}\right]\right\}^2} \tag{15}$$

In the given formula, f_1, f_2 to F_n represent a series of dimensionless intermediate parameters; And μ_L characterizes the dynamic viscosity of liquid substances, Pa•s.

2.4. Liquid/Wall Shear Stress

Due to the reflux phenomenon triggered by gravity, even in critical states, the liquid wall interface still experiences significant shear stress effects. To address this specific situation, the

Biberg research team has developed a computational model specifically designed for evaluating the shear stress at the liquid wall interface under extreme working conditions.

$$\tau_{wL} = f(\delta_L)\tau_i - \frac{8\mu_L V_L}{d_L(\delta_L)} \tag{16}$$

In the formula, δ_L represents the relationship between the quantified liquid phase content and angle, measured in degrees (°); $f(\delta_L)$ represents an integral expression that cannot be analytically solved, and during the range of H_L values from 0 to 0.5, δ_L correspondingly changes from 0 to π/2.

In the critical state, the average flow velocity of the accumulated liquid in the pipeline actually tends to be static, that is, the average velocity of the liquid phase is zero, specifically manifested as a V_L value of 0 meters per second. Therefore, in the critical state, the shear stress between the liquid and the wall can be expressed as:

$$\tau_{wL} = f(\delta_L)\tau_i \tag{17}$$

In the case of water as a liquid medium, its physical properties are manifested as a density of 997kg/m^3 and a dynamic viscosity of 0.001Pa•s.

$$f(\delta_L) = 0.55\beta - 0.215 \tag{18}$$

When examining the characteristics of liquid phase media, if the medium is a mixed solution containing 60% glycerol and water, its physical properties are characterized by a density $\rho_{G/W}$ of 1150 kg/m^3 and a viscosity $\mu_{G/W}$ of 0.0108 Pa•s.

$$f(\delta_L) = 0.45\beta - 0.445 \tag{19}$$

3. Prediction Results of Different Models

Table 1. Comparison table of prediction data and experimental results of critical liquid carrying velocity of each closed model in the air-water system

Pipeline inclination angle (°)	FLAT model (m/s)	ARS model (m/s)	Double ring model(m/s)	MARS model(m/s)	The model in this paper(m/s)	Experimental value(m/s)
1.3	7.53	7.45	7.66	7.57	7.97	7.98
1.7	8.33	8.20	8.09	8.36	8.55	8.46
2.1	8.59	8.53	8.55	8.61	8.98	8.99

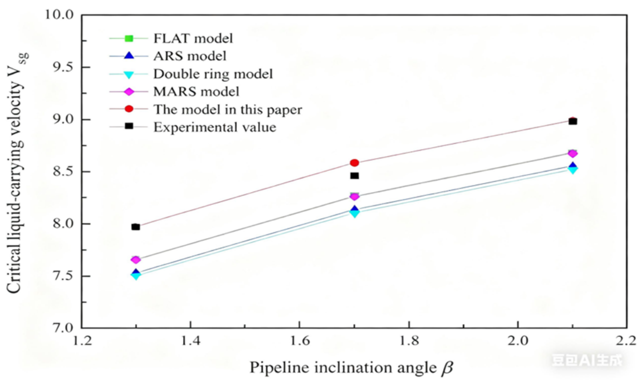

Fig 1. shows a comparative analysis of the calculation results of the critical liquid carrying velocity of different models in an air-water system.

Taking X gas field as an example, it is mainly located in the Ordos Basin, within the territory of Wushen Banner, Etuokeqian Banner, Inner Mongolia Autonomous Region, and Dingbian County, Shaanxi Province. Under pipeline inclination angles of 1.3°to 2.1°, the critical liquid holdup and critical liquid carrying velocity were analyzed in different solution systems. The critical liquid carrying velocity prediction data and critical liquid holdup values obtained from different calculation models were summarized, and then these prediction results were compared and analyzed with experimental data.

Table 2. Predicted and measured data of critical liquid retention ratio of different closed models of air-water system

Pipeline inclination angle (°)	FLAT model (m/s)	ARS model (m/s)	Double ring model(m/s)	MARS model(m/s)	The model in this paper(m/s)	Experimental value(m/s)
1.3	0.025	0.021	0.022	0.027	0.038	0.032
1.7	0.027	0.020	0.020	0.023	0.031	0.024
2.1	0.022	0.020	0.016	0.021	0.032	0.022

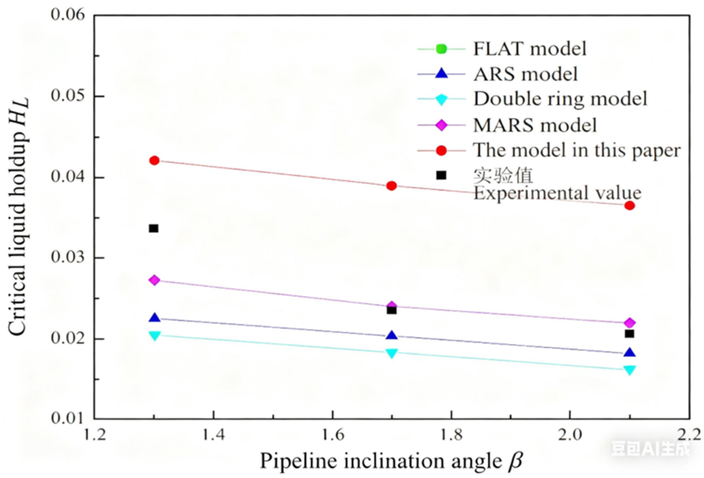

Fig 2. presents the analysis chart of the differences between various models for the calculation of critical liquid holding rate under the air-water system.

Table 3. Prediction results and actual experimental data of different closed models for critical liquid carrying flow under air-60% glycerol aqueous solution

Pipeline inclination angle (°)	FLAT model (m/s)	ARS model (m/s)	Double ring model(m/s)	MARS model(m/s)	The model in this paper(m/s)	Experimental value(m/s)
1.3	8.34	8.21	8.27	8.34	8.65	8.66
1.7	9.03	8.95	8.78	9.02	9.20	9.24
2.1	9.42	9.28	9.26	9.38	9.54	9.55

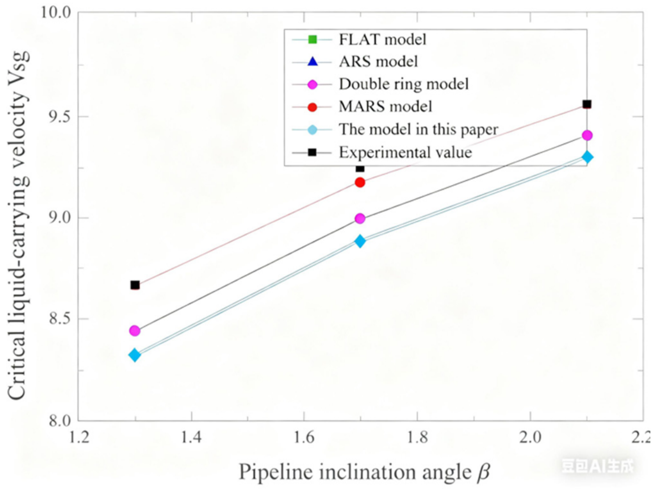

Fig 3. shows a visual representation of the results of different models comparing the results in calculating the critical carrying flow rate of air to a mixture of 60% glycerol aqueous solution

Table 4. Predicted and measured data of critical liquid holding rate of air-60% glycerol/water mixture system under different closed models

Pipeline inclination angle (°)	FLAT model(m/s)	ARS mode(m/s)	Double ring model(m/s)	MARS model(m/s)	The model in this paper(m/s)	Experimental value(m/s)
1.3	0.019	0.016	0.017	0.020	0.029	0.027
1.7	0.016	0.014	0.013	0.015	0.027	0.026
2.1	0.013	0.011	0.012	0.015	0.026	0.024

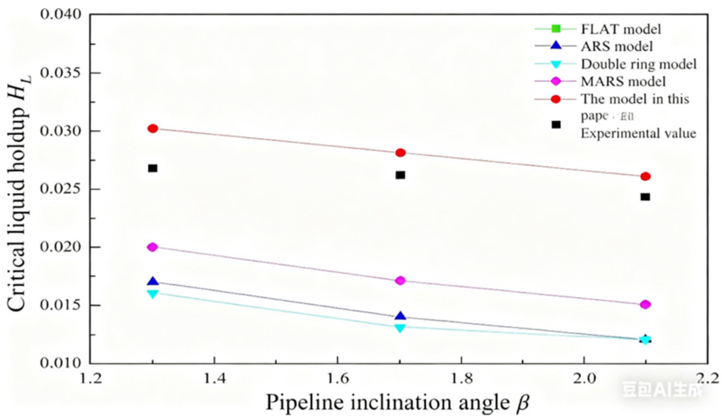

Fig 4. shows a comparative analysis of the critical liquid holding rate calculated by different models (involving air and 60% glycerol/water mixture)

4. Summary

(1) This study used an optimized formula for calculating gas/liquid/wall shear force, combined with the principle of droplet entrainment, to construct a critical liquid carrying velocity prediction model that includes droplet entrainment effect and gas-liquid interface shape. The model integrates a quantitative formula for droplet entrainment efficiency and compares the calculated values of the model with the low holdup gas-liquid two-phase flow model.

(2) The experimental results show that under air-water conditions, the model's prediction of critical liquid carrying velocity is basically consistent, while the calculated result of critical liquid holdup is slightly higher than the measured value; When the mixture of air-60% glycerol/water solution is used, the prediction accuracy of the model on the two key parameters of critical liquid carrying velocity and critical liquid holding capacity is in good agreement with experimental data.

(3) In low viscosity/high viscosity systems, achieving a critical liquid carrying velocity prediction error of ≤ 1% and a liquid holdup error of<8% is significantly better than traditional models such as FLAT/ARS, especially overcoming the failure problem of traditional models for high viscosity liquids, providing core technical support for the safety of natural gas pipeline flow.

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