

Article

Prediction Method for Critical Gas Velocity of Sulfur-Carrying in Gas–Liquid Two-Phase Flow in High-Sulfur Gas Wells

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Abstract

During the production of high-sulfur-content gas–water wells, elemental sulfur saturated in natural gas gradually precipitates as solid particles with decreasing wellbore temperature and pressure. When these sulfur particles cannot be continuously carried upward in the gas–liquid–solid three-phase flow formed with natural gas and formation water, they tend to deposit in the wellbore, potentially blocking the production string and even severely restricting the gas well’s deliverability. Current research on predictive models for the critical gas flow velocity required to carry sulfur particles remain inadequate. Therefore, accurately predicting this critical velocity and adjusting production to prevent deposition are crucial for managing high-sulfur gas wells. The primary innovation of this study lies in the development of a predictive model for the critical gas flow velocity required for sulfur particle entrainment. Grounded in the “gas–liquid coalescence–liquid film entrainment” coupling mechanism revealed by preliminary experiments, this model is established through a mechanical analysis of sulfur particles within liquid films in vertical and inclined pipes. Recognizing liquid film thickness and velocity as pivotal parameters for model solving, auxiliary models for predicting these two parameters in inclined pipe annular flow were developed based on experimental results and the momentum balance principle. The proposed model comprehensively incorporates factors such as well inclination angle, pipe diameter, liquid flow rate, and sulfur particle size, rendering it applicable to diverse well configurations including vertical, horizontal, and deviated wells. Evaluation against 48 sets of experimental data yielded a Mean Absolute Percentage Error (MAPE) of 2.28%, demonstrating high predictive accuracy. Furthermore, an engineering calculation program for the critical gas flow velocity was developed. A case study involving a well in the Puguang Gas Field was conducted to predict and diagnose sulfur deposition conditions, thereby verifying the model’s practical utility. This research provides a scientific basis for the safe and efficient development of high-sulfur gas fields.



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Keywords: annular flow; sulfur particles; critical sulfur-carrying velocity; model; inclined pipe

1. Introduction

High-sulfur gas fields account for approximately 10% of global natural gas reserves, with high-sulfur reservoirs widely distributed throughout the world. During the extraction of high-sulfur reservoirs, as the temperature and pressure of fluids in the wellbore decrease with depth, elemental sulfur saturated in natural gas is gradually precipitated to form

solid sulfur particles. These solid sulfur particles are interacted with natural gas and formation water to form a gas–liquid–solid three-phase flow. As gas well production declines, the flow velocity within the wellbore gradually decreases. When the flow velocity falls below the critical velocity required to carry sulfur particles, these particles deposit within the wellbore. This leads to reduced well production or even complete well blockage. Simultaneously, tubing corrosion is accelerated by sulfur deposition, preventing normal well operation. Therefore, accurately predicting the critical gas flow velocity required to carry sulfur particles within the wellbore and preventing sulfur deposition events by adjusting gas well production are crucial for managing high-sulfur gas wells. Furthermore, the accurate prediction of the critical gas flow velocity for carrying sulfur particles within the wellbore is one of the key theoretical foundations for predicting sulfur deposition conditions and selecting optimal gas production tubing.

Previous researchers have conducted relevant theoretical and experimental studies. Wang Zhizhong et al. developed a wellbore sand-carrying experimental apparatus to observe and document particle migration at different inclinations, and determined the critical flow rate at which sand particles of various sizes are carried out of the wellbore [1]. Leporini conducted preliminary experimental studies on gas–water–sand three-phase flow in horizontal pipelines. Through physical observation and data analysis, three flow patterns were established and the critical deposition velocity at different sand concentrations was determined [2]. Luo Rong et al. conducted static sedimentation experiments using a vertical multiphase flow apparatus. They investigated the influence of particle size and liquid phase viscosity on the terminal settling velocity of asphaltene particles, and established a formula for calculating the critical gas flow velocity [3]. Li Bo conducted experiments on oil flow carrying impurities under varying particle loading and pipeline inclination angles using a self-built experimental loop. A Fluent-DEM coupled method was employed to simulate the critical flow velocity at which particles are ejected from the pipeline under experimental conditions. Comparison with experimental results demonstrated that this simulation method can effectively predict the critical flow velocity for particles within pipelines [4]. Qin Hao conducted laboratory experiments on gas–sand transport in pipelines, performed mechanical analysis of pipeline sand particles, and derived a theoretical formula for the terminal velocity of sand particles [5]. Gillies et al. conducted gas–water–sand three-phase flow experiments to investigate sand transport characteristics under laminar and turbulent flow conditions. The results indicated that gas volume has a minor effect on sand transport in laminar flow, while it increases sand transport in turbulent flow [6]. Danielson conducted multiphase flow experiments in a 0.07 m ID, 215 m long flow loop, investigated critical conditions for sand transport under various parameters, and established a predictive model for critical sand velocity that shows a good match with experimental data [7]. King et al. adopted the definition of “Minimum Transport Condition (MTC) for sand particles.” A method was proposed based on a series of equations derived from Thomas, which predicted the “minimum critical sand transport condition”—the average flow velocity required to prevent a layer of sliding particles from accumulating at the bottom of horizontal pipelines [8]. Building upon previous liquid–solid two-phase flow models, a model predicting the critical settling velocity of sand particles in liquid–solid two-phase flow and gas–liquid–solid three-phase flow was developed by Salam [9]. Najmi et al. conducted gas–water–sand three-phase flow experiments in horizontal pipelines. The effects of particle size, sand shape, and sand concentration on the critical sand-carrying velocity under laminar and intermittent flow conditions were investigated [10]. Research on critical velocity models for multiphase flow pipelines remains in its infancy. To date, all proposed critical velocity formulas for multiphase pipelines have been

derived from single-phase pipeline critical velocity models for solid-carrying flows, as is shown in Table 1.

Table 1. Critical velocity models for gas–liquid–solid multiphase flow in pipelines.

Model	Modeling Approach	Calculation Formula	Limitations
Angelsen [11]	Extension of Wicks' single-phase flow model to multiphase flow.	$\psi_s = \frac{\rho_f^3 d_p V_s^4}{(\rho_p - \rho_f) g (s \cdot \sin \theta + \cos \theta) \mu_f^2}$ $S_s = \frac{D_H V_s \rho_f}{\mu_f} \left(\frac{d_p}{D} \right)^{2/3}$ $\psi_s = a S_s^b$	The model does not consider the effect of particle concentration and is only applicable to stratified flow.
Salama [9]	Extension of the single-phase flow model using a drift-flux model by introducing mixture velocity, based on the settling relationship of Oroskar and Turian and the Davies relationship.	$V_C = K d_p^a \left(\frac{\mu_f}{\rho_f} \right)^b \left(\frac{\rho_p - \rho_f}{\rho_f} \right)^c D^d$	Model parameters are dependent on experimental data.
Danielson [7]	Based on the settling relationship of Oroskar and Turian and the Davies relationship, the single-phase flow model is extended using a drift-flux model by introducing mixture velocity.	$V_C = 0.23 v^{-1/9} d_p^{1/9} \times [g D (s - 1)]^{5/9}$	The model does not consider the effect of sand concentration.

Domestic and international scholars have established numerous models for the critical velocity of single-phase fluid-carried particles in pipelines, as is shown in Table 2. A critical velocity formula accounting for particle randomness during initiation was developed by Zhao Dongwei through an analysis of the balance of forces. In this approach, particle gravity, hydraulic thrust, buoyancy force, hydrostatic pressure, interparticle cohesion, and the relationship between each force arm and submersion depth were considered [12]. Long Zhihui analyzed the primary forces acting on cuttings particles in different regions of the eccentric annulus and predicted their migration trends [13]. Niu Jun et al. constructed a mathematical model for coal dust migration within wellbores, investigating the transport mechanisms of coal dust by fluids in coalbed methane wells. Results indicated that the fluid's coal dust carrying capacity is positively correlated with drainage velocity [14]. Based on force analysis of ore particles, a computational model for the critical gas flow velocity causing ore particle detachment and migration was established by Zhou Yang et al., and the influence of factors such as particle size and friction coefficient on this critical velocity was investigated [15]. Zhu Guo analyzed the forces acting on sulfur particles in gas flow, deriving the critical sulfur-carrying velocity for sulfur particle migration with gas flow [16]. A theoretical method for determining sulfur deposition was established by Chen Yiwei, in which gas flow velocity at the sulfur precipitation location in the wellbore is compared with the critical sulfur-carrying velocity to judge whether sulfur particles deposit [17]. A sulfur deposition prediction model was developed by Fu Dequai, demonstrating that higher gas production rates increase mixed fluid flow velocity and enhance the fluid's liquid and solid carrying capacity, thereby reducing the likelihood of sulfur deposition [18]. A computational mechanics model for calculating the critical flow velocity of cuttings migration under

two transport mechanisms was developed by Song Xuncheng through force analysis, and a method to determine the critical annular circulation rate for maintaining cleanliness in deviated wells was proposed [19]. Based on the migration patterns of cuttings—primarily tumbling toward the wellhead in high-inclination wells and lifted to the surface via suspension in drilling fluid in low-inclination wells—Song Shijie conducted a force analysis on fine cuttings and established a predictive model for the critical migration velocity of cuttings under these two transport mechanisms [20]. Three-dimensional hydrodynamic and sediment motion simulations for sand particle transport in long straight pipelines were conducted by Gong Xinjie. By analyzing the profile velocity distribution characteristics along the pipeline and the critical velocity patterns for sediment deposition, a critical deposition velocity calculation formula considering transport length and pipeline roughness was proposed [21]. Mathematical models for cuttings transport in vertical/near-vertical sections, transition sections, and steeply inclined/horizontal sections were established by Zhang Jie based on a specialized rheological model for foamy fluids [22]. The first experimental study on solid transport in gas–liquid mixtures within horizontal pipelines was conducted by Scott and Rao [23]. The effects of solid concentration and pipe diameter on migration velocities under liquid–solid two-phase bubble flow, plug flow, and segmented plug flow conditions were investigated. Good agreement of their experimental results with the Durand [24] model was shown. A mathematical model for critical velocity in liquid/solid two-phase flow was established by Wicks by considering lift, drag, and gravity forces [25]. Building upon Wicks’ model, an extension to gas–liquid–solid three-phase flow was made by researchers, demonstrating its applicability to stratified flow. A numerical model for predicting critical velocity in solid particle transport was developed by Angelsen et al. by analyzing the forces causing particle movement, and it was subsequently extended to gas–liquid–solid three-phase flow [11]. A settling velocity model for drill cuttings in drilling mud and a subcritical settling velocity model for varying well inclination angles (40–90°) were proposed by Larsen based on over 700 experimental data sets [26]. Similar experiments were conducted and a critical velocity model for carrying drill cuttings in high-angle wells (50–90°) was developed by Ozbayoglu [27]. The critical gas velocity for particle migration was derived by Stevenson et al. using a dimensionless group relating liquid viscosity, particle diameter, and apparent gas–liquid flow velocity. Particle flow patterns in intermittent and laminar gas–water two-phase flow, with particle diameters ranging from 0.51 mm to 1 mm, were also investigated [28].

Based on the above analysis, current research on the critical velocity for solid particle transport mainly relies on numerical simulation and empirical models established from experiments, with horizontal pipes being the predominant research subject. Studies on gas–liquid two-phase flow carrying solid particles remain relatively limited. Existing theoretical methods and research insights are not directly applicable to predicting the critical gas flow velocity for sulfur particle transport in wellbores of high-sulfur gas wells. Accordingly, based on the “gas-flow carrying liquid—liquid-film carrying sulfur” coupling mechanism revealed in previous experiments, this study performs a force analysis of sulfur particle transport within the liquid film and develops a prediction model for the critical gas flow velocity of sulfur particle transport. In conjunction with momentum balance calculations for liquid film thickness and liquid film velocity in annular flow through inclined pipes, the model comprehensively accounts for factors including well inclination angle, pipe diameter, liquid flow velocity, and sulfur particle size, thereby making it applicable to various well types such as vertical, horizontal, and inclined wells. Additionally, an engineering calculation program is developed, and the model’s prediction accuracy and engineering practicality are validated using 48 sets of experimental data and field examples from the Puguang Gas Field.

Table 2. Critical velocity models for solid transport in single-phase flow in pipelines.

Model	Modeling Approach	Calculation Formula
Empirical Model	Model established based on dimensionless analysis.	Cabrejos [29] model: $f\left(\frac{\mu_g}{\sqrt{g d_p}}, \frac{\rho_p}{\rho_g}, \varphi, \frac{D}{d_p}, \frac{d_p \mu_g \rho_g}{\mu_g}\right) = 0$
		Kokpinar & Gogusm [30] model: $\frac{V_C}{\sqrt{g D}} = f\left[\left(\frac{\rho_p}{\rho_f} - 1\right), C_V, \frac{\rho_f \mu_p d_p}{\mu_f}, \frac{d_p}{D}\right]$
Theoretical Model	Model established based on particle force analysis.	Kalman [31] model: $n_1 \times 0.011 \text{Re}_{im50}^{2.34} + f \times 0.1 \left(\frac{d_p}{D}\right)^{0.29} \text{Re}_{im50}^{2.02} = 0.52 f Ar$
		Zhu Guo [16] model: $V_f = \frac{-12.88(\mu \rho_g)^{1/2} - \sqrt{165.894 \mu \rho_g - 8 C_D \rho_f \pi r_p (\rho_f - \rho_p) g}}{-2 C_D \rho_f}$
		Song Shijie [20] model: $V_{CD} = - \left[\frac{1}{1 - \left(\frac{d}{D}\right)^2} \right] \left[\frac{18.16}{2.1 + \frac{ROP}{D}} \right] + V_{slip} C_{ang} C_{size} C_{mw}$
Semi-Empirical Model	Model based on theoretical analysis and corrected with experimental data.	Oroskar & Turian [32] model: $\frac{V_C}{\sqrt{g d_p (s-1)}} = \left[5 C_V (1 - C_V)^{2n-1} \left(\frac{D}{d_p}\right) \left(\frac{D \rho_f \sqrt{g d_p (s-1)}}{\mu_f}\right)^{1/8} \frac{1}{x} \right]^{8/15}$
		AI-Mutathar [33] model: $V_C = 5.66 \left[f(C_V) \sqrt{d_p g (s-1)} \right]^{8/7} \left(\frac{D \rho_f}{\mu_f}\right)^{1/7} \left(\frac{1}{W}\right)^{8/7}$

2. Prediction Model for Critical Gas Flow Velocity Carried by Sulfur Particles

Wang Zhibin, Peng Jungang et al. designed the experimental flow parameters using the Froude number and Reynolds number to ensure hydrodynamic similarity between the laboratory experiments and field conditions. The Froude number represents the ratio of inertial forces to gravity, while the Reynolds number quantifies the ratio of inertial forces to viscous forces. Utilizing sulfur particles collected from the field, Wang Zhibin, Peng Jungang et al. conducted gas–liquid two-phase sulfur-transport experiments in an inclined pipe. The experimental observations revealed that the sulfur entrainment mechanism follows a “gas-driven liquid film–liquid film-driven sulfur particle” sequence, wherein the sulfur particles are primarily entrained while submerged within the liquid film. Initially, a mechanical analysis of sulfur particles within the liquid films of vertical and inclined pipes was performed to establish a calculation model for the critical liquid film velocity required for particle entrainment. Within the scope of the operating conditions investigated in this study, the influence of particle shape on the settling velocity was found to be negligible. Therefore, assuming spherical sulfur particles is deemed sufficient to meet the accuracy requirements of the critical gas flow velocity prediction model; consequently, the sulfur particles are treated as uniform and regular spheres herein [34,35]. Subsequently, a force analysis was conducted on both the liquid film and the gas core in inclined pipe annular flow. Accounting for the non-uniform distribution of liquid film thickness, a predictive model for the critical gas flow velocity for sulfur entrainment was ultimately established based on the momentum balance principle.

2.1. Calculation Model for Critical Liquid Flow Velocity Carrying Sulfur Particles

(1) Vertical Pipe

The forces acting on sulfur particles within the liquid film of a vertical pipe include their own weight, the buoyancy exerted by the liquid film, and the drag force, as is shown in Figure 1.

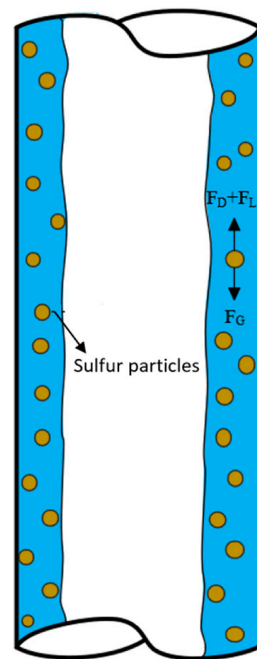


Figure 1. Schematic of force analysis on sulfur particles.

The drag force on sulfur particles in a liquid film is given by:

$$F_D = \frac{\pi}{8} C_D \rho_L v_{Lcr}^2 d_s \quad (1)$$

where: F_D —drag force, N; v_{Lcr} —relative velocity between particle and liquid film, m/s; C_D —drag coefficient; ρ_L —fluid density, kg/m³; d_s —particle diameter, m.

Simultaneously, sulfur particles are subject to their own gravitational force and a buoyancy force:

$$F_G = \frac{\pi}{6} d_s^3 \rho_s g \quad (2)$$

$$F_L = \frac{\pi}{6} d_s^3 \rho_L g \quad (3)$$

When the sulfur particle is in a critical suspension state within the liquid, the forces acting on it reach equilibrium:

$$F_D + F_L = F_G \quad (4)$$

From this, the following is obtained:

$$\frac{\pi}{8} C_D \rho_L v_{Lcr}^2 d_s + \frac{\pi}{6} d_s^3 \rho_L g = \frac{\pi}{6} d_s^3 \rho_s g \quad (5)$$

Simplification yields the critical liquid flow velocity for carrying the sulfur particle as:

$$v_{Lcr} = \sqrt{\frac{4(\rho_s - \rho_L) d_s g}{3 \rho_L C_D}} \quad (6)$$

(2) Inclined Pipe

Experimental observations indicate that when the wellbore inclination angle is large, the buoyant force acting on sulfur particles in the vertical direction increases, causing the particles to migrate in a suspended state. When the wellbore inclination angle is small, solid sulfur particles are transported forward by rolling along the pipe bottom. This occurs because the rolling torque acting on the particles exceeds the resistive torque, causing them to roll forward around their contact point. The force analysis is illustrated in Figure 2.

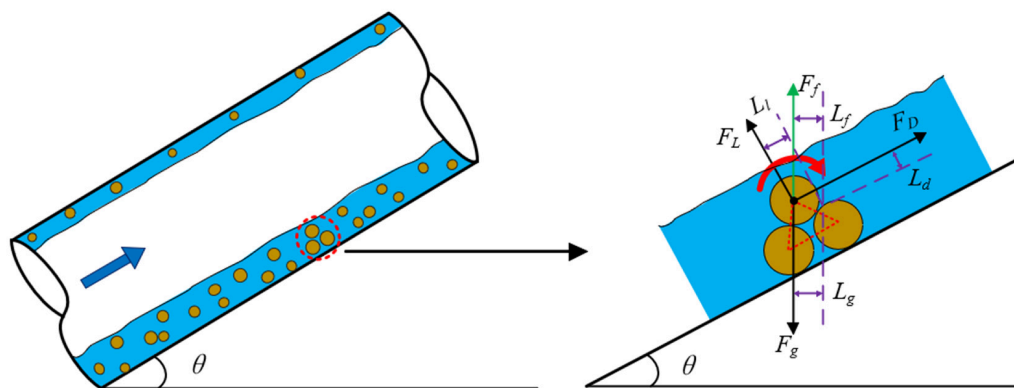


Figure 2. Schematic of forces acting on sulfur particles in a slightly inclined pipe.

- (a) For pipes with small inclination angles and horizontal pipes, the torque balance equations for sulfur particles rolling forward are:

$$F_D L_d + F_L L_l - F_W L_w = 0 \quad (7)$$

$$L_d = \frac{d_p}{2} \cos \theta \quad (8)$$

$$L_l = \frac{d_p}{2} \sin \theta \quad (9)$$

$$L_w = \frac{d_p}{2} \sin(\theta + \frac{\pi}{3}) \quad (10)$$

Substituting into the above equations yields:

$$F_D \frac{d_p}{2} \cos \theta + F_L \frac{d_p}{2} \sin \theta - F_W \frac{d_p}{2} \sin(\theta + \frac{\pi}{3}) = 0 \quad (11)$$

$$\frac{1}{2} C_D S \rho_L \Delta v^2 \frac{d_p}{2} \cos \theta + \frac{1}{2} C_L S \rho_L \Delta v^2 \frac{d_p}{2} \sin \theta - (\rho_p - \rho_L) V_s g \frac{d_p}{2} \sin(\theta + \frac{\pi}{3}) = 0 \quad (12)$$

Simplifying gives:

$$v_{gcr} = \sqrt{\frac{2(\rho_p - \rho_L) V_p g \sin(\theta + \frac{\pi}{3})}{S \rho_L (C_D \cos \theta + C_L \sin \theta)}} = \sqrt{\frac{4(\rho_p - \rho_L) d_p g \sin(\theta + \frac{\pi}{3})}{3 \rho_L (C_D \cos \theta + C_L \sin \theta)}} \quad (13)$$

- (b) In a steeply inclined pipe, the force equilibrium equation for the transport of elemental sulfur particles via suspension lift is:

$$F_D \sin \theta + F_L \cos \theta - F_W = 0 \quad (14)$$

Then

$$\frac{1}{2} S \rho_L \Delta v^2 (C_D \sin \theta + C_L \cos \theta) = (\rho_p - \rho_L) V_p g \quad (15)$$

The critical gas velocity for carrying sulfur particles is:

$$v_{scr} = \sqrt{\frac{2(\rho_P - \rho_L)V_p g}{5\rho_L(C_D \sin \theta + C_L \cos \theta)}} = \sqrt{\frac{4(\rho_P - \rho_L)d_p g}{3\rho_L(C_D \sin \theta + C_L \cos \theta)}} \quad (16)$$

The critical flow velocity of sulfur particles is related to the drag coefficient C_D , which is itself a function of the Reynolds number Re . Based on Reynolds number, the critical flow velocity can be divided into three regions: the viscous drag region, the transition region, and the pressure difference drag region. C_D can be approximated using Equations (17)–(19).

(a) Viscous drag region ($Re \leq 1$)

$$C_D = \frac{24}{Re} \quad (17)$$

(b) Transitional Region ($1 \leq Re \leq 500$)

$$C_D = \frac{10}{\sqrt{Re}} \quad (18)$$

(c) Pressure Difference Resistance Region ($500 \leq Re \leq 2 \times 10^5$)

$$C_D = 0.44 \quad (19)$$

According to Wang Zhizhong's experimental research, the critical solid-carrying liquid flow velocity was calculated using Equations (13) and (16) under identical conditions. The calculated results are compared with Wang Zhizhong's experimental data, as shown in Figure 3. As the pipe inclination angle increases, both the calculated critical liquid flow velocity and the experimentally measured values first increase and then decrease. The maximum critical liquid flow velocity occurs within the pipe inclination angle range of 50° to 60° . Although slight variations exist due to differences in experimental conditions, the error is less than 10%. This trend aligns with the test results reported by Ford [36] and Han Qiqing [37], which confirms the reliability of the derived critical liquid flow velocity formula for sulfur transport.

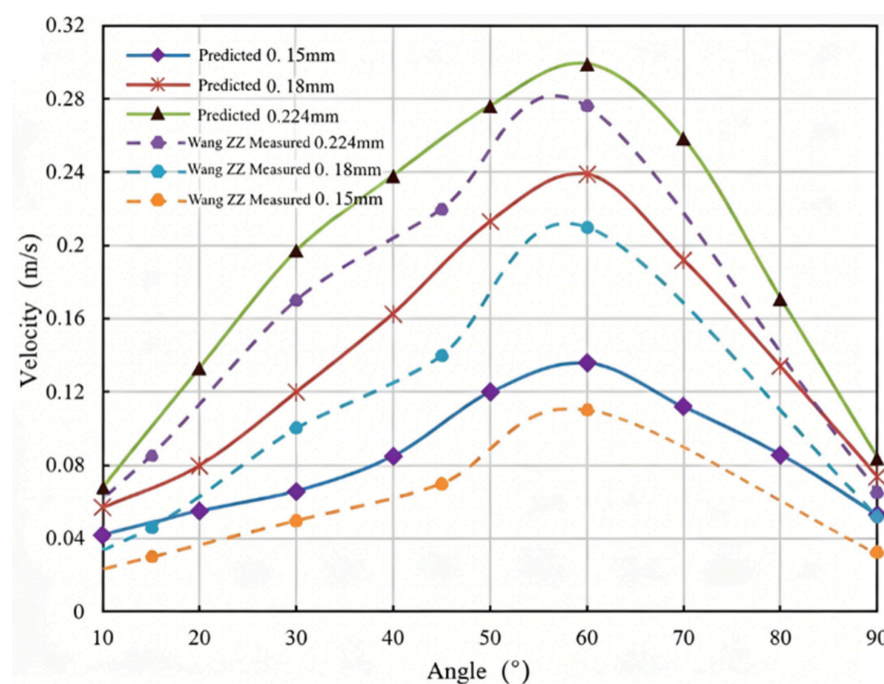


Figure 3. Comparison between predicted values and test data from Zhizhong Wang [1].

2.2. Prediction Model for Critical Gas Flow Velocity in Gas–Liquid Two-Phase Transport with Sulfur

The model couples the single-particle scale with the continuous liquid film scale by solving a system of equations that combines the critical carrying conditions for particles with the momentum balance of the liquid film. At the particle scale, the critical liquid film velocity required for sulfur particles to reach the critical entrainment state is determined based on the force balance acting on the sulfur particles within the liquid film; at the liquid film scale, the liquid film thickness and velocity are calculated using the shear stress at the gas–liquid interface, based on the gas core–liquid film momentum balance. The shear stress at the gas–liquid interface transfers momentum from the gas phase to the liquid film, and the liquid film velocity in turn determines the drag force acting on the sulfur particles. When the liquid film velocity reaches the value required for critical particle entrainment, the sulfur particles are in a state of critical entrainment, and the corresponding critical gas velocity can be determined accordingly.

(1) Liquid Film Model in Inclined Tubes

The upward movement of the liquid film primarily results from the shear force exerted by high-velocity gas flow. When the shear force applied by the gas significantly exceeds the combined resistance from the wall shear and the film's own weight, the gas carries the liquid film upward. However, gravity causes the thickness of the liquid film around the inclined pipe to be unevenly distributed; it is thicker at the pipe bottom and thinner at the top, as illustrated in Figure 4.

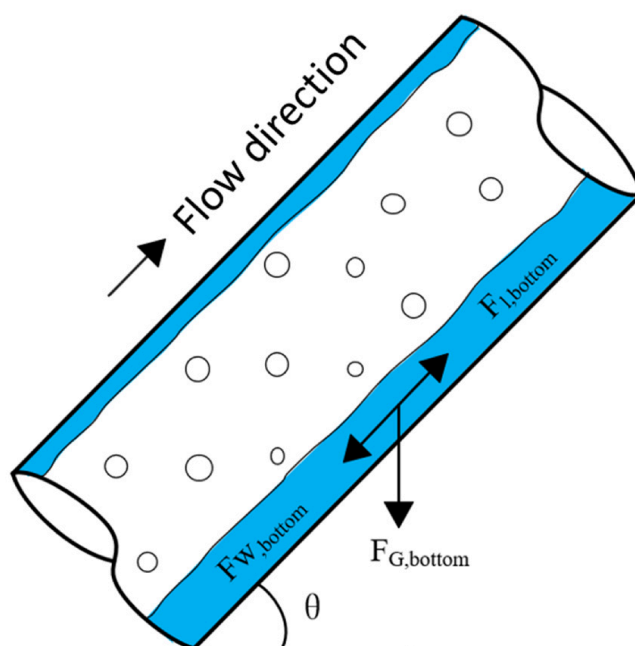


Figure 4. Schematic of liquid film distribution and force conditions.

When the shear stress at the gas–liquid interface balances the weight of the liquid film, the shear stress between the liquid film and the tube wall approaches zero. Under this condition, the liquid film at the bottom of the inclined tube begins to flow opposite to the gas flow direction. Within an inclined tube, reverse flow of the liquid film first occurs where the film is thickest across the cross-section and where gravity overcomes the interfacial shear stress. Since the liquid film is thickest at the tube bottom, this region is most susceptible to reverse flow. A force analysis performed on the thick liquid film at the bottom of the inclined tube yields:

$$F_{G,bottom} = \rho_L g h_f \sin \theta \quad (20)$$

where: h_f —liquid film thickness at the bottom of the inclined tube, m; θ —inclination angle, °; ρ_L —liquid density, $\text{kg}\cdot\text{m}^{-3}$; g —gravitational acceleration, m/s^2 .

The velocity of the liquid film is negligible compared to the gas flow velocity and can therefore be neglected. Under these conditions, the frictional force at the gas–liquid interface is simplified to the following expressions:

$$F_{Inter,bottom} = 0.5 f_I \rho_g v_g^2 \quad (21)$$

$$F_{Inter,bottom} = 0.5 f_I \rho_g \frac{v_{sg}^2}{(1 - 2h_a/d)^4} \quad (22)$$

where: f_I —interfacial friction coefficient between the liquid film and gas core; v_{sg} —gas superficial velocity, m/s ; h_a —average thickness of the liquid film, m.

At the critical condition for liquid carryover, the frictional force at the gas–liquid interface equals the gravitational force component of the liquid film. Solving Equations (20) and (22) simultaneously gives the critical gas flow velocity for the onset of liquid film carryover:

$$v_{crit} = \left(\frac{2\rho_L h_f g \sin \theta}{f_I \rho_G} \right)^{1/2} (1 - 2h_a/d)^2 \quad (23)$$

(2) Average liquid film thickness h_a

Models developed by Barnea [38] and Alve [39] predict the average liquid film thickness based on the momentum balance between the liquid film and the gas core. Evaluations of the Alves model demonstrate its high predictive accuracy for annular flow pressure gradients in vertical wells, with percentage errors of 3% in wellhead pressure and 10% in total pressure drop.

The physical model for annular flow in Alves [39] is illustrated in Figure 5. The model derivation employs linear momentum and mass conservation laws.

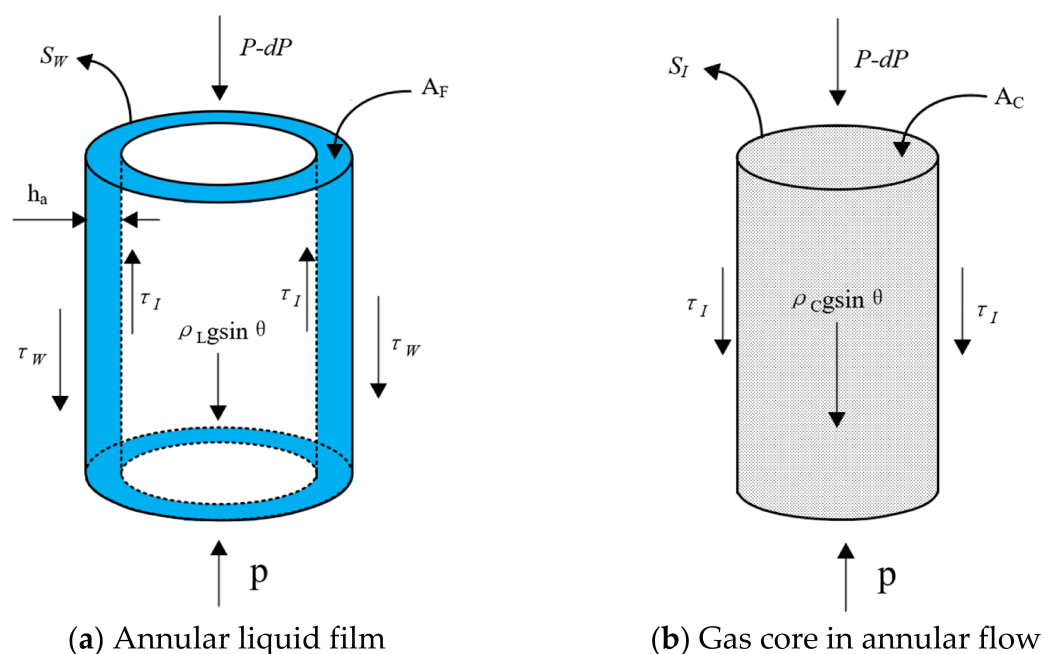


Figure 5. Average liquid film thickness predicted by the Alves model.

When considering a specific infinitesimal segment, the volume increment of the fluid is negligible, allowing the momentum change to be ignored. The momentum balance equation simplifies to a force balance equation, yielding

$$\tau_W \frac{S_W}{A_F} + \tau_I \frac{S_I}{A_F} + \left(\frac{dP}{dL} \right)_F - \rho_L g \sin \theta = 0 \quad (24)$$

where: τ_W —shear stress of the pipe wall on the liquid film, N/m²; τ_I —shear stress at the gas core–liquid film interface, N/m²; S_I —wetted perimeter length between the gas core and the liquid film, m; S_L —wetted perimeter length between the pipe wall and the liquid film, m; A_F —flow cross-sectional area of the liquid film, m²; $(\frac{dp}{dL})_F$ —pressure gradient of liquid film, Pa/m.

For the gas core, the momentum conservation principle gives:

$$-\tau_I \frac{S_I}{A_C} + \left(\frac{dP}{dL} \right)_C - \rho_C g \sin \theta = 0 \quad (25)$$

where: A_C —flow cross-sectional area of the gas core, m²; ρ_C —density of gas core, kg/m³; $(\frac{dp}{dL})_C$ —pressure gradient within gas core, Pa/m.

For an infinitesimal segment dL , the pressure gradients at both ends of the liquid film are equal to those at both ends of the gas core. Combining Equations (24) and (25) yields:

$$-\tau_W \frac{S_W}{A_F} + \tau_I S_I \left(\frac{1}{A_F} + \frac{1}{A_C} \right) - (\rho_L - \rho_C) g \sin \theta = 0 \quad (26)$$

The average liquid film thickness, h_a , is obtained using the Alves model. According to Wang [40], Equations (23) and (27) are solved simultaneously to determine the gas–liquid two-phase flow parameters under non-uniform liquid film conditions in an inclined pipe. Equations (13) and (16) provide, respectively, the liquid film flow velocities required for critical sulfur particle entrainment under different well inclination conditions, which serve as criteria for determining the liquid film flow state; Equations (23) and (27) establish the relationships among the critical gas flow velocity, liquid film thickness, and liquid film flow velocity. When the local liquid film flow velocity calculated from the liquid film momentum balance reaches the critical liquid film flow velocity determined by Equation (13) or Equation (16), the corresponding gas flow velocity is the critical gas flow velocity for sulfur transport in the gas–liquid two-phase flow.

$$\frac{h_f}{h_a} = (-0.0003\theta^2 + 0.0015\theta + 3.16)[2.77(v_{sl} - 0.007) + 1][0.45\ln(d/0.0381) + 1] \quad (27)$$

where: h_f —bottom liquid film thickness of the inclined tube, m; θ —inclination angle, °; v_{sl} —liquid apparent flow velocity, m/s; h_a —average liquid film thickness, m.

(3) Model Solution

The model solution involves incrementally increasing the gas flow rate and liquid film thickness while ensuring momentum balance and critical velocity conditions are satisfied at each step. This iterative process determines the minimum gas velocity required to maintain sulfur-carrying capacity. Liquid film thickness influences flow resistance and interfacial shear stress, and the liquid film velocity must exceed a critical threshold to suspend particles. These factors collectively govern the stability of the multiphase flow system. The flowchart of the solution procedure is shown in Figure 6.

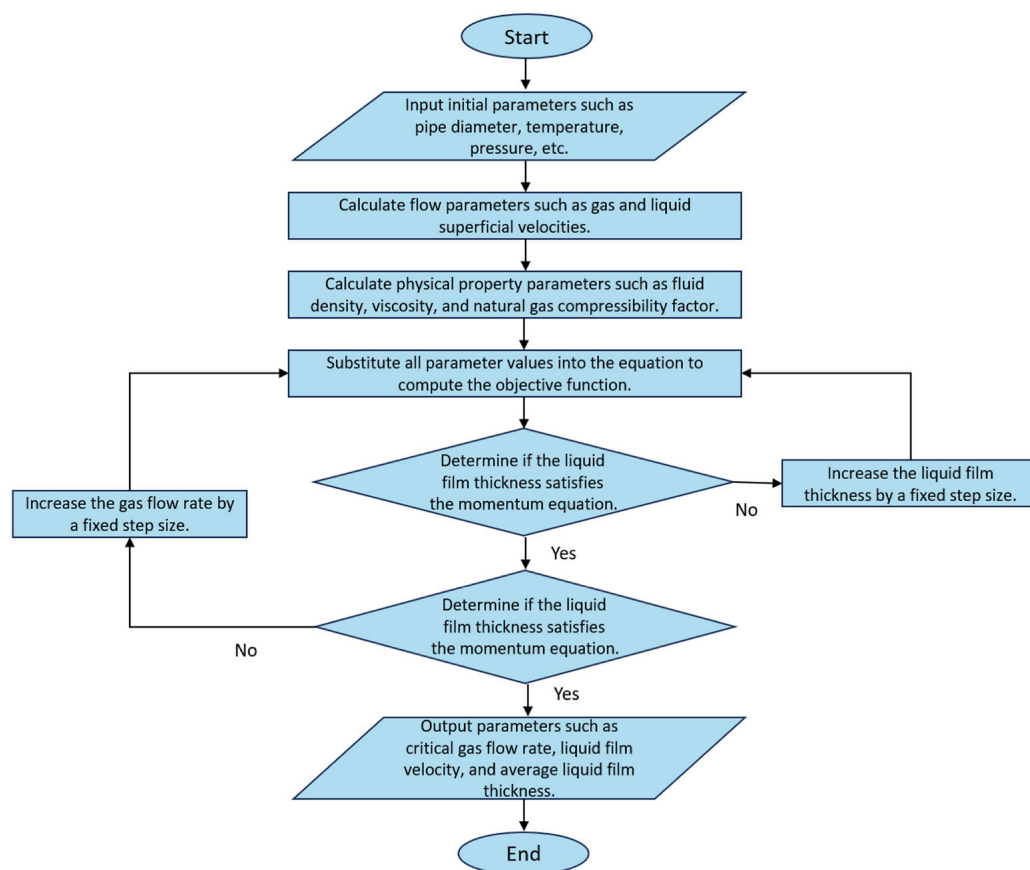


Figure 6. Flowchart of the model solution procedure.

3. Model Validation and Application

3.1. Experimental Data Validation

Wang Zhibin, Peng Jungang, and others measured the critical flow velocity of gas–liquid two-phase flow carrying sulfur at Southwest Petroleum University’s State Key Laboratory, using a pipe diameter of 40 mm, particle sizes of 0.5 mm, 1 mm, and 2 mm, and inclination angles of 0°, 15°, 30°, 45°, 60°, 75°, and 90° [41]. All 48 sets of experiments utilized an air–water-based simulant–sulfur particle system and were calculated under uniform experimental conditions. The density and dynamic viscosity of air were taken as 1.20 kg/m³ and 1.81 × 10^{−5}, respectively; the density of the water-based simulant was set at 1000 kg/m³, and its dynamic viscosity was controlled at 0.01 Pa·s; the air–liquid interfacial tension was set to 50 mN/m; and the density of the sulfur particles was set to 2070 kg/m³. The densities and viscosities of the gas and liquid phases were used to calculate the Reynolds number, the particle drag coefficient, and the interfacial shear stress; the interfacial tension was used for calculations related to interfacial interactions; and the density and particle size of the sulfur particles were used for calculations of particle force equilibrium. A comparison of the experimental data from 48 test sets with the model predictions is shown in Figure 7. As shown, the model predictions are very close to the experimental values. The prediction errors are shown in Figure 8, with a Mean Absolute Percentage Error (MAPE) of 2.28%, indicating high prediction accuracy and demonstrating the reliability of the established model for predicting the critical gas flow velocity for sulfur-carrying gas–liquid two-phase flow.

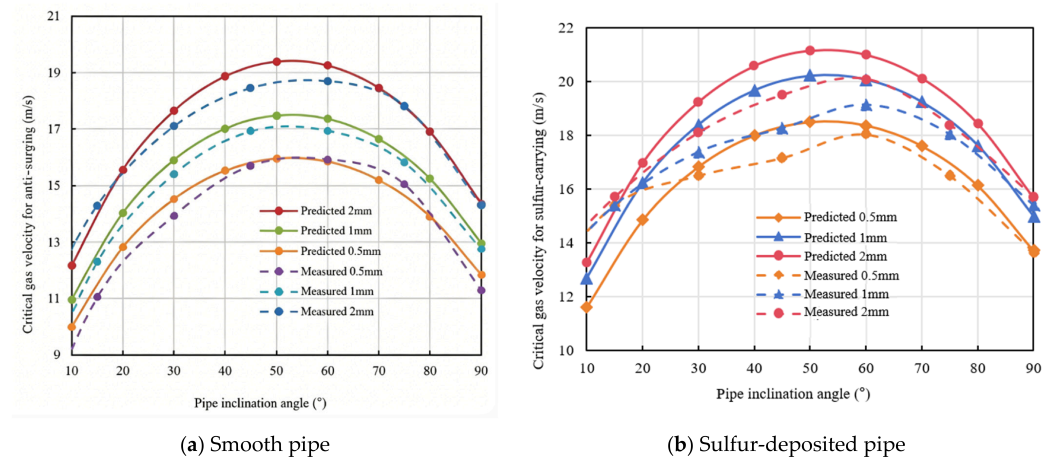


Figure 7. Comparison between model predictions and experimental test data.

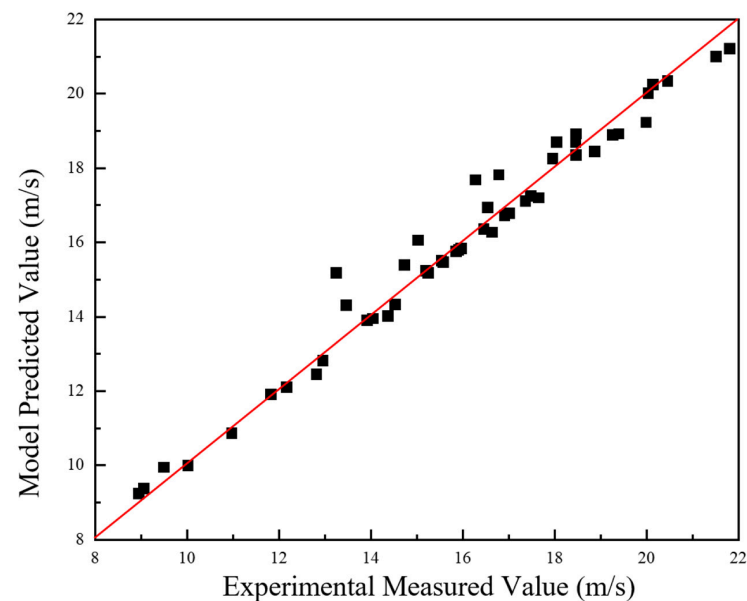


Figure 8. Evaluation of model prediction errors.

The Mean Absolute Percentage Error is defined as follows:

$$MAPE = \frac{100\%}{n} \sum_{i=1}^n \left| \frac{Q_{pre,i} - Q_{exp,i}}{Q_{exp,i}} \right| \quad (28)$$

where: $Q_{pre,i}$ —the predicted value from the i -th model; $Q_{exp,i}$ —the experimental measurement from the i -th group; n —the number of data sets.

The coefficient of determination is defined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^n (Q_{exp,i} - Q_{pre,i})^2}{\sum_{i=1}^n (Q_{exp,i} - \bar{Q}_{exp})^2} \quad (29)$$

where: $\bar{Q}_{exp}$ —the average of all experimental test values.

The Mean Absolute Percentage Error is defined as follows:

$$MAPE = \frac{100\%}{n} \sum_{i=1}^n \left| \frac{Q_{exp,i} - Q_{pre,i}}{Q_{exp,i}} \right| \quad (30)$$

Based on the same 48 sets of experimental test data from Southwest Petroleum University, a comparison of prediction accuracy was conducted between the new model proposed in this paper, the Guo [42] model, and the Zhu Guo [16] model. The results are shown in Figure 9, “Model Prediction Comparison.” Compared with the Guo and Zhu Guo models, the model proposed in this paper takes into account the shear stress at the gas–liquid interface and the critical Weber number constraint for droplet breakup, resulting in higher accuracy in predicting the critical sulfur transport velocity under high-sulfur-content produced water conditions. To further quantitatively evaluate the predictive performance of the different models, the RMSE, R^2 , and MAPE were calculated for the new model proposed in this paper, the Guo model, and the Zhu model (see Equations (28)–(30)), and the results are presented in Table 3, which shows the statistical evaluation of the predictive performance of the different models. Compared with the Guo and Zhu models, the new model proposed in this study exhibits lower RMSE and MAPE values and a higher R^2 value, indicating better agreement with experimental data and the ability to more accurately predict the critical gas flow velocity for sulfur particle transport in high-sulfur-content produced water gas wells. Our analysis suggests that these differences primarily stem from the varying approaches each model takes toward the gas–liquid interface friction factor and the droplet/particle drag coefficient. The Guo model employs a simplified empirical relationship that does not fully account for the influence of sulfur particles on flow patterns; although the Zhu model represents an improvement, it does not consider the critical Weber number constraint for droplet breakup. In contrast, our model introduces a coupled interfacial shear stress term and a Weber number correction, thereby more accurately describing multiphase flow behavior under high-sulfur conditions. Furthermore, the Guo and Zhu models are primarily applicable to the flow and physical property conditions covered in their original studies; the model presented in this paper is tailored to high-sulfur water-producing gas wells and has been validated using 48 sets of experimental data and field well conditions. Therefore, the model presented in this paper is more suitable for high-sulfur, water-producing conditions.

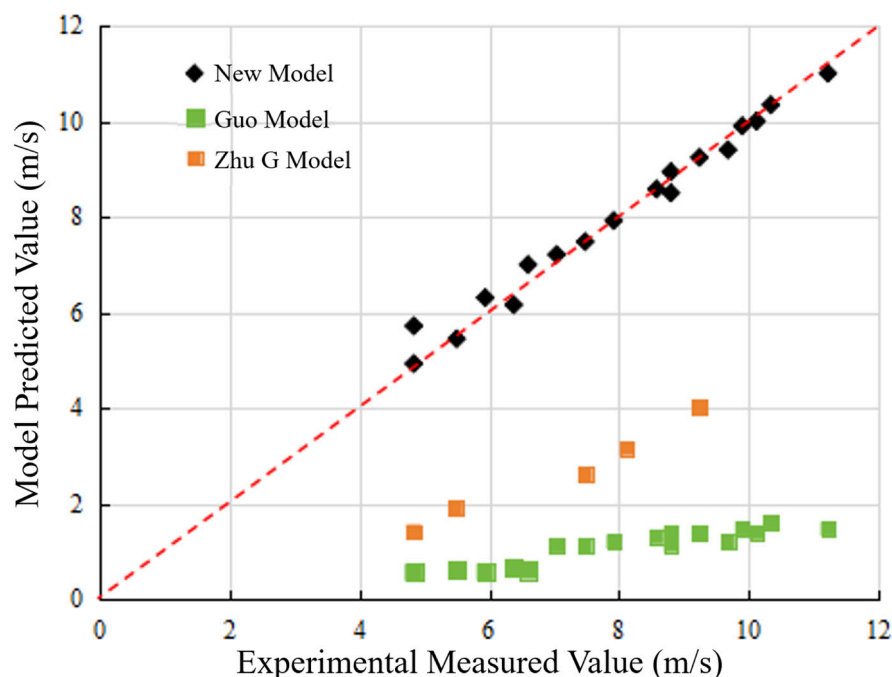


Figure 9. Model prediction comparison chart [16,42].

Table 3. Statistical evaluation results of the predictive performance of different models.

Model	RMSE (Root Mean Square Error)	R ² (Coefficient of Determination)	MAPE (%) (Mean Absolute Percentage Error)
the proposed model	0.5262	0.9709	2.2890
the Guo model	7.2031	−14.8208	86.9052
the Zhu model	4.4739	−6.4283	63.8202

3.2. Gas Well Case Study Calculation and Analysis

Experimental results indicate that for uniform transport of sulfur particles by annular liquid films, the required gas flow velocity increases with particle size. Determining the maximum sulfur particle diameter enables calculation of the critical gas flow velocity required to carry all particles. Since sulfur particles form from solidified sulfur droplets, only the maximum diameter of sulfur droplets needs to be determined. According to prior research [43–46], the critical Weber number W_e for droplet breakup is approximately 50. This Weber number criterion remains applicable to the droplet breakup mechanism under the high-temperature, high-pressure, and high-sulfur-content natural gas field conditions described in this paper, with a corresponding comprehensive coefficient (CD) of 2.65.

$$v_G = \frac{Q_G}{AB_G} = \frac{4Q_G}{\pi D^2 B_G} \quad (31)$$

$$D = \frac{W_e \sigma}{\rho_G v_G^2} \quad (32)$$

where: σ —interfacial tension, N/m; D —pipe diameter, m; d —particle diameter, m; B_G —gas volume coefficient, m; Q_G —gas production rate, m³/d; W_e —Weber number.

Taking the inclined well PG102-X as an example, on 26 December 2023, the measured wellhead oil pressure was 8.2 MPa, casing pressure was 5.4 MPa, daily gas production was 34.2×10^4 m³/d, daily water production was 6.45 m³/d, and formation temperature was 130 °C. The natural gas composition was: CH₄ content 85.4%, CO₂ content 5%, and H₂S content 6.7%. Using Equation (31), the gas flow velocity at the surface wellbore was calculated to be 4.66 m/s. According to Equation (32), the maximum diameter of sulfur droplets was determined to be 0.6 mm.

The critical gas flow rate for sulfur transport along the entire wellbore, predicted by the model, is shown in Figure 10. From 0 to 4300 m, the well consists of a vertical section. The critical gas flow rate increases with depth in this interval. From 4300 m onward, the well enters a deviated section where the inclination angle gradually increases. The predicted maximum critical gas flow rate occurs at a depth of approximately 4700 m, corresponding to an inclination angle of about 30°. As depth increases further and the inclination becomes steeper, the critical gas flow rate required for particle transport gradually decreases.

A comparison between the predicted critical gas flow rate curve for the PG102-X well and its actual production rate of 34.2×10^4 m³/d reveals that the two values are equal at a depth of about 4000 m. Below 4000 m, the required critical flow rate exceeds the actual production rate. This indicates that below this depth, sulfur particles cannot be continuously transported, leading to deposition. This prediction agrees with the actual well conditions, which include significant sulfur deposition and blockage.

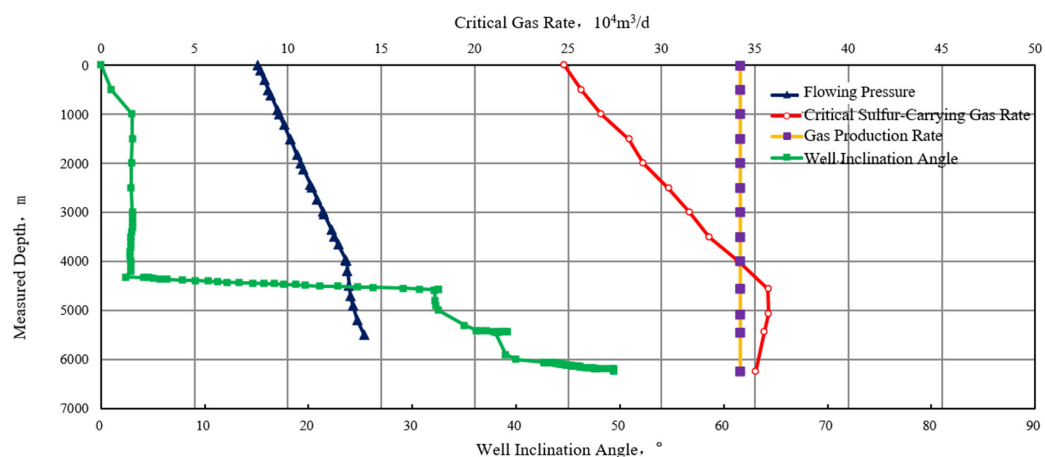


Figure 10. Variation in critical gas flow rate for sulfur transport and flowing pressure with depth in Well PG102-X.

4. Conclusions

- (1) Based on a force analysis of sulfur particles in annular flow liquid films, a calculation model for the critical sulfur-carrying liquid flow velocity in vertical and inclined pipes was derived and established. Validation using experimental data from Wang Zhizhong [1] showed the model's prediction error to be less than 10%. Furthermore, the variation patterns of the critical sulfur-carrying liquid flow velocity with pipe inclination angle and particle size were consistent with results from literature studies.
- (2) Based on the gas–liquid two-phase transport mechanism involving gas-driven liquid film and liquid-film-driven sulfur particles, a theoretical model for predicting the critical gas flow velocity was developed. This model is derived from a force analysis of the liquid film and gas core, utilizing momentum conservation. Evaluation using 48 sets of experimental data demonstrates high model accuracy, with an average relative error of 1.8%.
- (3) Taking the deviated well PG102-X in the PG gas field as an example, a case study was conducted to calculate the critical gas flow rate for sulfur particle transport. The variation pattern of the critical gas flow rate for sulfur particle transport along the wellbore was analyzed. The calculation results indicate that sulfur particle deposition is prone to occur at depths below 4000 m in this gas well, which is fully consistent with the actual field observations, thereby verifying the reliability of the predictive theoretical model established in this study.

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