Parameter Optimization of the Critical Liquid-Carrying Flow Model based on The Field

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Abstract

The critical liquid-carrying flow rate is a core parameter for the dynamic regulation and reasonable production capacity assessment of gas Wells. The accuracy of its calculation formula directly affects the early warning of liquid accumulation in gas Wells, the optimization of production systems and the development benefits. The critical liquid-carrying flow calculation formulas widely used at home and abroad (such as Turner model, Min Li model, etc.) often have significant deviations from the on-site measured values under complex working conditions (high sulfur content, high pressure, low production, etc.) due to the failure to fully consider the flow state changes of gas-liquid two-phase, the coupling effect of fluid physical property parameters, and the actual structural differences of the wellbore. It is difficult to meet the precise development requirements. To enhance the applicability of the formula and the calculation accuracy, based on the theory of gas-liquid two-phase flow and combined with the on-site measured data of 325 production Wells in a certain gas field, this paper optimizes the critical liquid-carrying flow model.

Keywords

Critical Liquid-carrying Flow Rate; Gas Reservoir Development; Dynamic Analysis.

1. Introduction

In 1996, Turner, through his research on the flow mode of the liquid phase in vertical pipe flow, proposed a spherical droplet model to predict the formation of liquid accumulation and derived the formula for calculating the critical liquid-carrying flow rate[1]. Subsequently, many scholars have done a great deal of work respectively in aspects such as model coefficients, liquid phase flow patterns, and droplet shapes based on the droplet model. In 2001, Min Li believed that when liquid droplets move in high-speed gas flow, they would transform into ellipsoids due to the pressure difference effect[2]. From this, he derived the critical liquid-carrying model for continuous liquid discharge from gas Wells. In 2007,Yizhong Wang, based on the spherical cap-shaped droplets moving in high-speed gas flow, believed that the droplets in the model should be spherical cap-shaped, and thus derived the calculation formula for the minimum liquid-carrying critical flow rate of gas Wells[3]. However, in the droplet model, the interfacial tension between gas and water is usually regarded as a constant of 60mN/m, but experiments show that its value varies with changes in pressure and temperature. The deviation factor Z of natural gas is usually taken as a constant of 0.88, but its value is significantly affected by temperature and pressure. Therefore, when solving the critical liquid-carrying flow rate of gas Wells, it is necessary to consider the influence of the actual gas-water interfacial tension and the deviation factor of natural gas.

2. Optimization of the Critical Liquid-carrying Flow Model

2.1. Liquid-drop Model

The main droplet models include the Turner model, the Ming Li model, and the Yizhong Wang model. The critical flow rates for carrying liquid in each model are different, as shown in Table 1.

Table 1. Comparison of critical liquid-carrying flow rates of each model

Model	Turner Model	Min Li Model	Yizhong Wang Model
Critical liquid-carrying flow rate	$v_g = 1.3\left[\frac{\sigma(\rho_l - \rho_g)}{\rho_g^2 C_d}\right]^{0.25}$	$v_g = \left[\frac{4\sigma(\rho_l - \rho_g)g}{\rho_g^2 C_d}\right]^{0.25}$	$v_g = \left[\frac{4\sigma(\rho_l - \rho_g)g}{3\rho_g^2 C_d}\right]^{0.25}$

Among the three droplet models, the assumed conditions are spherical, ellipsoidal and spherical cap droplets in three states respectively[4]. The drag coefficient Cd is the ratio of the drag force exerted by the fluid on the particle to the product of the projected area of the particle in its direction of motion and the hydrodynamic pressure, which is related to the droplet shape. Therefore, different states of droplets correspond to different drag coefficients Cd. In the Turner model, the drag coefficient of the spherical droplet was taken as 0.44, in the Ming Li model as 1.0, and in the Yizhong Wang model, the drag coefficient of the spherical cap-shaped droplet was taken as 1.17 based on the experimental data[5-9]. By substituting the corresponding Cd into the critical flow velocity formulas of each model, the model coefficients a of each model were obtained, as shown in Table 2.

Table 2. Comparison of coefficients of each droplet model

Model	Turner Model	Min Li Model	Yizhong Wang Model
Droplet morphology	Spherical	Ellipsoid	Spherical cap shape
Drag coefficient C_d	0.44	1.00	1.17
Coefficient a	6.6	2.5	2.25

2.1.1. Critical Liquid-carrying Flow Rate

The liquid-carrying critical flow rates of each model can all be expressed by the following formula:

$$v_g = a\left[\frac{\sigma(\rho_l - \rho_g)}{\rho_g^2}\right]^{0.25}$$

$$\rho_g = 3.4844 \times 10^3 \frac{\gamma_g p_{wf}}{ZT} = 0.12037 \times 10^3 \frac{M_g p_{wf}}{ZT}$$

$$q_c = \frac{2.5 \times 10^4 A v_g p_{wf}}{ZT} = \frac{1.9625 \times 10^4 D^2 v_g p_{wf}}{ZT}$$

In the formula:

v_g—Critical liquid-carrying flow velocity,m/s;

q_c—critical liquid-carrying flow rate,$10^4 m^3/d$;

ρ_g—Natural gas density,kg/m^3;

ρ_l—Formation water density,kg/m^3;

σ—Gas-water interfacial tension,N/m;

a—Model equation coefficient;

γ_g—Natural gas relative density;

p_{wf}—Bottom-hole flowing pressure,MPa;

T—Bottom-hole temperature,K;

Z—Gas deviation factor;

A—Tubing cross-sectional area,m^2;

D—Tubing diameter,m。

2.2. Determination of Key Parameters for Critical Liquid-Carrying Flow Rate Model

In the critical liquid-carrying flow rate model, the gas-water interfacial tension σ, deviation factor Z, and gas density ρ_1 are significantly influenced by pressure and temperature. Using generalized values for these parameters may lead to substantial errors[10]. The gas-water interfacial tension can be determined using the empirical formula:

$$\sigma(p,T) = \frac{248.004 - 1.8t}{206}(\sigma_1 - \sigma_2) + \sigma_2$$

$$\sigma_1 = 76e^{-0.0362575p}; \sigma_2 = 52.5 - 0.87018p$$

In the formula:

σ—Interfacial tension of water at temperature t°C, in mN/m;

σ_1—Interfacial tension of water at 23.33°C, in mN/m;

σ_2—Interfacial tension of water at 137.78°C, in mN/m;

t—Instantaneous water temperature, in °C;

p—Instantaneous pressure value, in MPa.

The deviation factor Z and gas density ρ_1 are determined through numerical simulation based on actual gas composition analysis from the block-operated region and data from high-pressure physical property studies. This allows derivation of empirical formulas for the deviation factor Z (Fig. 1) and gas density ρ_1 (Fig. 2) as functions of pressure p and temperature T.

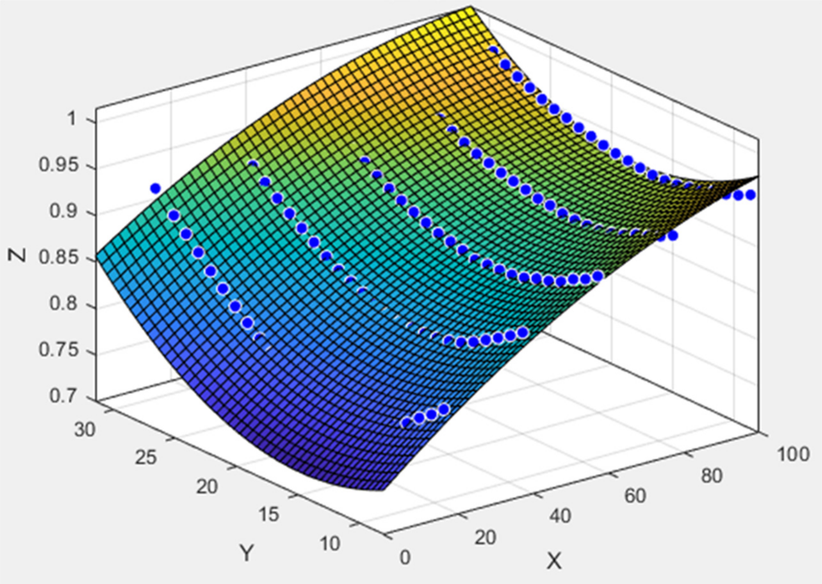


Fig 1. Deviation factor fitting curve

2.3. Liquid Loading Diagnosis In Choked Wells

For wells equipped with chokes, conventional critical liquid-carrying flow rate models may not be applicable. When liquid loading initiates in a choked well, the downstream section of the choke is more prone to meeting liquid accumulation conditions compared to the upstream section. Specifically, during production, liquid accumulation does not occur simultaneously in both sections of the wellbore. Instead, the flow rate downstream of the choke first falls below the critical liquid-carrying threshold, leading to liquid accumulation, after which the upstream section gradually begins to accumulate liquid. Thus, liquid loading occurs in the gas well even if the flow rate through the choke has not dropped below the critical liquid-carrying value[11-13].

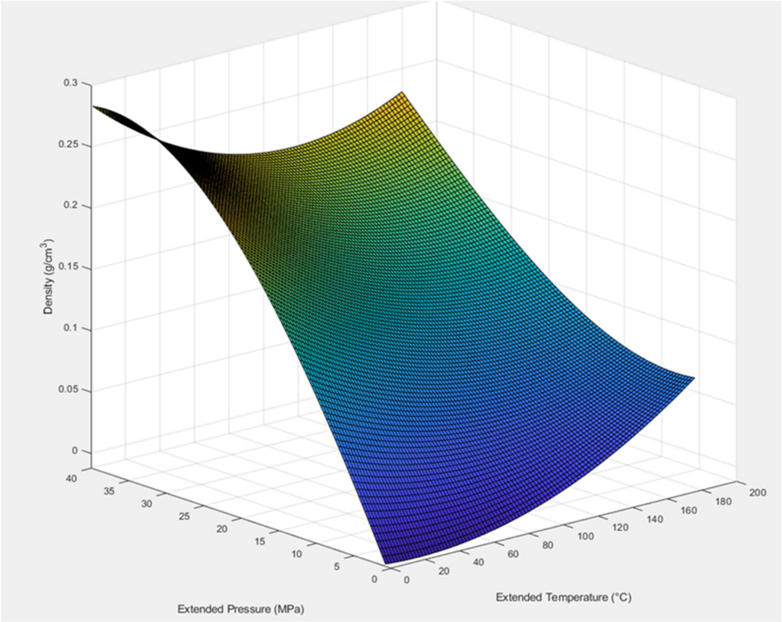
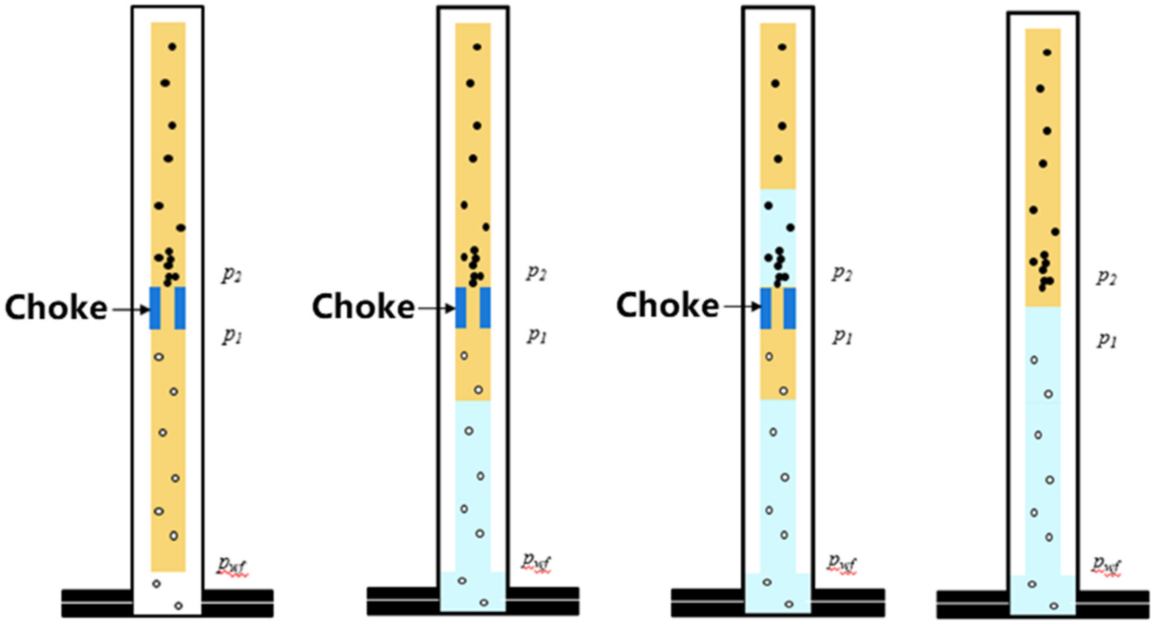


Fig 2. Natural gas density fitting curve



(a)During Normal Gas Well Production (b)Liquid Accumulation Downstream of the Choke (c)Liquid accumulation upstream of the choke (d)After choke retrieval

Fig 3. Liquid Loading Process in Choked Wells

A choke functions as a throttling device, adhering to the principles of orifice flow. When fluid passes through a fixed-size choke under critical flow conditions, the gas passing through the choke reaches a maximum flow rate. As the pressure ratio between the upstream (outlet, p_1)

and downstream (inlet, p_2) sections of the choke (p_1/p_2) continuously increases, the gas flow rate decreases accordingly, indicating a transition to subcritical flow conditions.

Under critical flow conditions, the gas flow rate through the choke is given by:

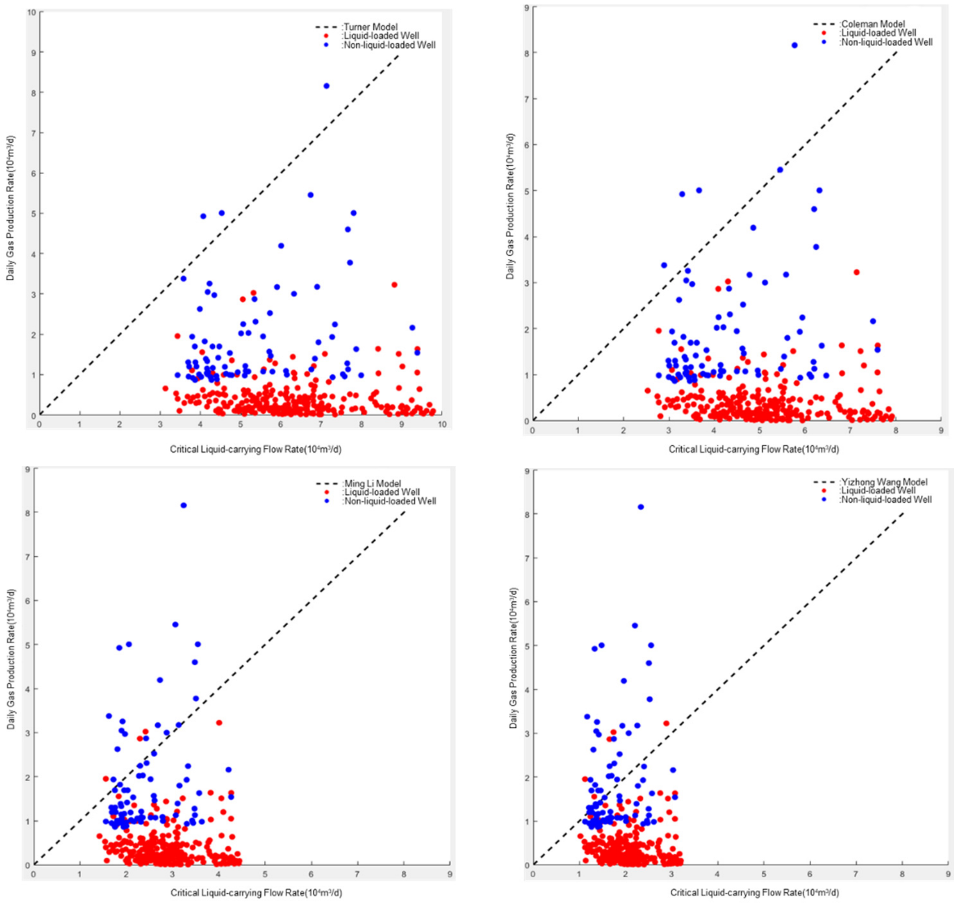
$$Q_g = \frac{4.066 \times 10^3 P_1 d^2}{\sqrt{r_g T_1 Z_1}} \sqrt{\frac{K}{K-1}\left[\left(\frac{2}{K+1}\right)^{\frac{2}{K-1}} - \left(\frac{2}{K+1}\right)^{\frac{K+1}{K-1}}\right]}$$

Under subcritical flow conditions, the gas flow rate through the choke is expressed as:

$$Q_g = \frac{4.066 \times 10^3 P_1 d^2}{\sqrt{\gamma_g T_1 Z_1}} \sqrt{\frac{K}{K-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{K}} - \left(\frac{P_2}{P_1}\right)^{\frac{K+1}{K}}\right]}$$

2.4. Optimization of Parameters for Critical Liquid-Carrying Flow Rate Model

The critical liquid-carrying flow rates of 325 gas wells in a specific gas field were calculated using four critical liquid-carrying models. These wells underwent actual liquid level measurements using pressure gauges. When the daily gas production fell below the critical liquid-carrying flow rate, the gas wells were considered likely to experience liquid accumulation. A comparison between the model-calculated data and the dynamic monitoring data of liquid levels revealed the following accuracy rates: Turner model: 75.93%; Coleman model: 76.54%; Ming Li model: 79.63%; Yizhong Wang model: 83.02%. The results indicate that the Yizhong Wang model has the highest applicability for this gas field.



(a)Turner Model (b) Coleman Model (c) Ming Li Model (d) Yizhong Wang Model

Fig 4. Calculation Results of Four Critical Liquid-Carrying Flow Rate Models

Based on pressure gauge liquid level measurement data, the four models were respectively modified to improve their applicability rates. The accuracy rates of the modified models are as follows:Modified Turner model: 78.70%;Modified Coleman model: 81.17%;Modified Ming Li model: 88.89%;Modified Yizhong Wang model: 91.36%.The modified Yizhong Wang model is applicable to the majority of gas wells in the study area.

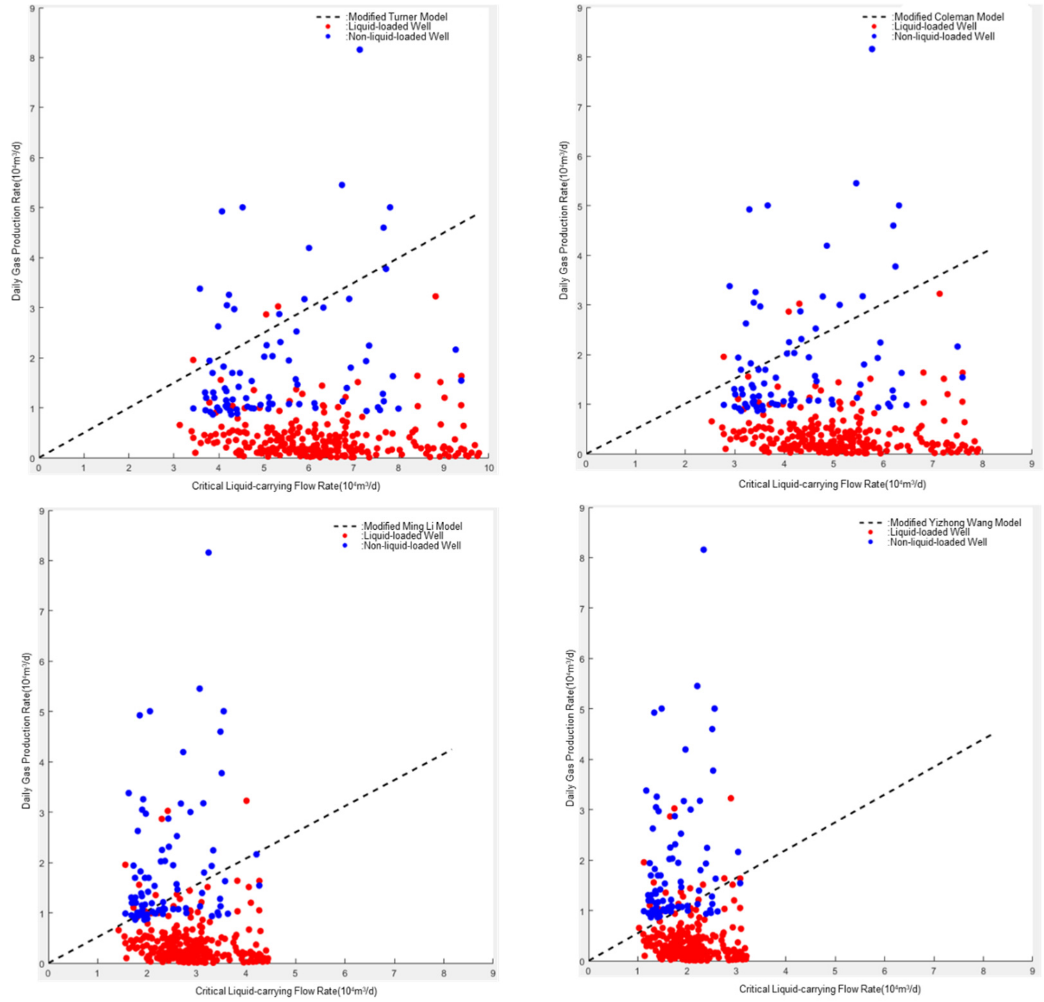
The modification formula is as follows:

Critical liquid-carrying flow velocity of the Yizhong Wang model:

$$u_c = 1.8\left[\frac{\sigma\left(\rho_L - \rho_g\right)}{\rho_g^2}\right]^{0.25}$$

Modified Yizhong Wang model's critical liquid-carrying flow rate formula:

$$q_c = 0.55 \times 2.5 \times 10^4 A u_c \frac{p}{ZT}$$



(a)Modified Turner Model (b)Modified Coleman Model (c)Modified Ming Li Model (d)Modified Yizhong Wang Model

Fig 5. Calculation Results of the Four Modified Critical Liquid-Carrying Flow Rate Models

3. Conclusion

Based on the actual pressure gauge liquid level measurement data from the study area and considering the effects of gas-water interfacial tension, deviation factor, and gas density, the four models were modified accordingly. The accuracy rates of the modified models are as follows: Modified Turner model: 78.70%;Modified Coleman model: 81.17%;Modified Ming Li model: 88.89%;Modified Yizhong Wang model: 91.36%.The modified critical liquid-carrying flow rate models show significant improvement in accuracy. The modified Yizhong Wang model is applicable to the majority of gas wells in the study area. The optimal modification parameter for the Yizhong Wang model is determined to be 0.55.

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