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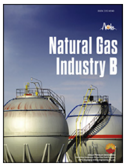

Research Article

A calculation model of critical liquid-carrying velocity of gas wells considering the influence of droplet shapes☆,☆☆

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Abstract

To clarify the existence of liquid loading and optimize the production allocation in gas wells, we constructed a model for calculating the critical liquid-carrying velocity based on the equal relationship between the total surface free energy of droplets and the total turbulent kinetic energy of gas and considering the droplet size, droplet deformation and the influence of droplet deformation on surface free energy. Based on the ellipsoid hypothesis and by analyzing the influence of droplet deformation on the surface area and free energy of droplets, the equation for calculation of the maximum diameter of windward surface of droplets was developed. With consideration to the influence of droplet deformation on drags, the expression for the critical liquid-carrying velocity of ellipsoid droplets was clarified. With consideration to the influence of deformation and internal flow of droplets, the drag coefficient of the ellipsoid droplets was determined to be 20% higher than that of the Brauer Model for spheroid. A functional relationship between the deformation parameter K and the critical Weber number W_{ec} was established based on the energy conservation law. In addition, the calculation results were reduced by 10%. During the course, the impacts of gas-well pressure and temperature on surface tension were taken into account. The proposed model was compared with the models developed by Turner, Li Min, Wang Yizhong, Wang Zhibin and Xiong Yu, and on-site verification was conducted in 44 gas wells. The results show that the proposed model provides the prediction results in best coincidence with the actual performance of gas wells. In conclusion, the proposed model can be used to predict liquid loading in gas wells effectively.

Keywords: Water-bearing gas well; Liquid loading; Critical liquid-carrying velocity; Liquid droplet shape; Deformation parameter; Drag coefficient; Critical Weber number; Surface tension

During the development of water-bearing gas reservoirs, especially in the mid-late stage, with the gradual decrease of reservoir pressure and the increase of water production, water at the well bottom cannot be carried by gas flow to the surface, thus leading to liquid loading [1]. Such liquid loading will impose an additional back pressure to reservoirs, thus causing lower well production, or even worse, kill the well [2,3]. To solve this problem, researchers proposed various models to calculate the critical liquid-carrying velocity of gas wells. Turner et al. [4] first established a model, based on particle mechanics theory, to calculate the continuous liquid carrying of gas wells, but this model provided an over estimated value.

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Later, many scholars revised the Turner model [5—8]. Typically, the Li Min model has been widely applied in China [6]. Wang Zhibin and Li Yingchuan [9], Zhou Ruili et al. [10], and Xiong Yu et al. [11] established universal critical liquid-carrying velocity models based on the ellipsoid droplet hypothesis. Tan Xiaohua and Li Xiaoping [12] constructed a model according to the equal relationship between the total surface free energy of droplets and the total turbulent kinetic energy of gas, but this model fails to consider the droplet deformation and its influence on the droplet surface free energy. In this study, we developed a model to estimate the critical liquid-carrying velocity based on the equal relationship between the total surface free energy of droplets and the total turbulent kinetic energy of gas, with the droplet size, droplet deformation and its influence on surface free energy taken into account.

1. Model building

Taitel et al. [13] believed that the droplet size is determined by the turbulent force that shatters the droplet and the surface tension that holds it. Under the mist flow conditions in the wellbore, liquid phase primarily exists in the form of droplets. When the gas phase turbulent force is bigger than the gas/liquid phase surface tension, the droplets will shatter to smaller-sized ones; conversely, when the gas phase turbulent force is smaller than the surface tension, the droplets will aggregate to bigger ones. Thus, the maximum stable droplet size can be achieved when the two forces reach a balance. The droplet will deform slightly due to the pressure drop between its windward and leeward sides [1]. Therefore, as the Reynolds number varies, the droplet will present different shapes. The droplet deformation may lead to the following phenomena: 1) the windward surface area of the droplet and the drag coefficient will increase, and the droplets will be more easily lifted by the gas flow; 2) surface free energy of a single droplet will increase, while the total turbulent kinetic energy remains the same, the maximum diameter of the droplet will increase. In this paper, we assume that the liquid phase is distributed in the form of the largest droplets, and the droplets are ellipsoid shown in Fig. 1.

Based on the above hypothesis, we analyzed the influence of droplet deformation on the maximum windward diameter of droplets, the critical liquid-carrying velocity, and the drag coefficient. Accordingly, we provided the expression for the critical Weber number and the droplet deformation parameter. With consideration of the impacts of gas-well pressure and temperature on surface tension, we eventually developed a new model to calculate the critical liquid-carrying velocity of gas wells.

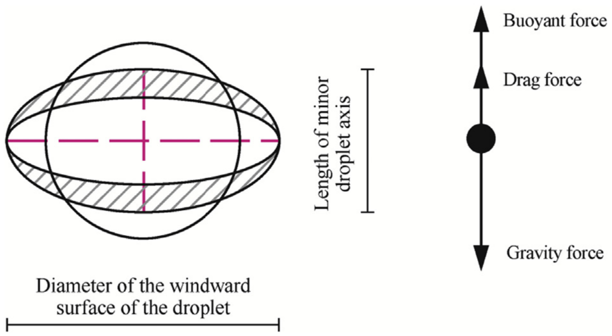

Fig. 1. Droplet deformation and force analysis.

1.1. The maximum windward diameter of the droplet

The shear force in the wellbore makes the liquid phase to form a certain number of droplets, and the number per unit time is determined by the following equation:

$$N=\frac{6v_{\mathrm{sl}}A}{\pi d^3} \tag{1}$$

where N is the number of the droplets; v_{sl} is the liquid phase superfacial velocity, m/s; A is the pipe cross sectional area, m^2; d is the windward diameter of the droplet, m.

The droplet deformation parameter is defined as Eq. (2):

$$K=\frac{d_{\mathrm{E}}}{d_{\mathrm{B}}} \tag{2}$$

where K is the droplet deformation parameter, dimensionless; d_{E} is the windward diameter of the ellipsoid droplet, m; d_{B} is the diameter of the spherical droplet, m.

The surface area of a single droplet can be calculated according to the following equation:

$$s=\frac{4}{3}\pi\left(\frac{K^2d^2}{4}+\frac{Kdh}{2}\right) \tag{3}$$

where s is the surface area of a single droplet, m^2; h is the length of the minor axis of the ellipsoid droplet, m.

Since the volume of the droplet remains constant in deformation process, we can obtain that

$$h=d/K^2 \tag{4}$$

Substituting Eq. (4) into Eq. (3), the surface area of a single droplet can be derived

$$s=\frac{4}{3}\pi\left(\frac{K^2d^2}{4}+\frac{d^2}{2K}\right) \tag{5}$$

and thus the total surface area S can be calculated according to Eq. (6):

$$S=sN=\left(\frac{2K^3+4}{K}\right)\frac{v_{\mathrm{sl}}A}{d} \tag{6}$$

Adamson et al. [14] suggested that the total surface free energy of the droplet per unit time can be calculated according to the following formula

$$E_{\mathrm{s}}=S\sigma \tag{7}$$

where E_{s} is the total surface free energy of the droplet, W; σ is the surface tension, N/m.

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