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An improved model for the prediction of liquid loading in gas wells

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A B S T R A C T

Liquid loading is a major limiting production factor for maturing gas wells, whereas the modeling of liquid loading behavior is still quite immature and the prediction of the critical gas rate is not very reliable.

On the basis of Turner's model, a new approach for calculating the critical gas flow rate is introduced in this paper, which takes into account the liquid amount in addition to the deformation and size of the liquid droplets. A dimensionless parameter is introduced in the new model to account for the deformation, distribution and maximum size of the liquid droplets. Well data from Turner's paper and Li Min's paper are used to validate the model. The prediction results agree well with both of the data.

1. Introduction

Since 20th century, there are so many research efforts on the reservoir performance subject to acid gas injection (Zhang et al., 2012a, 2012b, 2013; Wu et al., 2014), CO_2 sequestration/EOR (Zhang et al., 2015a, 2015b; 2016), multi-phase flow regimes (Wu et al., 2010; Yao et al., 2012; Xiong et al., 2013; Zhang et al., 2014). Not many studies are related to the liquid loading in the wellbore, which plays an important role during gas production from the well. It is a process when the gas is incapable of removing the liquid to the surface. The liquid accumulated downhole increases the back pressure, restricts the production capacity and even kills the well in severe cases. Previous mathematical equations were proposed to calculate the critical gas velocity necessary to keep gas-well unloaded (Nosseir, 2000; Boyun and Ali, 2006; Belfroid et al., 2008; Zhou and Yuan, 2010; Fadairo et al., 2013; Zhao et al., 2015a, 2015b). The Turner model (Turner et al., 1969) is the most widely used currently. The entrained droplet model is based on a force balance of a spherical liquid droplet entrained in the gas stream to calculate the critical gas velocity and critical flow rate (Appendix A). Min et al. (2001) contended that the droplet entrained in a high-speed gas stream will become ellipsoid in shape because of the pressure difference on the fore and rear of the droplet. The critical velocity is about 38% of Turner's model (Appendix B). The calculation of the flat-shaped droplet model is more suitable for the Li Min's gas field records than Turner's model. Some researchers have conducted a series of experiments (Awolusi, 2005; Wei et al., 2007). In their experiments, the droplets in the high-speed mist flow are flat-shaped and don't maintain a fixed posture. Their experimental results are between the calculated results of Turner's model and Li Min's model. Some researchers (Zhou and Yuan, 2009) pointed out that the concentration of liquid droplets was also a major factor for the prediction of the liquid loading. The liquid droplets nearby may collide and coalesce into a bigger one. If there is more liquid amount, the chance of liquid droplet collision, coalescing and falling increases and can't be ignored. The single droplet model presented by Turner and Li Min doesn't include the droplets collision effect. The empirical model proposed by D. Zhou on the basis of Turner data is a further improvement on the droplet model. A loss factor is introduced to account for the impact of the changes of gas-lifting efficiency caused by the rollover of droplets (Luan and He, 2012). Wang Zhibin presented a model taking account of the liquid-droplet deformation and size on the minimum flow rate, while the liquid amount is not taken into consideration (Zhibin and Yingchuan, 2012). The all models presented above agree well with their own test data used, however the accuracy is lower when other data from different sources are used. There is not a general model which is applicable to all the data.

This paper presents a model including the effect of liquid holdup and the drop deformation magnitude on the critical gas velocity calculation. Test-well data from Turner et al. and Li Min are

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employed to validate the new model.

2. New model

According to experimental analysis, we know that the liquid droplets are deformed to be flat-shaped. Introduce a distorted parameter k,

$$k = \frac{d}{d_0} \tag{1}$$

where k is the distorted parameter, dimensionless; d_0 is the diameter of the original spherical liquid droplet, m; d is the diameter of the projection plane of the distorted oblate spheroid, m.

Applying the force balance on a free-falling particle in a fluid medium, we can derive:

$$F_G = F_D + F_B \tag{2}$$

F_G is the gravity of the droplet, N, which can be expressed as,

$$F_G = \frac{1}{6}\rho_l g \pi d_0^3 \tag{3}$$

where ρ_l is the liquid density, kg/m^3; g is gravity acceleration, m/s^2.

F_D is the drag force on the droplet, N, which can be expressed as,

$$F_D = \frac{1}{8}C_D \pi d^2 \rho_g u_g^2 \tag{4}$$

where C_D is the drag coefficient, dimensionless; ρ_g is the gas density, kg/m^3; u_g is the velocity of gas flow, m/s.

F_B is the buoyancy force of the droplet, N, which can be expressed as,

$$F_B = \frac{1}{6}\rho_g g \pi d_0^3 \tag{5}$$

From Eqs. (1)–(5), the critical gas velocity for lifting the liquid droplet is then deduced:

$$u_{gc} = \sqrt{\frac{4\left(\rho_1 - \rho_g\right) g d_0}{3 C_D k^2 \rho_g}} \tag{6}$$

where u_{gc} is the terminal gas velocity, m/s. Measurements of the drop size in a gas stream represent a log-normal distribution (Al-Sarkhi and Hanratty, 2002). From Eq. 6, u_{gc} increases with increasing the drop size and that $u_{gc} \sim d_0^{05}$. As a result, d_0 is replaced by maximum drop diameter d_{max} to calculate u_{gc}.

Most of the models for predicting the size of drops in turbulent flow field are based on Hinze model (Hinze, 1955), which represents the droplet entrained is subjected to the external force that tends to deform the drop and the counteracting surface tension force to keep it integrated. The force balance of a single droplet is analyzed and droplet coalescence, rollover and collision is not taken into account. The prediction results above (Turner et al., 1969; Nosseir, 2000; Min et al., 2001; Boyun and Ali, 2006; Luan and He, 2012; Zhibin and Yingchuan, 2012) don't vary with liquid holdup, while the measurements (Azzopardi et al., 1991) indicate that the size and distribution of the liquid droplets depend on the liquid velocity in addition to the gas velocity. In this paper, the drop size is calculated through a balance between the turbulent kinetic energy and the droplets' surface energy.

The gas turbulent kinetic energy per unit volume is modeled by

$$E_k = \frac{1}{2}\rho_g\left(u_r'^2 + u_\theta'^2 + u_z'^2\right) \tag{7}$$

where E_k is the gas turbulent kinetic energy per unit volume, J/m^3; u_r', u_θ', u_z' is the radial, tangital and axis fluctuating velocity respectively, m/s, and can be evaluated based on the friction velocity u^* which is shown as (Hinze, 1955)

$$u^* = \left(\frac{\tau_w}{\rho_g}\right)^{1/2} \tag{8}$$

τ_w is the wall shear stress, N/m^2, and can be calculated by

$$\tau_w = \frac{1}{2} f \rho_g u_g^2 \tag{9}$$

where f is the friction factor, dimensionless, and can be calculated by Blasius equation,

$$f = \frac{0.079}{Re_g^{0.25}} \tag{10}$$

where Re_g is the gas Reynolds number, dimensionless, and can be expressed as

$$Re_g = \frac{\rho_g u_g D}{\mu_g} \tag{11}$$

where D is the pipe diameter, m; μ_g is the dynamic viscosity of gas, $Pa\cdot s$.

The rate of turbulent energy supply $\dot{E}_k$, W, is given by

$$\dot{E}_k = E_k Q_g \tag{12}$$

where Q_g is the gas flow rate, m^3/s.

The surface energy per unit volume E_s, J/m^3, is modeled by (Brauner, 2001)

$$E_s = \frac{\pi d_{max}^2 \sigma}{\pi d_{max}^3 / 6} = \frac{6\sigma}{d_{max}} \tag{13}$$

where σ is the surface tension, N/m; d_{max} is the maximum size of drop diameter, m.

The rate of surface energy $\dot{E}_s$, W, thus formed is given by (Brauner, 2001)

$$\dot{E}_s = E_s Q_l = \frac{6\sigma}{d_{max}} Q_l \tag{14}$$

where Q_l is the liquid flow rate, m^3/s.

The rate of turbulent energy supply $\dot{E}_k$ is proportional to the rate of surface energy $\dot{E}_s$ (Brauner, 2001).

$$\dot{E}_k = C_H \dot{E}_s \tag{15}$$

where C_H is a constant.

The maximum size of drop diameter is hence calculated via Eqs. (7)–(15),

$$d_{max} = \frac{8 C_H \sigma Q_l}{f \rho_g u_g^2 Q_g} \tag{16}$$

Substituting Eq. (16) into Eq. (6) yields