CHANGE MECHANISM OF TRANSIENT GAS-LIQUID TWO-PHASE FLOW IN WELLBORE DURING MARINE NATURAL GAS HYDRATE RESERVOIR DRILLING

by

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In the drilling process of a marine natural gas hydrate reservoir, the original temperature and pressure condition of the hydrate will change due to the influence of construction, and gas will be released from the hydrate. The decomposition gas makes the wellbore flow into a complex gas-liquid-solid multiphase flow after entering into the wellbore, and thus poses a great threat to the well control security. Accordingly a transient gas-liquid two-phase flow drift flux mathematical model is established in this paper. The numerical method is proposed and verified, and an example analysis is carried out. Finally the change mechanism of transient gas-liquid two-phase flow in wellbore is obtained. This study provides an important foundation for the safe design of an offshore gas hydrate. Meanwhile, it is of great positive significance to find the decomposition gas and to optimize drilling parameters in the drilling process of a marine natural gas hydrate reservoir.

Key words: *marine natural gas hydrate, transient gas-liquid two-phase flow, drilling, numerical calculation, wellbore pressure*

Introduction

In recent years, the marine natural gas hydrate has attracted more and more attention due to its huge resource. In the drilling process of a marine natural gas hydrate reservoir, the original temperature and pressure condition of the hydrate will change due to the influence of construction, and then the phase equilibrium state of the hydrate is destroyed, and gas will be released due to the hydrate decomposition. The decomposition gas makes the wellbore flow into a complex gas-liquid-solid multiphase flow after entering into the wellbore, and thus poses a great threat to the well control security. Because the solid phase content in the wellbore is low, its influence on wellbore flow can be ignored. Therefore, it is urgent to carry out research on the behaviors of gas-liquid two-phase flow in the offshore gas hydrate reservoir.

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Most scholars focused on phase equilibrium [1, 2], formation [3, 4], and decomposition of hydrate [5, 6], and wellbore flow safety during pipeline transportation [7, 8]. However, there are few researches on wellbore flow in the drilling process of a marine natural gas hydrate. Weng [9] and Wang *et al.* [10] studied the transition mechanism of annulus multiphase flow with natural gas hydrate phase transition. Wang *et al.* [11] studied the annulus multiphase overflow characteristics during the drilling process of natural gas hydrate, and established the multiphase flow equation of wellbore during the overflow. Wei *et al.* [12, 13] studied the wellbore flow pattern of the drilling of gas hydrate reservoir, and established a wellbore flow model based on steady-state analysis. Wei *et al.* [14, 15] studied the hydrate phase transition and multiphase flow pattern in the gas hydrate reservoir, and established the relevant steady-state mathematical model.

In this paper, based on the gas-liquid two-phase flow process after decomposition gas' entering into the wellbore in marine gas hydrate reservoir drilling, the transient gas-liquid two-phase flow drift flux mathematical model is established, the numerical method is proposed and verified, and example analysis is carried out. Finally the change mechanism of transient gas-liquid two-phase flow in wellbore is obtained, providing an important foundation for the safe design of offshore gas hydrate. Meanwhile, it is of great positive significance to find the decomposition gas and to optimize drilling parameters in the drilling process of marine natural gas hydrate reservoir.

Transient gas-liquid two-phase flow drift flux mathematical model

Based on the gas-liquid two-phase flow process after decomposition gas' entering into the wellbore in marine gas hydrate reservoir drilling, a 1-D transient gas-liquid two-phase flow drift flux model is established:

$$\frac{\partial(\rho_l \alpha_l)}{\partial t} + \frac{\partial(\rho_l \alpha_l v_l)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\rho_g \alpha_g)}{\partial t} + \frac{\partial(\rho_g \alpha_g v_g)}{\partial x} = 0 \tag{2}$$

$$\frac{\partial(\rho_g \alpha_g v_g + \rho_l \alpha_l v_l)}{\partial t} + \frac{\partial(\rho_g \alpha_g v_g^2 + \rho_l \alpha_l v_l^2 + p)}{\partial x} = -F_G - F_f - F_A \tag{3}$$

where

$$\alpha_g + \alpha_l = 1 \tag{4}$$

where ρ_l and ρ_g [kgm^{-3}] are the liquid and gas phase densities, respectively, v_l and v_g [ms^{-1}] – the liquid and gas phase velocities, respectively, α_l and α_g [–] – the liquid and gas phase volume fractions (dimensionless), respectively, p [Pa] – the wellbore pressure, t [s] – the time, x [m] – the space, and F_G, F_f, and F_A [Pam^{-1}] – the source terms representing gravity, frictional, and acceleration force, respectively. The parameters are solved as follows.

– The wellbore pressure is written:

$$\mathrm{d}p = (F_G + F_f + F_A)\,\mathrm{d}x \tag{5}$$

– The gravity force term can be represented by:

$$F_G = \rho_m g \sin(\theta) \tag{6}$$

– The frictional force term can be represented by:

$$F_{\mathrm{f}} = \frac{2f\rho_{\mathrm{m}}v_{\mathrm{m}}|v_{\mathrm{m}}|}{D-d} \tag{7}$$

– The acceleration force term can be represented by:

$$F_{\mathrm{A}} = \rho_{\mathrm{m}}v_{\mathrm{m}}\frac{\partial v_{\mathrm{m}}}{\partial x} \tag{8}$$

– The basic constitutive equation of drift flux model [16] is written:

$$v_{\mathrm{g}} = C_0 v_{\mathrm{m}} + v_{\mathrm{t}} \tag{9}$$

where

$$\rho_{\mathrm{m}} = \alpha_{\mathrm{l}}\rho_{\mathrm{l}} + \alpha_{\mathrm{g}}\rho_{\mathrm{g}} \tag{10}$$

$$v_{\mathrm{m}} = v_{\mathrm{l}}\alpha_{\mathrm{l}} + v_{\mathrm{g}}\alpha_{\mathrm{g}} \tag{11}$$

where ρ_{l} [kgm^{-3}] is the mixture density, v_{m} [ms^{-1}] – the mixture velocity, g [ms^{-2}] – the gravitational acceleration, θ [rad] – the inclination angle measured from the horizontal position, f [–] – the friction factor (dimensionless), D [m] – the inner diameter of the outer tube in drilling annulus, d [m] – the outer diameter of the inner tube in drilling annulus, C_0 [–] – the distribution parameter (dimensionless), and v_{t} [ms^{-1}] – the gas drift velocity.

The C_0 and v_{t} are empirical parameters which are dependent on flow condition. We use the Shi *et al.* [17] slip relation in this paper to calculate C_0 and v_{t}. They are solved as follows.

– The gas drift velocity is calculated by:

$$v_{\mathrm{t}} = \frac{(1-C_0\alpha_{\mathrm{g}})V_{\mathrm{c}}Km_{\theta}}{C_0\alpha_{\mathrm{g}}\sqrt{\dfrac{\rho_{\mathrm{g}}}{\rho_{\mathrm{l}}}} + 1 - C_0\alpha_{\mathrm{g}}} \tag{12}$$

where

$$K = \begin{cases} \dfrac{1.53}{C_0} \quad \text{if } \alpha_{\mathrm{g}} \le a_1 \\ \dfrac{1.53}{C_0} + \left[1-\cos\left(\pi\dfrac{\alpha_{\mathrm{g}}-a_1}{a_2-a_1}\right)\right]\dfrac{C_0K_{\mathrm{u}}-1.53}{2C_0} \quad \text{if } \alpha_1 < \alpha_{\mathrm{g}} \le a_2 \\ K_{\mathrm{u}}, \quad \text{if } \alpha_{\mathrm{g}} > a_2 \end{cases} \tag{13}$$

$$m_{\theta} = m_0(\cos\theta)^{n_1}(1+\sin\theta)^{n_2} \tag{14}$$

where K [–] is defined to optimize and smooth the v_{t} as α_{g} and v_{m} variation (dimensionless), K_{u} [–] – the Kutateladze number (dimensionless), [18], a_1 and a_2 are dimensionless number, which are defaulted to 0.2 and 0.4, respectively, m_{θ} [–] – the influence of gas drift velocity by wellbore inclination (dimensionless), m_0, n_1, n_2, are fitted parameter, which are defaulted to 1.27, 0.24, 1.08, respectively.

– The distribution parameter is calculated by:

$$C_0 = \frac{C_{\max}}{1 + (C_{\max} - 1)\gamma^2} \tag{15}$$

where $C_{\max}$ [–] is the C_0 in bobble and slug flow regimes, which is defaulted to 1.2 (dimensionless), γ – the parameter to lead C_0 to reduce to 1.0 at high α_g or v_m.

Numerical calculation method and verification

Numerical calculation method

In the process of gas-liquid two-phase flow after decomposition gas entering into the wellbore in marine gas hydrate reservoir drilling, for the calculation of transient gas-liquid two-phase flow drift flux mathematical model, with adapting the schemes developed by Liou *et al.* [19] for gas dynamic, we split the fluxes into convective and pressure parts which are treated separately for transient gas-liquid two-phase flow:

$$\mathbf{f}(\mathbf{u})_{j+1/2} = \mathbf{f}(\mathbf{u})_{l,j+1/2} + \mathbf{f}(\mathbf{u})_{g,j+1/2} + \mathbf{f}(\mathbf{u})_{p,j+1/2} \tag{16}$$

Taking the numerical convective fluxes of interface $x_{j+1/2}$ as example, the formulations of numerical convective fluxes that consist of mass flux and momentum flux for each phase are:

– mass flux

$$(\rho\alpha v)_{i,j+1/2} = \frac{1}{2}(\rho\alpha)_{i,L}\left(v_{i,j+1/2} + \left|v_{i,j+1/2}\right|\right) + \frac{1}{2}(\rho\alpha)_{i,R}\left(v_{i,j+1/2} - \left|v_{i,j+1/2}\right|\right) \tag{17}$$

– momentum flux

$$(\rho\alpha v^2)_{i,j+1/2} = (\rho\alpha v)_{i,L} V^+(v_{i,L}, c_{j+1/2}, \chi_L) + (\rho\alpha v)_{i,R} V^-(v_{i,R}, c_{j+1/2}, \chi_R) \tag{18}$$

where

$$v_{i,j+1/2} = V^+(v_{i,L}, c_L, \chi_L) + V^-(v_{i,R}, c_R, \chi_R) \tag{19}$$

$$c_{j+1/2} = \max(c_L, c_R) \tag{20}$$

where L and R [ms^{-1}] are left and right sides of cell interface $x_{j+1/2}$; c is the sound velocity of mixture.

Numerical calculation verification

For the verification of numerical calculation method of transient gas-liquid two-phase flow after decomposition gas entering into the wellbore in marine gas hydrate reservoir drilling, we choose the simulation test by Evje *et al.* [20], which particularly regarding mass transport, features transitions between genuine two-phase and pure liquid regions. In the test, a horizontal pipe of length 1000 m and diameter 0.1 m is initially full filled with static liquid. The liquid density is 1000 kg/m^3 and the outlet pressure is constant $0.1 \cdot 10^6$ Pa. The mass inflow rates of liquid and gas are increased from 0 to 12.0 kg/s and 0.08 kg/s, respectively, during the start 10 seconds of calculation. Then the mass inflow rates of liquid is to remain constant, while the mass inflow rates of gas is linearly decreased to 0 from 50 seconds to 70 seconds. The calculation ends at 175 seconds.

The numerical calculation results by our method are performed in fig. 1. It is obvious that converges uniformly to the reference solution, and the discontinuity of gas volume fraction is described well where no overshoots are visible. The numerical calculation method in this paper illustrates the excellent agreement between calculations results and references, and performs well stability and accuracy.

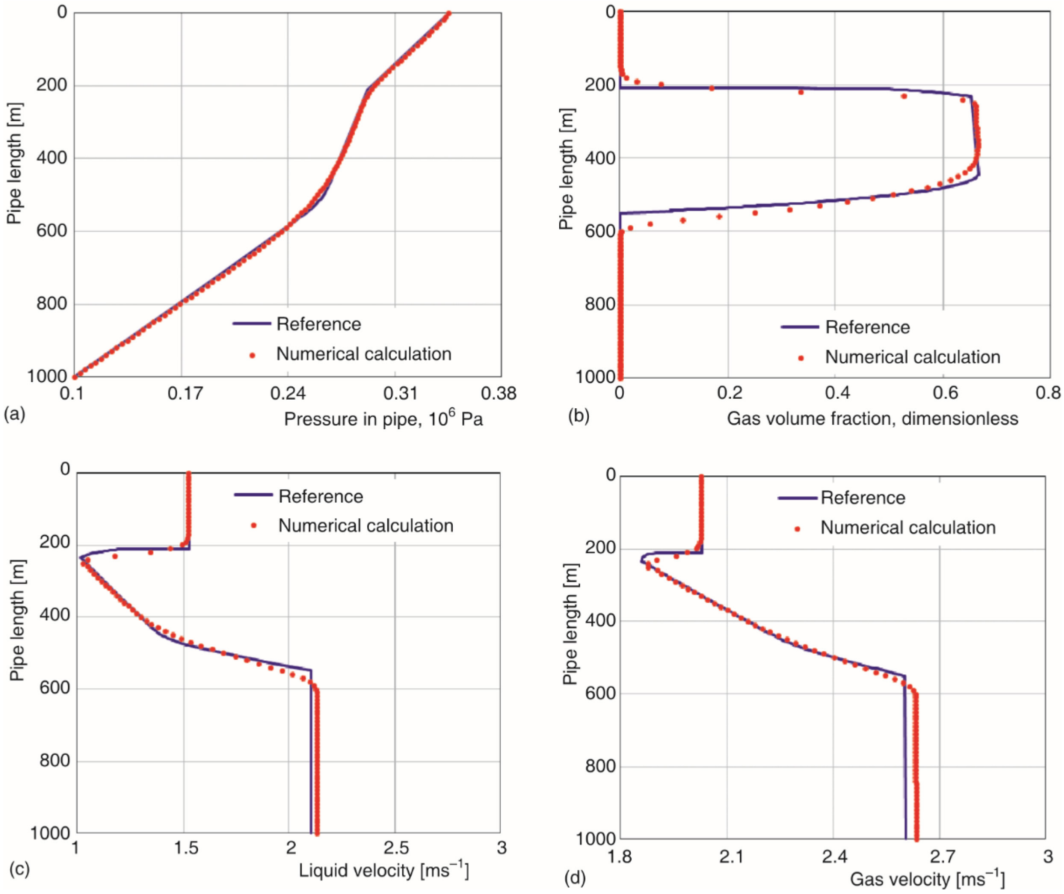

Figure 1. The comparisons of numerical calculation results and reference; (a) pressure in pipe, (b) gas volume fraction (c) liquid velocity, (d) gas velocity

Numerical calculation analysis

The basic parameters of marine gas hydrate reservoirs drilling are as follows. The well depth of this vertical well is 3000 m, the seawater depth is 2500 m, the inner diameter of marine riser is 0.3684 m, the inner diameter of casing pipe is 0.224 m, the outer diameter of drill pipe is 0.102 m, the circulated drilling fluid mass-flow rate is 18.35 kg/s, the drilling fluid density is 1025 kg/m^3, the outlet pressure (at well head) is constant $0.1 \cdot 10^6$ Pa. Before hydrate decomposition gas entering into the wellbore, the vertical well is full filled with circulated drilling fluid. Then the hydrate decomposition gas enters into the wellbore at 100 seconds and gas is linearly increased from 0 kg/s to 0.3 kg/s in 10 seconds at well bottom.

Based on the numerical calculation method of transient gas-liquid two-phase flow after decomposition gas entering into the wellbore in marine gas hydrate reservoir drilling, the change mechanism of transient gas-liquid two-phase flow in wellbore is obtained, figs. 2-5.

Figure 2(a) is the change of wellbore pressure with well depth at different times. It indicates that wellbore pressure decreases as time goes on after the decomposition gas of hydrate enters into wellbore. Figure 2(b) is the change of bottom hole pressure with time. The bottom hole pressure increases about $0.1 \cdot 10^6$ Pa at first. As gas rises and expands in wellbore, the drilling fluid is gradually displaced out of wellbore, and then the bottom hole significantly decreases about $4.2 \cdot 10^6$ Pa. At last, the bottom hole pressure tends to be stable when the steady gas-liquid two-phase flow forms in wellbore.

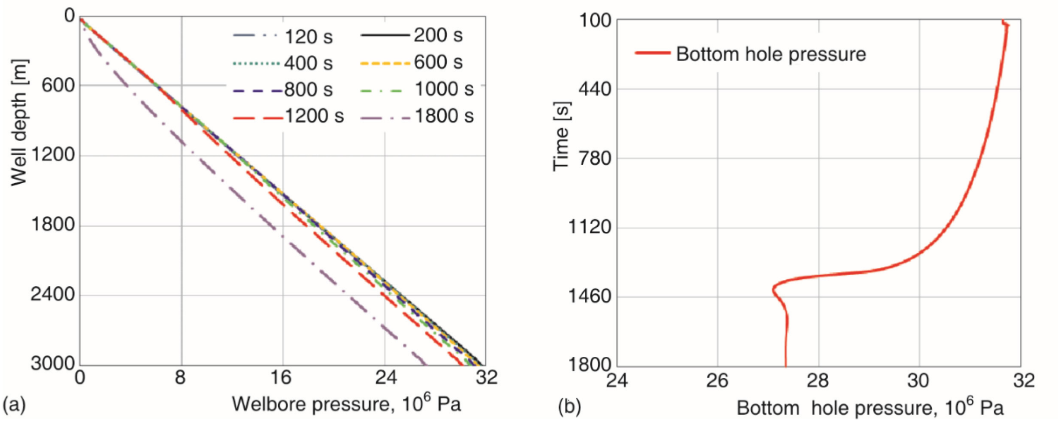

Figure 2. The change of wellbore pressure with well depth at different times (a) and that of bottom hole pressure with time (b)

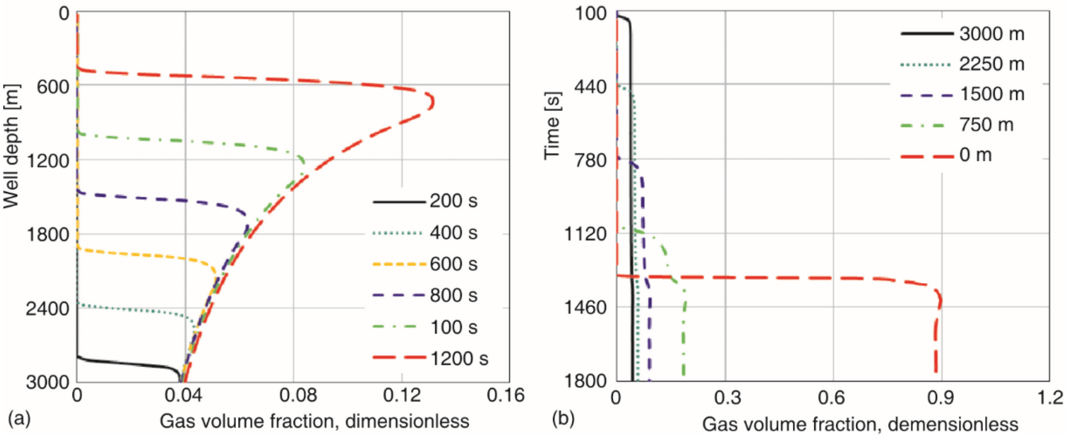

Figure 3. The change of gas volume fraction with well depth at different times (a) and with time at different well depths (b)

In fig. 3(a), gas rises in wellbore and the wellbore pressure decreases as time goes on. Then the gas volume fraction increases significantly. At a certain well depth, as time goes on, gas volume fraction increases slightly because of the wellbore pressure decreases in fig.

2(a). As can be seen from fig. 3(b), before gas reaching a certain well depth in wellbore, the gas volume fraction keeps zero. At a certain time after gas reaching, the gas volume fraction is larger at the well depth closer to wellhead.

As can be seen from fig. 4(a), before gas reaching a certain well depth in wellbore, the gas mass-flow rate keeps zero. The length of gas-liquid two-phase flow elongates as time goes on and gas rises in wellbore. Figure 4(b) indicates that when gas reaches wellhead, the gas mass-flow rate reveals the typical sharp peak caused by increasing gas rate and gas drift velocity. Then the gas mass-flow rate tends to stable when the steady gas-liquid two-phase flow forms in wellbore.

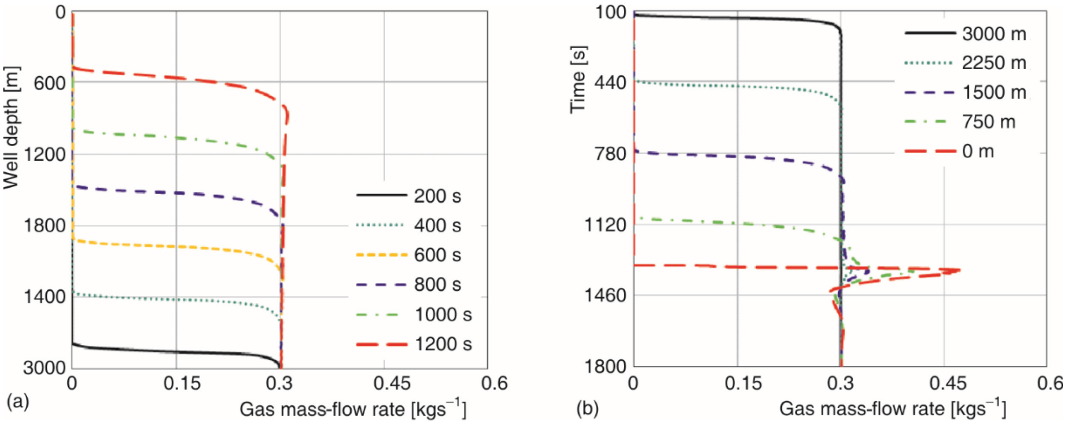

Figure 4. The change of gas mass-flow rate with well depth at different times (a) and with time at different well depths (b)

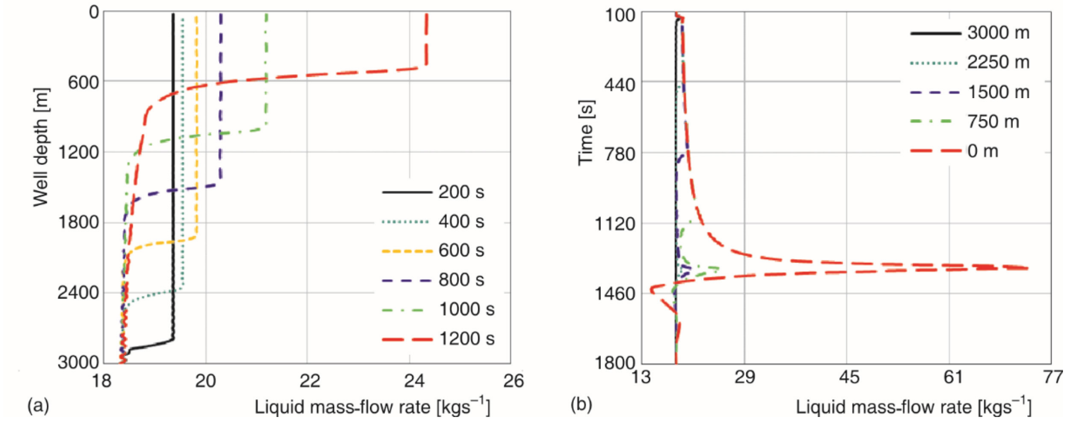

Figure 5. The change of liquid mass-flow rate with well depth at different times (a) and with time at different well depths (b)

As can be seen from fig. 5(a), because gas continuously enters into wellbore and gas volume fraction increases, the space of liquid is gradually occupied by gas, the length of pure liquid flow shortens as time goes on and gas rises in wellbore. In addition, the pure liquid mass-flow rate increases. In fig. 5(b), before gas reaching a certain well depth in wellbore, the pure liquid mass-flow increases. When gas reaches wellhead, the liquid mass-flow rate reveals the typical sharp peak like gas mass-flow rate. Then the liquid mass-flow rate drops to initial mass-flow rates in the new steady-state situation.

Conclusions

In this paper, based on the gas-liquid two-phase flow process after decomposition gas entering into the wellbore in marine gas hydrate reservoir drilling, the transient gas-liquid two-phase flow drift flux mathematical model is established. The numerical calculation method is proposed and verified. The numerical calculation method in this paper illustrates the excellent agreement between calculations results and references, and performs well stability and accuracy. Finally, the example analysis is carried out and the change mechanism of transient gas-liquid two-phase flow in wellbore is obtained as follows.

- Wellbore pressure decreases as time goes on after the decomposition gas of hydrate enters into wellbore. The bottom hole pressure increases at first, then significantly decreases, and tends to be stable when the steady gas-liquid two-phase flow forms in wellbore.
- The gas volume fraction increases significantly as time goes on and it is larger at the well depth closer to wellhead.
- Before gas reaching a certain well depth in wellbore, the pure liquid mass-flow increases. In addition, the length of gas-liquid two-phase flow elongates and that of pure liquid flow shortens as time goes on and gas rises in wellbore. When gas reaches wellhead, the liquid and gas mass-flow rates reveal the typical sharp peak, and then they tend to a new steady-state situation.

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