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Effects of phase transition on gas kick migration in deepwater horizontal drilling

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ABSTRACT

A reliable kick simulator is a valuable tool in improving forward-looking predictions and making correct decisions during well control operations. In this study, a transient coupled model is developed for kick simulation in deepwater horizontal drilling. The model incorporates the mass, momentum, and energy conservation equations within the wellbore, and is coupled with a mass and heat transfer model for gas, liquid, and hydrate phase transitions, a slip relation for gas distribution and rise velocity, and a gas influx model for reservoir coupling. In the model, the transient mass transfer model is used in conjunction with an unsteady temperature model to study the effects of phase transition on gas kick migration.

The simulator is validated through comparisons with the measurement results of a kicking well and full-scale kick experiments. The simulated results show consistent trends and are in good quantitative agreement with the collected measurement data.

The kick development under various reservoir and construction parameters is analyzed. Gas dissolution and hydrate formation are found to significantly suppress the kick development process, especially at low influx rates or during the early kick stage. For a given pit gain of 3 m^3, the error in kick prediction can reach 17.6% if phase transition effects are neglected.

1. Introduction

Open-hole horizontal wells are increasingly popular in deepwater applications, as the economic viability of such projects requires the reservoir to be drained using the minimum number of wells. However, the water depth, severe reservoir conditions, and complex geotechnical properties can pose a wide variety of technical challenges, such as complicated wellbore configurations, well trajectory control, wellbore dynamics, hole cleaning, and wellbore stability. Among these, an appropriate well control procedure is important in addressing the associated safety issues. Furthermore, it is helpful in optimizing the casing program and in avoiding wellbore stability problems. Therefore, a precise kick simulator is required to improve our understanding of kick evolution and assist drilling engineers in making decisions during field operations. Compared with onshore or shallow water counterparts, the following factors make it difficult to predict the kick migration in deepwater horizontal drilling:

(1) Complicated wellbore temperature profile. The dynamical temperature distribution has a significant influence on variations in the properties of fluids, particularly gas.
(2) Gas dissolution in the drilling fluid.
(3) Phase transition of gas hydrate. The low temperature of deep and ultra-deep water can lead to the formation of hydrates during kick migration in the wellbore.
(4) Slip velocity between phases and flow pattern transition.
(5) Reservoir coupling in the long open-hole section.

In the past five decades, starting from the first well control model by LeBlanc and Lewis (1968), extensive studies have been conducted on kick development under different drilling conditions, such as different mud types (White and Walton, 1990; Van Slyke and Huang, 1990), different influx gases (Szczepanski et al., 1998; He et al., 2015), different well depths (Schoffmann and Economides, 1991; Starrett et al., 1990; Sun et al., 2013), different well geometries (Schubert et al., 2006; Vefring et al., 1995; Wang et al., 1994), and kicks in deepwater drilling (Santos, 1991a; Nunes et al., 2002; Velmurugan et al., 2016). Furthermore, the mechanistic modeling of multiphase flow has also been widely used in the prediction of wellbore

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dynamics (Shirdel and Sepehrnoori, 2009, 2012). Advances in kick simulators have allowed more accurate predictions of fluid flow during well control procedures.

As the gas influx is initiated, the single liquid flow is converted into a complicated gas–liquid flow in the wellbore. The migration mechanism of the gas can be divided into two types: free gas transport and phase transition transport.

The accumulation and migration processes of free gas in a horizontal well are quite different from those in a vertical well. Wang et al. (1994) coupled the fluid flow along the horizontal section with the gas influx from the formation, and compared the kick rules of a heterogeneous reservoir with those of a flat homogeneous reservoir. Vefring et al. (1995) conducted an interesting experimental and modeling study of the accumulation and removal mechanisms of gas traps in a horizontal section. Furthermore, Santos (1991b) and Starrett et al. (1990) calculated the kick rules in a horizontal flow, with the wellbore geometry found to have a moderate effect. The unique aspect of their models is that different slip relations are used to describe the migration of free gas along the well.

The unsteady variation of wellbore temperature, which can be regarded as an early sign of well kick, is important for the transformations of gas into liquid and hydrate. The phenomenon by which gas dissolves into liquid can cause many gas kicks to become undetectable in the early stages (Van Slyke and Huang, 1990; Szczepanski et al., 1998; Tarvin et al., 1991). Moreover, the low temperature of the seawater section makes the formation of gas hydrate possible in deepwater drilling (Yapa et al., 2001). The previous study mainly focuses on predicting the hydrate formation region based on calculations of temperature and pressure distributions in the annulus (Petersen et al., 2001; Yousif and Young, 1993; Wang et al., 2008). These phase transition processes can alter the proportion of the gas–liquid mixture and the multiphase flow parameters.

Considering the unsteady transfer of mass and heat during the phase transition, and the dynamical variation of the wellbore temperature field, this paper describes the development of a fully coupled transient model to simulate the kick migration in deepwater horizontal drilling. Additionally, a drift flux model, which is independent of the flow pattern, is selected from the existing correlations to conform to the kick scenarios. The remainder of this paper proceeds as follows. First, we describe the modeling of multiphase flow, heat transfer, phase transition, and reservoir coupling. Next, we compare the simulation results with the measurement results of a real gas kick well and those of the kick experiments, and validate the performance of the proposed model. Subsequently, the effects of drilling parameters and phase transitions on kick migration are demonstrated via numerical simulations. Finally, the conclusions are presented.

2. Model formulation

As shown in Fig. 1, gas kick migration in deepwater horizontal drilling is a complicated process that is affected by the well geometry, surrounding temperature field, and reservoir coupling. To describe the multiphase flow characteristics such as velocity, void fraction, pressure and temperature, a transient wellbore multiphase flow model is needed.

In contrast to the single-phase flow, the most important feature of multiphase flow is the phase interactions, which include the mass transfer and slip relation. Therefore, we develop a mass transfer model to account for the gas dissolution and hydrate phase transition, and present the slip relation that describes the velocity–void fraction relation between different phases. Furthermore, a wellbore–reservoir coupling model and the auxiliary equations (such as the thermo-physical properties of gas and the phase equilibrium of hydrate) are needed to ensure the closure of the integrated model.

2.1. Transient multiphase flow model

The transient wellbore multiphase flow model includes the continuity equations, momentum conservation equation, and energy conservation equation. The main assumptions are as follows:

1. The flow is considered to be one-dimensional and compressible.
2. Heat transfer in the wellbore in the radial direction is considered.
3. Variations in thermo-physical properties (such as specific heat capacity and thermal conductivity) of the drill pipe, casing, cement, and formation are neglected.
4. Slip between hydrate and liquid is neglected.

2.1.1. Mass conservation equation

The equations expressing the mass conservation laws among the gas, liquid, and hydrate can be expressed as follows:

2.1.1.1. Mass conservation of free gas.

$$\frac{\partial}{\partial t}\left(A\alpha_g\rho_g\right)+\frac{\partial}{\partial s}\left(A\alpha_g\rho_g v_g\right)=-\dot{m}_{g\to L}-\dot{m}_{g\to h}+q_g \tag{1}$$

where t is the time, s; s is the depth, m; ρ_g is the density of free gas, kg/m^3; A is the cross-sectional area, m^2; α_g is the void fraction of free gas; v_g is the flow velocity of free gas, m/s; $\dot{m}_{g\to L}$ is the mass transfer rate from the vapor phase to liquid phase, kg/(m·s); $\dot{m}_{g\to h}$ is the mass transfer rate from the vapor phase to hydrate phase, kg/(m·s); and q_g is the gas influx rate per unit length along the wellbore, kg/(m·s).

2.1.1.2. Mass conservation of liquid.

$$\frac{\partial}{\partial t}(A\alpha_l\rho_l)+\frac{\partial}{\partial s}(A\alpha_l\rho_l v_l)=\dot{m}_{g\to L}-\dot{m}_{L\to h} \tag{2}$$

where ρ_l is the density of liquid, kg/m^3; α_l is the volume fraction of liquid; v_l is the flow velocity of liquid, m/s; and $\dot{m}_{L\to h}$ is the mass transfer rate from the liquid phase to hydrate phase, kg/(m·s).

2.1.1.3. Mass conservation of dissolved gas.

$$\frac{\partial}{\partial t}[A\alpha_l x_{sol}\rho_l]+\frac{\partial}{\partial s}[A\alpha_l x_{sol}\rho_l v_l]=\dot{m}_{g\to L} \tag{3}$$

where x_{sol} is the mass fraction of dissolved gas, kg/kg.

2.1.1.4. Mass conservation of gas hydrate.

$$\frac{\partial}{\partial t}[A\alpha_h\rho_h]+\frac{\partial}{\partial s}[A\alpha_h\rho_h v_h]=\dot{m}_h \tag{4}$$

where ρ_h is the hydrate density, kg/m^3; α_h is the volume fraction of hydrate; v_h is the flow velocity of hydrate, m/s; and $\dot{m}_h$ is the hydrate formation rate, kg/(m·s).

$$\dot{m}_h=\dot{m}_{g\to h}+\dot{m}_{L\to h} \tag{5}$$

In the above equations, the terms $\dot{m}_{g\to L}$, $\dot{m}_{g\to h}$, and $\dot{m}_{L\to h}$