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Predicting pressure behavior during dynamic kill drilling with a two-phase flow

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A B S T R A C T

Dynamic kill drilling technology can effectively handle well kick, loss of circulation and wellbore collapse during surface drilling in deepwater. To ensure a safe and successful dynamic kill drilling operation, accurately predicting wellbore pressure is highly important. Based on dynamic kill drilling characteristics in deepwater, this paper develops a wellbore pressure prediction model with variable flow rate proportions. The complexity of the gas–liquid two-phase flow inside the annulus is included in the model. An analysis of the liquid holdup, annular density, annular pressure, annular pressure loss and bottom hole pressure during dynamic kill drilling is performed for a deepwater well using the wellbore pressure prediction model described in this paper. The results suggest that the key issue for dynamic kill drilling technology is controlling the mixture density by regulating the flow rates of the seawater and weighted drilling fluid. To demonstrate the model's validity, it was used to predict the wellbore pressure of two deepwater wells that had been constructed using dynamic kill drilling in the Gulf of Mexico (GOM). The wellbore pressure prediction model presented in this paper is valuable for guiding field operations involving dynamic kill drilling.

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1. Introduction

Drilling at the surface layer in deepwater without risers is affected by the seawater depth and the marine environment. There are two critical problems: 1) High-pressure gas can be found in shallow formations of deepwater (McConnell et al., 2012; Rowden, 2001). If shallow gas is encountered during surface drilling, it is likely to flow into the annulus, causing a gas kick. Nevertheless, wellhead blowout preventers (BOPs) have not been installed in surface drilling process, so the conventional well killing methods cannot be used to circulate out the kick. 2) Due to the “narrow drilling window” (Beall, 1976; Garcia et al., 2008) between formation's pore pressure and fracture pressure, the circulation rate, equivalent circulation density (ECD) and tripping speed can cause downhole problems. Dynamic kill drilling is a key technology that has the potential to solve these problems in deepwater surface drilling (Kouba et al., 1993; Viera et al., 2014). In this drilling method, seawater and a weighted drilling fluid are mixed in an appropriate proportion by an automatic mixing system (Geng et al., 2012). The mixing proportion is determined by the annular behavior through the annular pressure measurement while drilling (APWD) system. Therefore, control of the mixture density can be maintained during dynamic kill drilling. As a result, the wellbore pressure is controlled by the combined effects of the annular hydrostatic fluid pressure and the circulation pressure loss, ensuring safety while drilling in the surface layer of deepwater.

Some studies on safety top-hole drilling in deepwater from a shallow blowout perspective have been conducted in previous years. C. Marken developed a simulation tool for evaluating the shallow gas kick for a top-hole drilling operation (Marken et al., 2000). O. V. Carlos presented a calculation procedure for the dynamic kill method and optimized the kill flow rate for field operations (Carlos et al., 2001). S. F. Noynaert simulated blowout initial conditions and blowout control in simple wellbore geometries using the newly-developed dynamic kill simulator COMASim (Noynaert and Schubert, 2005). Y. H. Gao proposed a model for dynamic kill drilling parameters at a constant flow rate. It determined the density of the relevant mixture according to the flow rates of the seawater and the weighted drilling fluid, then

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calculated the wellbore pressure distribution (Gao et al., 2010). X. L. Jiang considered the impact of low temperatures on the rheological parameters and calculated the equivalent circulating density of the fluid in dynamic kill drilling (Jiang et al., 2012).

The present paper considers the characteristics of dynamic kill drilling and the complexity of two-phase flows, then proposes a wellbore pressure control method for situations in which the drilling fluid's composition varies. When the flow rates of the seawater and the weighted drilling fluid are allowed to change, the proportion of each in the mixture varies. As a result, the density of the mixture in the wellbore changes with time and depth. The flow rate and density of the mixture are adjusted in real-time according to the APWD system, allowing dynamic control of the wellbore pressure to be established in drilling operations. This study establishes a physical model of dynamic kill drilling, then presents a mathematical model of the wellbore pressure in the variable proportion scenario. To study the behavior of the pressure in dynamic kill drilling, simulations and an analysis of the liquid holdup, annular density, annular pressure, annular pressure loss and bottom hole pressure in a deepwater well are presented in this paper. Finally, the model is applied to actual deepwater wells in the GOM to demonstrate its effectiveness.

2. Physical model

In the wellbore pressure prediction model, the following assumptions are made:

(1) There is a gas kick at the bottom hole, so the flow in the drill string is a single-phase flow and the flow in the annulus is a gas–liquid two-phase flow. The two-phase flow can be modeled as steady-state from the perspective of the annulus unit.
(2) The rate of gas kick is constant.
(3) Gas solubility in the drilling fluid can be ignored.

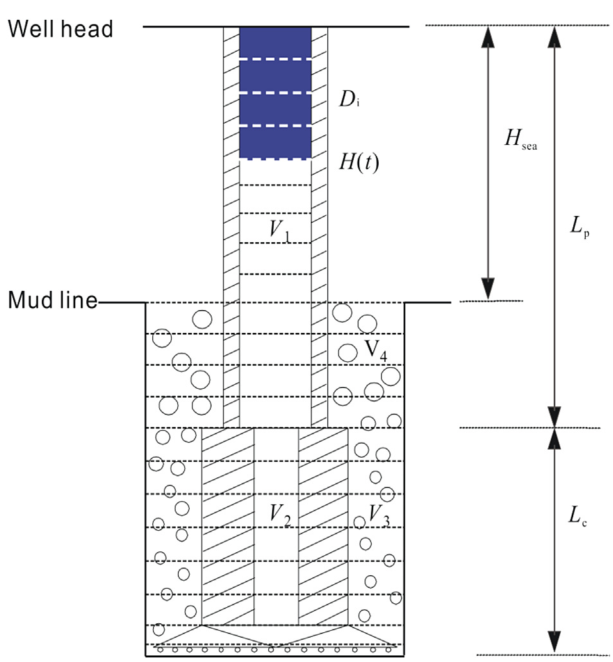

Fig. 1. Physical model of the wellbore during dynamic kill drilling, in which the blue area represents the mixture of seawater and weighted drilling fluid. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(4) The drill string used in surface drilling is modeled as a simple drill pipe with a drill collar added.
(5) The surface hole has a regular geometry.

A physical model of the wellbore is shown in Fig. 1. The wellbore flow path is divided into four regions: inside the drill pipe, V_1; inside the drill collar, V_2; the annulus outside the drill collar, V_3; and the annulus outside the drill pipe, V_4. In this model, L_p and L_c represent the lengths of the drill pipe and drill collar respectively, and H_{sea} represents the depth of the seawater. D_i is the distance from the interface of the i-th unit to the wellhead, and the distances from the interfaces of the corresponding units in the drill string and annulus to the wellhead are equal. The interface of the unit at the bottom hole is n_1, and the interface of the unit at the mud line is n_2.

3. Mathematical model

3.1. Liquid density distribution

Due to their variable proportions, the flow rates of the seawater and the weighted drilling fluid vary with time. Their instantaneous flow rates determine the instantaneous density of the mixture at the wellhead. Flow rate's rate of change is used in this model, with the seawater's instantaneous flow rate $Q_w(t)$ given by:

$$Q_w(t) = Q_1 + \alpha_1 t \quad (1)$$

where Q_1 is the initial flow rate of seawater (L/s) and α_1 is the seawater flow rate's rate of change.

The weighted drilling fluid's instantaneous flow rate $Q_{dF}(t)$ is given by:

$$Q_{dF}(t) = Q_2 + \alpha_2 t \quad (2)$$

where Q_2 is the initial flow rate of the weighted drilling fluid (L/s) and α_2 is the weighted drilling fluid flow rate's rate of change.

Therefore, at time t, the instantaneous density of the mixture $\rho(t)$ at the wellhead can be written as:

$$\rho(t) = \frac{\rho_w Q_w(t) + \rho_{dF} Q_{dF}(t)}{Q_w(t) + Q_{dF}(t)} \quad (3)$$

where ρ_w and ρ_{dF} represent the densities of the seawater and the weighted drilling fluid in kg/m^3, respectively.

The fluid density is calculated in four different scenarios based on the position of the mixture front. In each scenario, the mixture front propagates in the drill pipe, drill collar, annulus outside the drill collar or annulus outside the drill pipe. When the mixture front is in the drill pipe, the liquid density distribution along the entire flow path is determined in three steps:

(1) Position of the mixture front

The total volume of the mixture $V(t)$ pumped into the well is:

$$V(t) = \int_0^t Q_w(t)\mathrm{d}t + \int_0^t Q_{dF}(t)\mathrm{d}t \quad (4)$$

The distance from the wellhead to the mixture front L can be obtained by:

$$L = \frac{V(t)}{A_{DP}} \quad (5)$$

where A_{DP} is the drill pipe's cross-sectional area (m^2).

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