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Study of transient responses in the APWD measurements during gas influx

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ABSTRACT

Gas influx detection is one of the most important ways to improve well control safety. The responses of annular pressure while drilling (APWD) measurements have been used to provide a rapid and early warning of the development of gas influx. Considering the water hammer effect at the initial stage of gas influx, a new model has been established to describe the APWD pressure variation accurately. The accuracy of the mathematical model and the method for solution have been verified by a full-scale experiment. Combined with case analysis, the APWD pressure variations during gas influx under different conditions were simulated. Moreover, the probabilities of different APWD response patterns are presented. Calculation results show that the gas influx can be identified when the invaded gas volume is 0.5–0.8 m^3.

1. Introduction

Gas-influx detection is one of the most important ways to improve well control safety. More accurate and reliable gas influx detection has become increasingly important as more offshore drilling is conducted with a narrower mud window and a lower influx tolerance (Fraser et al., 2014; Karimi Vajargah and van Oort, 2015). In addition to surface logging information, underground drilling information has also been applied to gas influx detection. In addition to the acoustic and mud-resistivity responses of annular measurement while drilling (MWD) (Bryant et al., 1991), the responses of the annular pressure while drilling (APWD) measurement (Aldred et al., 1998) are also used to provide a rapid and early warning of the development of gas influx.

During gas influx, the responses of APWD are dominated by two phenomena, namely, reduced hydrostatic pressure of the mud column as the drilling fluid is replaced by gas, and increased annular pressure due to friction resistance and inertial force when accelerating the mud column above the gas influx (Aldred et al., 1998). However, how to combine the two dominating phenomena is still an open question. Thus, the indication of APWD responses to detect gas influx is ambiguous. Because of the reduced hydrostatic pressure of the mud column, Indication One says the measured value of the APWD will decrease. Because of the increased annular pressure due to friction resistance and inertial force, Indication Two says the measured value of APWD will increase first, then decrease. Indication One is proposed for typical boreholes, and Indication Two is proposed for slim wellbore geometries. However, it is very difficult to distinguish typical and slim wellbores in a convincing manner. Furthermore, in addition to wellbore geometries, the annular pressure at the APWD sensor location is also influenced by the magnitude of the gas influx, the suddenness of the gas influx, the properties of the drilling fluid, etc.

In the initial stage of gas influx, the invasion of the formation fluid will change the fluid velocity rapidly in the wellbore, causing the occurrence of the water hammer phenomenon. Water hammer due to a sudden momentum change is widely encountered in the field of petroleum exploration and development. Han et al. (2013) used a commercial software to characterize the fluid hammer effects of well shut in and start up. Wang et al. (2008) conducted a field trial and simulation work to understand the magnitude, frequency, and energy dissipation of the water hammer effect. Tang and Ouyang (2010) simulated the water hammer in two different scenarios to provide an operational reference for well injection operation and valve installation. However, the water hammer effect caused by the sudden intrusion of formation fluid into the drilling process has not been investigated.

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With the increase of gas, the flow in the annulus becomes gas-liquid two-phase flow. Both the two fluid model and the drift flux model have been utilized to formulate gas-liquid two-phase flow (Bendlksen et al., 1991; Nickens, 1987). Compared with the two fluid model, the drift flux model is more flexible and more easily programmed (Meng et al., 2015). Because of these characteristics, the drift flux model is more suitable for two phase flow simulation in wellbores. Ekrann and Rommetveit (1985) introduced the application of the drift flux model to simulate gas kick during drilling. Many scholars including Nickens (1987), Santos (1991), Nunes et al. (2002), Sun et al. (2013), and Meng et al. (2015) have contributed to the application and development of the drift flux model in the drilling field. However, when they applied the drift flux model to predict annulus pressure after gas influx occurred, the water hammer effect at the initial stage of gas influx was not considered.

Therefore, a reliable and accurate mathematical model that integrates the two dominating phenomena of gas influx needs to be established to obtain a better interpretation of APWD responses during gas influx.

2. Model development

Gas influx is most likely to occur at the bottom of the well. An APWD pressure sensor is located in the bottom hole assembly and is usually 15–20 m above the bit. Tens of seconds are required for the invading gas to migrate from the bottom to the APWD sensor location. Therefore, this paper studied the gas influx mathematical model and the solving method for both conditions before and after the front of the gas reached the APWD.

2.1. Gas influx water hammer model and solving method

Before the front of the gas reaches the APWD sensor location, the wellbore between the bit and the APWD sensor location is filled with a gas liquid mixture. Drilling fluid fills up the wellbore between the APWD sensor location and the wellhead, so the single-phase water hammer model formulates the gas influx accurately.

2.1.1. Model equations

The control equations of water hammer during gas influx are

$$L_1 : \frac{\partial v}{\partial t} + v\frac{\partial v}{\partial s} + g\frac{\partial z}{\partial s} + \frac{1}{\rho}\frac{\partial p}{\partial s} + \frac{\lambda v|v|}{2D} = 0 \tag{1}$$

$$L_2 : \frac{\partial p}{\partial t} + v\frac{\partial p}{\partial s} + \rho a^2\frac{\partial v}{\partial s} = 0 \tag{2}$$

where v is the liquid velocity, m/s; ρ is the liquid density, kg/m^3; and $D = D_{out}$ - D_{in}, D_{out} is the borehole diameter, m; D_{in} is the outer diameter of the drillstring, m; λ is the friction factor; p is the pressure, Pa; a is the propagation velocity of the pressure wave, m/s; g is the acceleration of gravity, m^2/s; t is time, s; and s is the spatial coordinates, m. The details of the derivation of the control equations are illustrated in Appendix A.

The propagation velocity of the pressure wave in the pipeline (Ghidaoui et al., 2005) is

$$a = \frac{1}{\sqrt{\rho\left(\frac{1}{A}\frac{dA}{dp} + \frac{1}{\rho}\frac{d\rho}{dp}\right)}} \tag{3}$$

$1/\rho\ d\rho/dp$ in Eq. (3) indicates the compressibility of the liquids. To simplify calculations, the compressibility of water at 50 °C and 50 MPa is used to replace the compressibility of drilling fluid (Hao, 1992), thus:

$$\frac{1}{\rho}\frac{d\rho}{dp} = 0.39 \times 10^{-9} Pa^{-1} \tag{4}$$

$1/A\ dA/dp$ represents the elastic coefficient of the flow channel. For annuli between the drillstring and the casing, the elastic coefficient is determined by Eq. (5) (Hao, 1992).

$$\frac{1}{A}\frac{dA}{dp} = \frac{2}{E_s}\left[\frac{1}{R_2^2 - 1}\left(R_2^2 \cdot \frac{R_3^2 + 1}{R_3^2 - 1} + \frac{R_1^2 + 1}{R_1^2 - 1}\right) + \mu_s\right] \tag{5}$$

For annuli between the drillstring and the open hole, the elastic coefficient is determined by Eq. (6) (Hao, 1992).

$$\frac{1}{A}\frac{dA}{dp} = \frac{2}{R_2^2 - 1}\left[\frac{R_2^2}{E_f}\left(1 + \mu_f\right) + \frac{1}{E_s}\left(\frac{R_1^2 + 1}{R_1^2 - 1} - \mu_s\right)\right] \tag{6}$$

where E is the elastic modelling quantity, Pa; μ is the Poisson ratio; $R_1 = D_2/D_1$; $R_2 = D_3/D_2$; $R_3 = D_4/D_3$; D_1 is the inner diameter of the drillstring, m; D_2 is the outer diameter of the drillstring, m; D_3 is the inner diameter of the casing, m; D_4 is the outer diameter of the casing, m; subscripts s and f indicate steel and formation, respectively.

2.1.2. Solving method

Model equations are solved by the characteristic line method. Fig. 1 shows the temporal and spatial mesh for the gas influx water hammer model, where $\Delta t = \Delta s/a$, and the slope of the characteristic line is $\pm 1/a$. The abscissa is the space, and the ordinate is the time. By defining $t^{n+1} = t^n + \Delta t$ and $s_{j+1} = s_j + \Delta s$, we obtain the discrete equations of the gas influx water hammer model. By the derivation presented in Appendix B, we obtain:

$$V_i^j = \frac{\left(V_{i-1}^{j-1} + V_{i+1}^{j-1}\right)}{2} + \frac{1}{2\rho a}\left(p_{i-1}^{j-1} - p_{i+1}^{j+1}\right) - \left(g\cos\theta + \frac{\lambda V_{i-1}^{j-1}\left|V_{i-1}^{j-1}\right|}{4D} + \frac{\lambda V_{i+1}^{j-1}\left|V_{i+1}^{j-1}\right|}{4D}\right)\Delta t \tag{7}$$

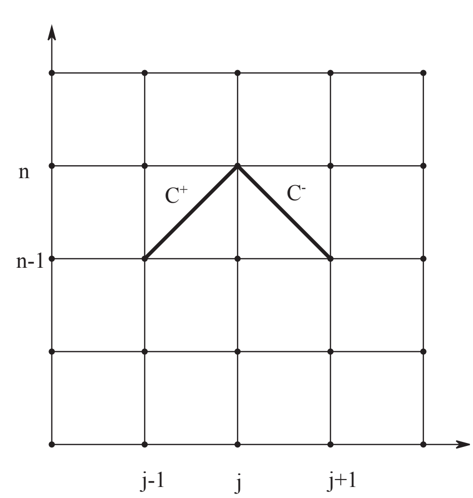

Fig. 1. Gas influx water hammer model: time and space mesh.