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Model for calculating the gas volume fraction of a gas-cut wellbore through natural gamma-ray logging

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ABSTRACT

Well blowout – caused by the formation fluids invading a wellbore because of the imbalance of the bottom-hole pressure and formation pressure – is the most hazardous accident in deepwater drilling and well completion engineering. Blowout accidents can be effectively prevented through early gas-cut detection, but detection of gas invasion is challenging. The earlier the gas cut is detected, the smaller the gas loss is. Conventional gas-cut detection methods are based on monitoring the drilling parameter changes at the wellhead; however, because of the large distance between the wellhead and the well bottom, detection through this approach is not timely. In this study, a theoretical model for gas-cut detection through natural gamma ray (NGR) logging is established in which the gas-cut annulus equivalent diameter as well as the influence of a gas cut on the liquid–gas spatial distribution and the absorption capacity of the drilling fluid are considered. This model, which can predict the real-time gas void fraction, was validated experimentally: on observing the variation in NGR logging under various gas-cut conditions, the NGR logging value was found to increase with the increase in the gas void fraction. Moreover, the experimental and predicted void fractions varied by less than 8% on average, evidencing that the model can accurately predict the gas volume fraction in a wellbore after gas cut. The proposed model is expected to serve as a strong foundation for the further development of early gas-cut detection technology.

1. Introduction

The safe and efficient development and operation of deepwater oil and gas fields entail high risks and challenges because of their complex marine environment and unique geological conditions. If a gas cut in a wellbore is not detected and addressed in a timely manner, serious drilling accidents such as well kick and blowout may occur, which may result in well destruction, fire, land subsidence, and damage to the hydrocarbon reservoir. Furthermore, the entire deepwater drilling platform may sink, polluting the marine environment. All of these accidents can lead to substantial loss of life and economic resources. Nevertheless, such accidents can be prevented using deepwater well control technology, specifically, the early detection of deepwater well kick.

The well kick–detection method currently practiced in deepwater drilling platforms is a type of water surface (wellhead) detection method (Chen and Tian-Shou, 2014) that is based on the theory that gas inflation leads to an abnormal increase in the flow rate of the drilling fluid (Sun et al., 2011). In this approach, the flow rate at the wellhead is monitored using a mass flow meter. However, any change in flow rate can only be detected when the gas flow reaches the wellhead, and this lag makes the early detection of gas cuts impossible (Yang and Cao, 2008). Moreover, this approach does not reflect the actual gas-cut conditions at the well bottom. In addition, the flow-meter measurements are influenced by the wind-, wave-, and current-induced vertical and traverse movement of deepwater drilling platforms. Hence, the development of early gas-cut detection methods for deepwater drilling operations is imperative.

In addition to serving as a reliable basis for geosteering and formation evaluation, natural gamma ray (NGR) logging can be used to detect gas cuts by monitoring the changes in a measured parameter at a certain location. More importantly, these changes can be rapidly transmitted (1000–1500 m/s) to the ground level through mud pressure pulses for quick, real-time analysis of the formation parameters at the well bottom thousands of meters deep by using logging while drilling (LWD) instruments. This approach can thus detect a gas

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cut in the wellbore 75–90% earlier and more accurately than can conventional overflow detection technology (Zhuo et al., 2009).

Numerous recent studies have focused on the detection of the characteristics of multiphase flow by using GR. For example, Kemoun et al. (2001) employed GR imaging to measure multiphase flow patterns by studying distributions of the total void fraction in the cross-section of bubble columns. Abro and Johansen (1999) studied the void fraction in pipe flow by using a multi-GR attenuation system, and Yin et al. (2002) employed a GR system to measure the liquid holdup in a large-diameter closed cylinder. Boyer and Fanget (2002) measured liquid-phase distributions in large-diameter trickle beds by using a GR imaging system. Stahl and Von Rohr (2004) measured the void fraction in gas–liquid two-phase pipe flow by using a single GR densitometer. Li et al. (2005) applied the basic principles and mathematical algorithm of a double-energy GR system to detect liquid holdup in a multiphase flow and experimentally developed a GR-based detection method that is based on the accurate measurement of the absorption coefficient. Tjugum et al. (2002) studied the gas volume fraction in saline solutions and reported that salinity strongly influenced the test results when using low-energy GRs. Nazemi et al. (2014) proposed a neural network–based method to eliminate the liquid density–induced errors in the measurement of the gas volume fraction. The aforementioned approaches are based on GR systems with known composition and energy, whereas few studies have examined gas detection through NGR logging for evaluating a wellbore formation of unknown radioactivity. This unknown nature of radioactivity makes it difficult to study the gas-cut response characteristics of LWD NGR logging.

Many scholars agree that a gas cut would change the wellbore flow status of the drilling fluid from single-phase flow to gas–liquid two-phase flow. In addition, a gas cut would result in changes in the liquid–gas spatial distributions in the drilling fluid and in the NGR absorption capacity of the drilling fluid. Consequently, these changes can be detected using an NGR instrument. However, these relationships have been ignored in the literature.

In this study, an NGR logging–based theoretical method for the early detection of gas cuts and for determining the real condition of the gas cut at the well bottom is proposed. First, through theoretical analysis, an NGR logging–based model for predicting the gas void fraction was established. Then, the proposed model was validated using a gas-cut simulating experiment. In addition, through analysis of the experimental data, the relationships between the NGR logging data and the gas void fraction were established. The experimentally measured and model-predicted void fractions varied by less than 8% on average, verifying that the proposed model can accurately predict the gas volume fraction in a wellbore after a gas cut. Furthermore, this model real gas-cut condition at the well bottom can be determined through quantitative analysis of the magnitude and velocity of gas invasion at the well bottom. The results reported herein are expected to serve as a theoretical basis for further development of early gas-cut detection technology for deepwater drilling.

2. Theoretical model

The NGR logging characteristics are determined by geological and oil-bearing features of the formation, such as lithological characteristics, formation thickness, and rock composition and structure. In addition, the diameter of the well bottom and the properties of the drilling fluid, such as density and composition, influence NGR logging.

2.1. Main factors influencing NGR logging

2.1.1. Drilling fluid density

Drilling fluids of different density have different GR radioactivities. Thus, whether the gas drilling fluid is water-based or oil-based and the solid-particle composition of the drilling fluid influence NGR logging.

2.1.2. Drilling fluid composition

The composition of the drilling fluid influence the scatter of the NGR reflection and the capacity of the drilling fluid to absorb NGR from the formation. In particular, NaCl and KCl substantially increases the NGR radioactivity of the drilling fluid. Similarly, barite and bentonite increases radioactivity of the drilling fluid and the photoelectric absorption capacity of the drilling fluid, which can induce errors in NGR logging.

2.1.3. Instrument characteristics and well conditions

Instrument characteristics, such as the central degree, and well conditions, such as the drill-hole diameter and casing pipe diameter and thickness can influence the NGR logging response.

During a gas cut, the liquid–gas spatial distribution in the drilling fluid in the well changes, which in turn causes the NGR logging readings to change. These variations in the NGR logging data can be used to characterize the gas-cut intensity at the well bottom.

2.2. Calculation of gas volume fraction

2.2.1. Correction model for NGR logging

Among the many factors influencing NGR logging, in formations with the same lithological characteristics and depth, the properties of the drilling fluid exerts the strongest influence on NGR logging. Usually, the radioactivity of the drilling fluid is lower than that of the formation. The drilling fluid absorbs some of the NGR from the formation. Therefore, the NGR readings decrease with increase in the density of the drilling fluid and the well diameter, and vice versa.

Eqs. (1) and (2) express the correction equations for NGR logging data at the open-hole section (Schlumberger, 1989; Klaus, 2010) for correcting for the effects of the well diameter and mud proportions. Using these equations, the real radioactivity of the formation can be derived from the data captured by the NGR logging instrument.

$$N'_{GR} = N_{GR} \times A \times 10^{x} \tag{1}$$

$$x = \left(\frac{d_{\mathrm{well}} - d_{\mathrm{tool}}}{K}\right)[0.047(\rho_m - 8) + 0.38] - 0.1548 \tag{2}$$

where ρ_m is the mud proportion (lb/gal), K is the coefficient of eccentralization, A is the coefficient of outside diameter of the NGR logging instrument, d_{well} is the diameter of the wellbore, and d_{tool} is the outer diameter of the instrument.

2.2.2. NGR correction model for the effect of the gas cut

The properties of the drilling fluid, such as density and composition, substantially influences the logging response. If the gas invades the annulus from the formation, the annulus gas volume fraction and void fraction changes, which in turn changes the distribution characteristics of the drilling fluid around the NGR logging instrument. These changes consequently affect the logged NGR data because of changes in the detection environment.

The model presented in this paper is based on the assumption that during a gas cut, the gas returns from the well bottom. This gas occupies space in the annulus as it passes the NGR logging instrument, which changes the absorption capacity of the drilling fluid. Therefore, to correct the NGR logging data during a gas cut, the parameter gas-cut annulus equivalent diameter D_e (Yin et al., 2014) is defined on the basis of the gas void fraction of the gas cut flowing in the annulus.

Fig. 1a illustrates the cross-section of the annulus during a gas cut. The lateral grey area represents the stratum near the drill hole, the internal blue area represents the logging instrument, and the area between them represents the gas-cut drilling fluid. The yellow circular area represents the gas bubbles in the drill hole under the logging instrument. E_g is the gas volume fraction of the drilling fluid. Accordingly, the area of the drilling fluid in the annulus is $\frac{\pi}{4}(d_{well}^2 - d_{tool}^2) \times (1 - E_g)$.