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Monitoring and control strategies to manage pressure fluctuations during oil well drilling

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A R T I C L E I N F O

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A B S T R A C T

During drilling the mud flows through the drill string and exits through the choke valve. The mud density range has as constraints: pore pressure (minimum limit) and fracture pressure (maximum limit). In fact, annulus bottomhole (downhole) pressure needs to be higher than pore pressure, in order to prevent kick, and smaller than fracture pressure, for avoiding mud loss and formation damage. Experimental and simulation studies were implemented in order build a monitoring – diagnosing tool working together with a decision making routine based on an adaptive control scheme that employs gain scheduling. An experimental unit was built, presenting the most important characteristics of the drilling process. The transient nature of annulus bottomhole pressure is due to the process inherent disturbances: rheology, rate of penetration (ROP), kick and mud loss, which were all implemented at the experimental unit. The major objective of the present paper is using the experimental plant and a phenomenological model for implementing real time process automation, in order to assure drilling inside operational window, using in line measurements for flow and density disturbances under circulation loss and kick scenarios.

1. Introduction

The drilling of oil wells has been the focus of current research, mainly due to the need to drill deeper under adverse conditions, for example, a scenario of narrow operational window. Most researches are aimed at improving the performance of the drilling process, which is the most expensive stage of operation. Real time monitoring of properties and development of data transfer technology are tools that allow diagnosing problems, being linked to robustness and security of the drilling operations, aiming control and automation goals.

An important task during the drilling process is regulating the annulus bottomhole pressure (downhole pressure) inside an operational window, i.e., above the pore pressure and below the fracture pressure, Ajienka and Owolabi, 1991.

Helstrup et al. (2004) presented a mathematical model for predicting wellbore stability under variations on rock matrix, permeability, mud cake build up, in situ stress ratios, rock stiffness, fracture length and fracture orientation. Feng and Gray, 2017 presented a review concerning sealing fractures (lost circulation) and wellbore strengthening scenarios based on experimental and theoretical studies.

Chukwu and Ajienka, 1989 presented mathematical model simulations which unveiled that the rate at which a gas migrates to the surface increases as pressure and temperature decreases. Zilberman et al. (2001) presented the predictive precursors for predicting abnormally high formation pressures (AHFP), i.e., lithological barrier (anhydrite) with decreasing drilling rates and circulating mud with gas clay. Avelar et al. (2009) developed a two-phase flow model, validated with real data from an on-shore Brazil well, under a kick scenario. Ribeiro et al. (2006) presented experimental and simulation studies for predicting methane dissolution in synthetic muds.

According to Zhang et al. (2004), the fluid pressure depends on its density and this is the main property that provides the stability of the well. In fact, the drilling fluid is designed for carrying the cuttings to surface, avoiding the wall collapse of the well, lubricating the drill and exerting a pressure gradient along the well in order to prevent migration of fluid from the reservoir into the well annulus. This drilling fluid also has the function of restoring the balance that existed before drilling. If this balance is not restored, some ruptures might occur (traction or

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collapse). These ruptures may lead to invasion of mud toward the rock formations. The instability problems faced during drilling oil wells are often related to the uncertain knowledge of in situ stresses and pore pressure, besides, the use of inadequate drilling fluid density.

Keeping the annulus bottomhole pressure within the operational window, between fracture pressure (upper limit) and pore pressure (lower limit), is fundamental during the drilling process for avoiding kick and circulation loss problems. There are several factors that can impact the bottomhole pressure during the drilling process, i. e., solids insufficient removal by the drilling fluid, collapse of the well, mud loss, abnormally pressured zones with varying pressure gradient, inflows from reservoir to the well (kick), fluctuations of the weight of the drilling fluid and the pipe connection process, which is periodically performed during the drilling process. Khan and May 2016 employed a mathematical model for predicting transient bottomhole temperature under flow rate, inlet temperature, density and rheology disturbances.

Therefore, it is noteworthy that modeling, optimization and control techniques for oil well drilling are fundamental due to process delay, nonlinearities and transient inherent nature. Using these tools helps drilling within operational windows, especially when dealing with pre-salt region and under offshore drilling. There is a growing interest and enthusiasm of the oil industry at building systems for intelligent drilling, that is, analyze and interpret large amounts of data in real time for process optimization. In recent years, hybrid intelligent systems that integrate different techniques and fields of knowledge have become research objects (Sheremetov et al., 2008, Zhang et al. 2016). For expertise processing in a reliable manner, an expert system should be able to represent the perception based in evaluation of uncertainty of the measurements and based on facts and rules, reach conclusions and decisions based on measured or inferred variables. Prassl et al. (2005) combined expert knowledge under uncertainty bounds with a mathematical model for drilling within gas hydrate environments. In fact, the need to integrate the systems in computing environments introduces new levels of complexity when seeking automation and control.

Nowadays, drilling operations are facing new extremes considering more complex wells, fractures and cavernous formations, narrower operating windows (drilling in pre-salt fields), drilling deeper and longer than before. In addition to circulation losses, fractured regions are also an ongoing risk of kicks and blowouts. Thus, conventional drilling shows itself unable to ensure the objective of remaining within the established limits (above pore pressure and below fracture pressure), requiring such a precise control of the downhole pressure that conventional drilling method use is simply not feasible. New techniques provide a better way to deal with these extreme feature areas such as the use of the Managed Pressure drilling (MPD) technique, continuous circulation, wired pipe and PWD and mud-logging tools.

The monitoring tool called PWD (Pressure While Drilling) provides ECD (Equivalent Circulating Density) values, while the pump is on, and ESD (Equivalent Static Density) data, when pump is turned off. In addition, the mud logging tool performs drill cuttings analysis, evaluation of gas hydrocarbon, rate of penetration (ROP), pump rate, weight on bit, drill string weight, rotary speed, rotary torque, RPM (Revolutions Per Minute), SPM (Strokes Per Minute) mud volumes, mud weight and mud viscosity. The main drawback for pressure control purposes is the absence of pressure measurements, during the periodic disturbance named pipe connection procedure, when the mud circulation is interrupted. Instead of using telemetry, Wind et al., 2005 have developed an electro-magnetic transmission system which, however, might present problems due to attenuation of signals in deep wells.

Concerning real time measurements, Fu et al. (2015) proposed a kick detection method using an ultrasonic device for annular flow velocity monitoring. Azadpour et al. (2015) developed studies concerning pore pressure prediction using well-log data in one of the Iranian gas fields. Fan et al. (2015) developed a reservoir gas seepage model using real time monitoring of the total hydrocarbon value. Zuo et al. (2016) studied oil-based mud contamination using real time measurements in order to predict economic value of reserves. Al-Sudani (2017) built a method to predict the drilling efficiency, using the transferred mechanical energy as function of real time bit wear. The literature unveils that real time monitoring data by employing PWD and Mud-logging tools are very efficient ways to anticipate drilling problems (clean, well stability, gelling, kick, hydrates, etc.). As a result, these tools can be implemented for monitoring and controlling the drilling process, seeking automation.

The development of robust sensors, on line monitoring, mathematical modeling, optimization and control are essential tools to regulate the drilling process, being associated to robustness and safe of drilling operations, providing the diagnosis of spurious situations and the implementation of actions for disturbance rejection. Thus, control and automation of drilling operations are necessary for the future challenges of petroleum engineering, especially under a scenario of narrow operating windows. An analysis of the literature reveals that most of the papers employ monitoring (Alvarado et al, 2004; Mohaghegh, 2005; Nikravesh et al, 2002; Zhang et al., 2004; Sheremetov et al, 2005 e Sheremetov et al, 2008, Hermann, 2014), without coupling with diagnosis analysis and decision making (control) studies.

The present paper presents the efforts aiming oil well drilling automation. The first step includes real time monitoring software which operates with online real-time data analysis. The second step includes the concept of an integrated diagnosing and adaptive controlling tool to regulate the drilling process and the third an experimental pilot scale facility constructed to validate the methodology under flow and density disturbances, gas kick and loss circulation scenarios. As a result, this article presents steps which are the path aiming drilling automation, a subject matter foreseen by the drilling engineering as a key for ensuring the success of the nowadays complex drilling fields. The steps include combined efforts on real time monitoring, diagnosing (coupled with expert knowledge) and decision making using an adaptive (PI with gain scheduling) control algorithm to anticipate problems and reject disturbances. The significance of the present paper is related to the fact that the control and automation of drilling operations will be a required activity for future challenge of petroleum engineering, primordially, under a scenario of narrow operational windows. However, a review analysis unveiled that most papers in the literature deals with monitoring studies without closed loop implementation (control strategy). The paper presents an experimental unit which design was based on a similarity analysis in order to provide experimental data representative of field conditions. The experimental facility depicts the most important characteristics of the drilling process and has been employed to validate the methodology.

The present study employed a modified version of Kaasa et al. (2008) mathematical model and an adaptive control approach validated by an experimental facility, which possesses the most important characteristics of the drilling process. As a result, experimental data was employed to validate the automation methodology, which comprises real time monitoring, diagnosis and decision making. Drilling within operational window is experimentally implemented for analyzing the performance of the methodology under scenarios of circulation loss and gas kick. During circulation loss, the liquid and suspended particles invade the permeable formation of the reservoir, producing severe formation damage (Oliveira et al., 2014). This disturbance may block pores and fractures with solids materials: fine particles, drilling solids, bridging materials and polymers, reducing well productivity, Sacramento et al. (2015). A gas kick occurs when formation pressure is higher than downhole pressure. This situation appears due to a reduction in ECD, a pump failure, loss of casing back-pressure or swabbing of the well (Vajargah and van Oort, 2015). In this paper, these field problems are addressed by the mathematical model and the experimental drilling unit.

Depending on the disturbance severity analysis, the decision making tool indicates the best manipulated variable for implementing the adaptive controller. One of the strategies adopted to control the bottomhole pressure is to manipulate the mud density or to change the rate