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Real-time estimation of reservoir influx rate and pore pressure using a simplified transient two-phase flow model

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ABSTRACT

The ability to perform accurate pore pressure and reservoir inflow estimation during a kick incident is necessary, particularly when drilling in formations with narrow pressure margins. Currently available techniques for pore pressure estimation and reservoir characterization either rely on empirical correlations requiring access to well logging data and other petrophysical information, or require downhole pressure sensing and advanced flow metering capabilities. This paper introduces a model-based estimation technique which uses surface measurements commonly available in a Managed Pressure Drilling (MPD) system, coupled with a simplified transient two-phase model. This model is capable of representing essential dynamics during a gas kick with reduced computational overhead, but without sacrificing significant modeling accuracy. First, the model is validated in a gas kick scenario against experimental data, showing good agreement between key measured parameters and the model predictions, and thereby justifying the model applicability to field operations. Next, data generated from a commercial simulator test case is used to evaluate the proposed estimation methodology. The estimated pore pressure and reservoir productivity are close to their respective values from the commercial simulator, and the flow out rate and surface back-pressure predicted by the simplified two-phase model yield very good match against the simulator results.

1. Introduction

When drilling wells in challenging subsurface environments, such as complex geo-pressured deepwater prospects, it is crucial to maintain the wellbore pressure at a value above both the reservoir pore pressure and the minimum mud pressure required for wellbore stability (or in the case of underbalanced operations, between the wellbore stability limit and the pore pressure). Furthermore, wellbore pressure should not exceed the fracture pressure at any depth in the open-hole section, which effectively limits the available pressure window for safe drilling. Of these pressure limits, the most critical is the pore pressure, as falling below this value in an uncased hole section (e.g. due to insufficient mud weight, poor hydraulics management, improper hole fill-up during tripping or an abnormally pressured zone) leads to influx of formation fluids (oil, water, gas, or a combination thereof) into the wellbore. Influxes (also known as "kicks") tend to be more hazardous when the formation fluids contain gas, which expands in the annulus causing large variations in annular pressure. An uncontrolled kick triggers a "blow-out", which has potentially catastrophic consequences, impacting rig personnel safety, the surrounding environment, project economics, company and industry reputation (Karimi Vajargah et al., 2014). As a result, the proper planning and execution of well control operations is a major concern in any well being drilled, and the ability to model the gas influx dynamics in real-time, in addition to robustly estimating pore pressure, can significantly improve the success of a well control procedure.

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With the development of MPD techniques enabling precise control of the annular pressure profile, wells can be drilled more safely in formations with narrow pressure margins. A particular variant of MPD, which has become more prevalent in recent years, is the constant bottom-hole pressure (CBHP) technique. This method relies on a dedicated choke manifold for applying back-pressure on the annular side, with the goal to maintain the bottom-hole pressure constant throughout the operation. Additionally, CBHP MPD systems include an accurate flow metering system, enabling early kick detection by constant monitoring of return flow in the closed-loop circulation system (Santos et al., 2003). The early kick detection, combined with immediate application of back-pressure by manipulating the size of the choke valve orifice, allows small and medium size kicks to be safely circulated out the of the well without the need for a conventional shut-in operation (Karimi Vajargah et al., 2014; Kinik et al., 2015; Aarsnes et al., 2016a).

In addition to state-of-the art actuation and sensing equipment, the CBHP MPD technique also requires an accurate hydraulic model with multi-phase flow capabilities. Although advanced models have been developed to this end, their complexity makes them impractical for real-time applications such as model-based closed-loop control and estimation. As a result, most MPD control systems in the industry still rely on single-phase dynamic models (e.g. Godhavn, 2010; Kaasa et al., 2012; Reitsma and Couturier, 2012). Therefore, introducing a fit-for-purpose model which can capture the essential dynamics of gas expansion with limited computational expense and complexity is highly desirable. One potential application of such a model is the real-time estimation of pore pressure and reservoir productivity during a kick incident. This paper introduces a model-based estimation methodology employing a simplified two-phase flow model developed by the authors (Ambrus et al., 2015; Aarsnes et al., 2016b). An experimental test data set is first used to validate the model, and subsequently the estimation algorithm is applied on a test case generated using a commercial multi-phase simulator.

2. Background

The proper knowledge of pore pressure, together with fracture pressure and the pressure required for wellbore stability is a primary factor in the design of a well program prior to drilling. Traditional methods for determining pore pressure in a drilling operation rely either on repeat formation tests and drill stem tests, or on empirical correlations to petrophysical logs, such as sonic, density and resistivity logs (Aadnoy et al., 2009). Among the most widely used correlation techniques are Eaton's method, used for estimating pore pressure in shales based on normal compaction trends and resistivity, sonic, or “d-exponent” logs, and Bowers' method, which uses a correlation between sonic velocity and effective stress accounting for the underlying causes of overpressure (Ameen Rostami et al., 2015).

The development of MPD techniques has enabled new approaches to real-time pore pressure estimation during kick incidents. Gravdal et al. (2010) used statistical modeling of the surface back-pressure buildup curve during shut-in to arrive at an estimate of pore pressure. A polynomial curve-fit was used to ascertain when the wellbore pressure balanced the formation pressure, such that the measured bottom-hole pressure could be used as the new pore pressure estimate. Application of this algorithm requires a downhole pressure sensor, or an estimate of bottom-hole pressure obtained using a transient hydraulics model. Santos et al. (2003) introduced a method for determining pore and fracture pressure while drilling through stepwise reduction or increase in surface back-pressure until a micro influx or leak off is detected. Ameen Rostami et al. (2015) showed a more recent application of this technique, where downhole pressure is continuously monitored during the test using a Pressure While Drilling (PWD) tool, and the readings are used to calibrate previous pore pressure estimates, obtained using Eaton's d-exponent method or other similar techniques.

Real-time reservoir characterization has also been facilitated by underbalanced drilling (UBD), where the bottom-hole circulating pressure is intentionally kept below the pore pressure, effectively producing formation fluids while drilling (Vefring et al., 2003). In addition to minimizing reservoir impairment and maximizing production, UBD enables a better understanding of reservoir properties through comparison between real-time production rates and well logging data (Culen and Killip, 2005). Additional information can be inferred from pressure buildup data and gas and liquid flow metering on surface, leading to more accurate estimates of reservoir pressure and productivity index for different reservoir sections (Suryanarayana et al., 2007; Shayegi et al., 2012).

In addition to the methodologies above, which are mostly empirical and/or measurement-intensive, several researchers have attempted model-based estimation techniques, relying on physics-based models of the drilling hydraulics. Zhou et al. (2011) used an adaptive observer in conjunction with a single-phase hydraulic model and a linear reservoir model to estimate influx rate and pore pressure in an MPD system. Their estimation algorithm did not take gas expansion into account, which reduced performance when gas was being circulated out. An adaptive observer was also used by Hauge et al. (2012) for estimating the influx rate as well as the depth of the influx zone. A more sophisticated approach, using an infinite-dimensional boundary observer was applied to a transmission line model of the drilling hydraulics in order to estimate influx or lost circulation events occurring in an MPD setting (Hauge et al., 2013).

In the context of UBD operations, Vefring et al. (2003) used an Ensemble Kalman Filter and the Levenberg-Marquardt method on the Drift-Flux Model coupled with a dynamic reservoir model to estimate reservoir pore pressure and permeability. Biswas et al. (2003) employed a genetic algorithm in conjunction with a transient two-phase reservoir simulator for the problem of estimating reservoir permeability as a function of depth. Aarsnes et al. (2014a) used the Drift-Flux Model in conjunction with an Extended Kalman Filter for on-line estimation of the productivity index, while uncertain model parameters, such as friction factor, choke model coefficients and slip velocity, required off-line calibration.

3. Theory

The methodology presented in this paper comprises a simplified transient two-phase hydraulic simulator (the “reduced Drift-Flux Model”) and an estimation algorithm which builds upon a reservoir inflow model. The information flow among these key components and their input and output parameters are schematically illustrated in Fig. 1. The models and algorithms used are detailed in Section 3.1 and Section 3.2. It should be noted that this approach only requires surface measurements (mud flow rate in and out of the well, pressure at the well head, and pit gain), whereas downhole pressure is computed using the reduced Drift-Flux Model.

3.1. The reduced DFM

The Drift-Flux Model (DFM) is one of the multi-phase models most frequently used in drilling applications. The DFM consists of separate mass balance equations and a combined momentum balance, together with several closure relations and a slip relation (see Appendix A for the mathematical formulation). Although