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Reservoir characterization in under-balanced drilling using low-order lumped model

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ABSTRACT

Estimation of the production index of oil and gas from the reservoir into the well during under-balanced drilling (UBD) is studied. This paper compares a Lyapunov-based adaptive observer and a joint unscented Kalman filter (UKF) based on a low order lumped (LOL) model and the joint UKF based on the distributed drift-flux model by using real-time measurements of the choke and the bottom-hole pressures. Using the OLGA simulator, it is found that all adaptive observers are capable of identifying the production constants of gas and liquid from the reservoir into the well, with some differences in performance. The results show that the LOL model is sufficient for the purpose of reservoir characterization during UBD operations. Robustness of the adaptive observers is investigated in case of uncertainties and errors in the reservoir and well parameters of the models.

1. Introduction

Since the number of depleted formations and cost of field exploration and development has increased, for the past two decades there has been increasing interest in new technology and automation of the drilling process which can improve drilling efficiency and increase oil recovery. UBD is a technology that enables drilling with the downhole pressure lower than the pore pressure of the formation. UBD has several advantages compared to conventional drilling in increasing the ultimate recovery from the reservoir, reducing the non-productive time (NPT), minimizing the risk of lost circulation, increasing the rate of penetration (ROP), reducing drilling-fluid costs through the use of cheaper, lighter fluid systems, and reducing drilling problems such as hole cleaning and differential sticking [1,2].

Real-time updates of reservoir properties may improve efficiency of the overall well construction by more accurate reservoir characterization while drilling, ultimately enabling increased oil recovery by better well completion. Reservoir characterization during UBD has been investigated by several researchers [3–7], focusing mainly on the estimation of the reservoir pore pressure and reservoir permeability by using the assumption that the total flow rate from the reservoir is known [5]. Kneissl proposed an algorithm to estimate both reservoir pore pressure and reservoir permeability during UBD while performing an excitation of the bottom-hole pressure [4]. However, the variations of fluid flow behavior in the downhole and the annulus section might introduce significant uncertainties to estimation of the reservoir pore pressure. Vefring et al. [5,6] compared and evaluated the performance of the ensemble Kalman filter and an off-line nonlinear least squares technique utilizing the Levenberg–Marquardt optimization algorithm to estimate reservoir pore pressure and reservoir permeability during UBD while performing an excitation of the bottom-hole pressure. The result shows that excitation of the bottom-hole pressure might improve the estimation of the reservoir pore pressure and reservoir permeability [5,6]. Gao Li et al. presented an algorithm for characterizing reservoir pore pressure and reservoir permeability during UBD of horizontal wells [7]. Since the total flow rate from the reservoir has a negative linear correlation with the bottom hole pressure, reservoir pore pressure can be identified by the crossing of the horizontal axis and the best-fit regression line between the total flow rate from the reservoir and the bottom hole pressure while performing an excitation of the bottom-hole pressure by changing the choke valve opening or pump rates.

In this paper, it is assumed that reservoir pore pressure is known by identification using Li's method [7] or other algorithms. The main focus is to estimate both production constants of gas and liquid during UBD operations, simultaneously. Due to the complexity of the multi-phase flow dynamics of a UBD well coupled with a

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reservoir, the modeling, estimation and control of UBD operations is still considered an emerging and challenging topic in drilling automation. Nygaard et al. compared and evaluated the performance of the extended Kalman filter, the ensemble Kalman filter and the unscented Kalman filter based on a low order model to estimate the states and the production index (PI) in UBD operation [8]. Lorentzen et al. designed an ensemble Kalman filter based on a drift-flux model to tune the uncertain parameters of a two-phase flow model in the UBD operation [9]. In Nygaard et al. [10], a finite horizon nonlinear model predictive control in combination with an unscented Kalman filter was designed for controlling the bottom-hole pressure based on a low order model developed in [11], and the unscented Kalman filter (UKF) was used to estimate the states, and the friction and choke coefficients. A Nonlinear Moving Horizon Observer based on a low-order lumped model (LOL) was designed for estimating the total mass of gas and liquid in the annulus and geological properties of the reservoir during UBD operation for pipe connection procedure in [12]. Aarsnes et al. introduced a simplified drift-flux model and estimation of the distributed multiphase dynamics during UBD operation. This model used a specific empirical slip law without flow-regime predictions [13]. The estimation algorithm separates slowly varying parameters and potentially more quickly changing parameters such as the PI. Fast changing parameters are estimated online simultaneously with the states of the model, but other parameters are calibrated infrequently and offline. Nikoofard et al. designed an UKF for estimation of unmeasured states, production and slip parameters of simplified drift-flux model using real time measurements of the bottom-hole pressure and liquid and gas rate at the outlet [14,15]. Di Meglio et al. designed an adaptive observer based on a backstepping approach for a linear first-order hyperbolic system of Partial Differential Equations (PDEs) by using only boundary measurements with application to UBD [16]. It is shown that this method has exponential convergence for the distributed state and the parameter estimation. This adaptive observer is applied to estimate distributed states and unknown boundary parameters of the well during UBD operations. Nikoofard et al. designed Lyapunov-based adaptive observer, a recursive least squares estimator and a UKF based on a LOL model to estimate states and parameters during UBD operations. For this estimation the total mass of gas and liquid was used as measurements. These values were calculated from pressure measurements using the LOL model [17]. In [17], the performance of the adaptive estimators was compared and evaluated for pipe connection procedure using a simple simulation model. In [18] the extended version of adaptive observer used in [17] was directly using real-time measurements of the choke and the bottom-hole pressures to estimate states and parameters. The performance of the adaptive observers was compared and evaluated for typical drilling case to estimate only production constant of gas using a simulated scenario with drift-flux model. In the present paper, the adaptive observers from [18] is compared and evaluated for an UBD case study to estimate both production constants of gas and liquid using some simulated scenarios with the OLGA simulator. The OLGA dynamic multiphase flow simulator is a high fidelity simulation tool which has become the de facto industry standard in oil and gas production, see [19]. These adaptive observers were tested by two challenging scenarios:

1. Changing for production constant of gas.
2. Pipe connection.

The performance of the estimation algorithms to detect and track the change in production parameters is investigated in a more realistic setting.

Lyapunov based adaptive observers and the Kalman filter are widely used for the estimation of state and parameters. A Lyapunov based adaptive observer is generally designed as Luenberger type observer for the state combined with an appropriate adaptive law to estimate the unknown parameters [20]. The unscented Kalman filter (UKF) has been shown to typically have a better performance than other Kalman filter techniques for nonlinear system [21,22].

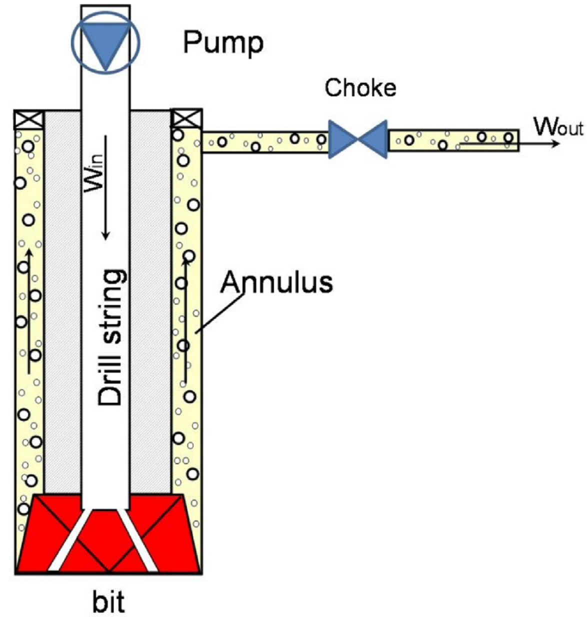

Fig. 1. Schematic of an UBD system.

The purpose of the paper is to evaluate the LOL model for reservoir characterization in UBD employing an adaptive observer that uses the bottom hole and choke pressure measurements from a simulated scenario with the OLGA simulator. This paper presents the design of a Lyapunov-based adaptive observer and an UKF based on LOL model, and an UKF based on a simplified drift-flux model, to estimate the states and geological properties of the reservoir (production parameters) during UBD operation. The performance of the adaptive observers based on LOL model is evaluated against UKF based on a simplified drift-flux model by using measurements from the OLGA simulator. The adaptive observers are compared with each other in terms of rate of convergence and accuracy. Robustness of the adaptive observers is investigated in case of errors in the reservoir and well parameters of the models.

This paper consists of the following sections: Section 2 describes the basic concept of the UBD process. The modeling Section 3 presents a LOL and simplified drift-flux model based on mass and momentum balances for UBD operation and the reservoir model. Section 4 explains the Lyapunov-based adaptive observer and joint UKF methods for simultaneously estimating the states and model parameters from real-time measurements. Section 5, at the end the conclusion of the paper is presented.

2. Under balanced drilling

In drilling operations, the drilling fluid is pumped down the drill string and through the drill bit into the well (see Fig. 1). The annulus is sealed with a rotating control device (RCD), and the drilling fluid exits through a controlled choke valve, allowing for faster and more precise control of the annular pressure. The drilling fluid carries cuttings from the drill bit to the surface.

In conventional (over-balanced) drilling, or managed pressure drilling (MPD), the pressure in the well is kept greater than the pressure of the reservoir to prevent influx from entering the well [23,24]. In UBD operations, on the other hand the pressure of the