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An innovative diagnosis method for lost circulation with unscented Kalman filter

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ABSTRACT

Lost circulation, as a widespread and costly drilling problem, not only wastes a lot of drilling fluid, but also produces a large amount of nonproductive time (NPT). Therefore, detecting the symptoms of lost circulation opportunely, pinpointing the loss depth and evaluating the loss rate precisely are extremely crucial.

A diagnosis method for detecting the occurrence of lost circulation and identifying the loss depth as well as loss rate at an early stage is proposed, which combines a transient pressure and temperature coupling model with unscented Kalman filter (UKF) estimation. We first establish the transient pressure and temperature coupling model under the conditions of normal drilling operation and lost circulation. Then the detection and identification estimators for estimating pressure-loss factors, flow rate factor, loss depth and loss rate are constituted by embedding the detection and identification models, which are derived from the transient pressure and temperature coupling model, into UKF estimation. In the end, a simulated case study is presented to illustrate the performance of the diagnosis method.

In the simulation, the estimated pressure and outlet flow rate trace the measurements well with the evolution of pressure-loss factors and flow rate factor. Moreover, the pressure-loss factor in annulus and flow rate factor, which fluctuate to a little extent in normal drilling condition, deviate from the base value once lost circulation occurs. The simulation indicates the superior performance of the diagnosis method with the introduction of pressure-loss factors and flow rate factor, and the average error of estimated loss depth is less than 5%. In addition, the parametric sensitivity analysis illustrates the universality of the diagnosis method, which has certain ability to improve drilling safety and efficiency with lower NPT.

1. Introduction

Lost circulation is a situation where less fluid is returned from the wellbore than is pumped into it (Lavrov, 2016). When a porous, cavernous or highly fractured zone intercepts the well path, part of drilling fluid will lost into formation instead of returning up the annulus under overbalanced pressure between the wellbore and formation. If lost circulation is not handled properly, it will cause many negative consequences, such as well control issues, poor hole cleaning and stuck pipe (Feng and Gray, 2017a; b; Xu et al., 2017). Therefore, research works on lost circulation have received a considerable attention for decades of years.

Among numerous issues on lost circulation, the detection of lost circulation (i.e., judging whether a lost circulation occurs or not) is an enduring research topic (Anfinsen and Rommetveit, 1992; Maus et al., 1979; Mills et al., 2012; Nayeem et al., 2016; Reitsma, 2010, 2011; Speers and Gehrig, 1987; Willersrud et al., 2015a, 2013). The monitoring of pit volume gain and delta flow rate has been proved to be an effective way to detect loss-and-gain problems. For example, Maus et al. (1979) points out that return flow rate, pit volume and standpipe pressure are sensitive indicators for the detection of lost circulation; based on this conclusion, delta flow rate approach which shows extreme sensitivity to the onset of simulated lost circulation and kicks is proposed (Speers and Gehrig, 1987). Afterwards, more surface mud logging and downhole measurement parameters, such as standpipe pressure, annular discharge pressure, and downhole annulus pressure, are used jointly to address loss-and-gain detection problems (Mills et al., 2012; Nayeem et al., 2016; Reitsma, 2010, 2011). For instance, the combination of standpipe

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pressure and annulus discharge pressure is successfully tested for the early detection of fluid loss, kick, drill string leak and plugging under testing conditions (Mills et al., 2012; Reitsma, 2010, 2011); experiments indicate that the downhole pressure, downhole mass flow rate, downhole density and conductivity of drilling fluid provide the clear evidence of formation fluid inflow in Nayeem et al. (2016), which show the potential of improving detection accuracy than surface parameters. Recently, a model-based detection system which relies on an ordinary differential equation (ODE) is presented (Willersrud et al., 2015a; b). This method quantifies the change in pressure-loss and outlet flow rate with an globally exponentially stable adaptive observer to detect downhole problems. Besides, data from a medium-scale horizontal flow loop test facility under conditions of lost circulation, washout, gas influx, and bit nozzle plugging are tested.

The identification of lost circulation (i.e., quantification of loss depth and loss rate) has been somewhat less extensively studied than the detection of lost circulation (Hossain and Al-Majed, 2015; Aghli et al., 2016; Tokhmechi et al., 2009; Hauge et al., 2013; Willersrud et al., 2015a; Chen et al., 2014, 2017). In existing literature, the survey of temperature, radioactive tracer, and spinner can be used to locate loss zone (Hossain and Al-Majed, 2015). However, the significant NPT and costs from tripping and logging operations hinder the broad field applications of such methods. Chen et al. (2017) presents an approach of predicting the location of single loss zone in a vertical well by interpreting the transient mud circulating temperature profile altered by lost circulation. In Hauge et al. (2013), an adaptive observer is adopted to estimate the loss rate and loss position, as well as the unknown states in ODE model. Based on the same observer theory, Anders Willersrud investigates loss identification with distributed pressure sensors in the annulus, which locates the position of drilling fluid loss between two sensors (Willersrud et al., 2015a).

Inspired by the ideas in Gravdal (2009),Gravdal et al. (2010b) and Willersrud et al. (2015a), we propose a diagnosis method for detecting the occurrence of lost circulation and identifying the loss depth as well as loss rate at an early stage, which combines the transient pressure and temperature coupling model with UKF estimation. We start with the transient pressure and temperature coupling model establishment under conditions of normal drilling operation and lost circulation. Then, UKF implementation is introduced to this topic. Afterwards, the detection and identification models, which are set up on the basic of the transient pressure and temperature coupling model, are embedded into UKF to develop the diagnosis method. Finally, a case study is presented to illustrate the performance of the proposed method, and parametric sensitivity analysis on estimated loss depth is further conducted to prove the universality of our method.

The main contribution of this paper can be summarized as follows. (1) UKF is used to estimate pressure-loss factor, flow rate factor, loss depth and loss rate in the detection and identification models, which relaxes the time increment of measurements updating. (2) Our identification model can quantify loss depth and loss rate, which benefits the cure of lost circulation greatly. (3) The temperature effect is taken into consideration both in the detection and identification models, which makes our method more practical.

2. Transient pressure and temperature coupling model

In this section, we dedicate to characterizing the flow and heat transfer behaviors of drilling fluid under normal drilling operation and lost circulation conditions by a mathematical model.

Lost circulation results in reduced mass flow rate above the loss zone, while maintains invariable mass flow rate below the loss zone, since port of drilling fluid is lost into formation through formation pores or fractures at loss zone. Further, the reduction of mass flow rate above the loss zone alters pressure distribution in the wellbore and heat transmission status between drill string, annulus, and near-wellbore formation. Based on this perspective, we first focus on the detection of lost circulation and then on its identification (i.e., quantify loss depth x as well as loss rate Δq_l in Fig. 1), via using data of topside and downhole measurements.

Clearly, the detection and identification of lost circulation need precise model to characterize the fluid flow and heat transfer behaviors of drilling fluid. For this purpose, the following assumptions are made:

(1) we only consider one dimensional flow along the flow direction both in drill string and annulus;
(2) thermophysical properties of drilling fluid are constant, while density and viscosity of drilling fluid are dependent on pressure and temperature, which are presented as $\rho = \rho(p, T)$ and $\mu_a = \mu_a(p, T)$;
(3) physical properties of formation (i.e., density, specific heat and thermal conductivity rate) are constant;
(4) cutting concentration in drilling fluid is negligible and uniform wellbore diameter is taken.

2.1. Governing equations

It is well known that mass, momentum and energy conservations ensure that the calculated pressure, temperature and flow parameters are functions of space and time. Referring to Lima et al. (1999); Gravdal et al. (2010b), the mass conservation equation of single-phase flow in drill string and annulus in normal drilling condition can be written as

$$\frac{\partial}{\partial z}(\rho A v)_k + \frac{\partial}{\partial t}(\rho A)_k = 0, k = a, d, \tag{1}$$

where ρ is the density, A is the cross-section area, v is the velocity of the fluid, z represents the length of the well, and t is the time variable. Besides, subscripts a and d denote the fluid in annulus and drill string respectively.

When lost circulation arises somewhere in annulus, equation (1) is no longer applicable to loss zone. Actually, the mass flow rate of drilling fluid along the wellbore under lost circulation condition can be demonstrated in Fig. 2, and thus the mass conservation equation at node i can be substituted by

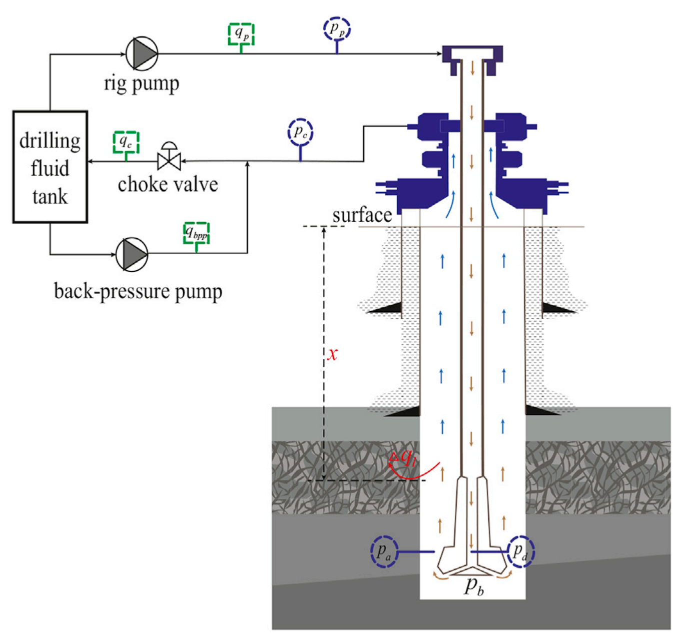

Fig. 1. Schematic of drilling system with lost circulation. p_p, p_c, p_a and p_d denote available pressure data; q_p, q_c and q_{bpp} denote available mass flow rate data. p_b denotes pressure-loss through the bit nozzle.