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An accurate model to predict drilling fluid density at wellbore conditions

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ABSTRACT

Knowledge about rheology of drilling fluid at wellbore conditions (High pressure and High temperature) is a need for avoiding drilling fluid losses through the formation. Unfortunately, lack of a universal model for prediction drilling fluid density at the addressed conditions impressed the performance of drilling fluid loss control. So, the main motivation of this paper is to suggest a rigorous predictive model for estimating drilling fluid density (g/cm^3) at wellbore conditions. In this regard, a couple of particle swarm optimization (PSO) and artificial neural network (ANN) was utilized to suggest a high-performance model for predicting the drilling fluid density. Moreover, two competitive machine learning models including fuzzy inference system (FIS) model and a hybrid of genetic algorithm (GA) and FIS (called GA-FIS) method were employed. To construct and examine the predictive models the data samples of the open literature were used. Based on the statistical criteria the PSO-ANN model has reasonable performance in comparison with other intelligent methods used in this study. Therefore, the PSO-ANN model can be employed reliably to estimate the drilling fluid density (g/cm^3) at HPHT condition.

1. Introduction

The temperature and the pressure increase as the depth increase in the well. By increasing pressure, mud density increases, too, but by increasing temperature the density decreases [1]. These changes could not cancel out each other. On the other way, the density is only known at the initial and standard condition. It's difficult to measure temperature and pressure at each depth both in time and cost aspect. When underbalanced drilling (UBD) method is used, kicks and blow-outs may occur if density is not that to be. In overbalanced drilling (OBD) method, fluid loss may occur if density is not correct.

In some formations, there is a small difference between pore pressure and formation fracture pressure. So correct mud density prediction at high pressures and temperatures is needed to manage time and cost, avoid mud lost and analyze fracture-gradient test data.

Osman et al. [1] presented a model using artificial neural networks (ANN) for prediction of both oil-based and water-based mud density based on mud type and it's density at standard condition. They predicted density for oil-based and water-based mud for pressures up to 1400 psi and temperatures up to 400 °F with an error of 0.367 with exact measurements. They also found that density predicted is insensitive to the initial mud density, the result which McMordie et al. [2] found it, too.

Peters et al. [3] presented a compositional material balance for oil-based mud. They predicted the density at higher pressure and temperature using the density of the mud constituents at ambient condition and the density of the liquid constituents HPHT condition. Their model is applicable for pressures up to 15,000 psig and temperatures up to 400 °F with an error less than 1%.

Hoberock et al. [4] presented a model in order to predict downhole densities for water and diesel-oil-based mud using compositional material balance model. His model is based on the change in mud volume before entering deeper part and after that, as follows:

$$\rho(P,T) = \frac{\rho_{oi}f_{vo} + \rho_{wi}f_{vw} + \rho_s f_{vs} + \rho_c f_{vc}}{1 + f_{vo}\left(\frac{\rho_{oi}}{\rho_o} - 1\right) + f_{vw}\left(\frac{\rho_{wi}}{\rho_w} - 1\right)} \quad (1)$$

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Where, ρ_{oi}, ρ_{wi} are the density of oil and water at initial condition- ρ_o, ρ_w are the density of oil and water at pressure P and temperature T- $f_{vo}, f_{vw}, f_{vs}, f_{vc}$ are the fractional volume of oil, water, solid material and chemical additives, respectively-P is pressure and T is temperature.

It should be noted that this model is only applicable for steady-state circulation temperatures and hydrostatic pressures.

Generally, in compositional models [3,4] the volumetric behavior of the mud based on its individual constituents is investigated. There are some assumptions in compositional models mentioned including Independency of solid density to pressure and temperature, change in density of liquid phases causes a change in mud density and no interaction between liquid and solid phases.

Tiantai et al. [5] presented a new method to model mud density in inclined wells. As we know the stability of borehole in vertical wells differs from the one in inclined wells. They predicted mud density according to the shear destruction and tensile failure of the borehole. In other words, initially, the found stresses at different depths using well wall surrounding stress analysis and then according to stresses determined, mud density was predicted.

Oil-based mud has some advantages making them useful in drilling industry [6]. Some of these advantages are Thermal stability in deep wells, high lubricity in deviated wells and high stability in shale layers. Since oil-based mud density is more dependent on pressure and temperature rather than water-based mud, more works have been done on this type of mud.

Golate et al. [7] combined techniques for determining mud-property with empirical pressure drop correlations. Theses correlations were found by Randall and Anderson [8], in which equations are provided empirically for the pressure losses in the drill string and wellbore annulus. Golate et al. used a general purpose wellbore thermal and hydraulic model called "WELLTEMP" which could predict oil-based mud density profiles.

Sorelle et al. [9] represented a mathematical model with minimum input data which could predict mud density in static drilling fluids at deeper parts of the well. The model was used for oil-based mud. They considered that the mud includes water, oil, and solids. Ignoring change in solid volume, they measured the change in oil and water volume. They found the final density as follows:

$$\rho_f = \frac{\rho_i}{1 + \frac{\Delta V_o}{V} + \frac{\Delta V_w}{V}} \quad (2)$$

Where, ρ_f is the final density of the mud, ρ_i is the initial density of the mud, V is the total volume of the mud, ΔV_o is the change in oil volume and ΔV_w is the change in water volume.

This method is only applicable for static mud columns with frictional pressure losses ignored.

Hydrostatic pressure is defined to be the pressure of the vertical column of drilling mud exerted at any point. Equivalent circulating density (ECD) is defined to be the pressure on the formation exerted by the mud column while the mud moves in the well. It's the sum of the hydrostatic pressure and the frictional pressure loss when the mud is circulating. Three main origins exist for ECD including circulation, rotation, and reciprocation (pipe vertical movements). There are also three different special tests for determining different sources of ECD: Step rate tests for measuring circulation source, rotation tests for measuring rotation source, and swab and surge tests for measuring reciprocation source [10].

Charlez et al. [10] used the hydraulic model to calculate downhole pressure and then predicted fluid downhole density. They compared their model results in the Dunbar field with different pressure while drilling results with an accuracy of 1%.

Hemphill [11] found that in deviated and extended reach wells physical properties of mud including density play an important role. In other words, hole cleaning and cuttings suspension parameters should be noticed in order to determine mud properties.

Some authors investigated drilling in deep water environments [12]. A cold environment causes mud gelation which could affect mud density prediction.

Isambourg et al. [13] analyzed mud density in a cell able to measure volumetric changes at pressures up to 1500 bar and temperatures up to 200 °C. They proved that in high-density mud measurements solid density should not be assumed constant. In other words, their nine-parameter polynomial mathematical model could predict mud density in high-pressure and high-temperature medium considering solid volume change.

Kutasov [14] introduced an empirical equation relating pressure, mud density and temperature as follows:

$$\rho_m = \rho_{mo} \exp[\alpha(P - P_0) - \beta(T - T_0) \mp \gamma(T - T_0)^2] \quad (3)$$

Where, ρ_m is mud density at pressure P and temperature T- ρ_{mo} is initial mud density at standard conditions- P_0 and T_0 are initial pressure and temperature at standard condition- α, β and γ are empirical constants.

He evaluated α, β, γ and ρ_{mo} for five muds introduced by McMordie et al. [2]. Density found using these coefficients had an error of 0.21% with empirically measured density.

Babu [15] investigated the influence of thermal gradient on hydrostatic gradients like others [16] who worked on the effect of temperature gradient on equivalent static density. Babu compared the results from three models for twelve muds. These models include empirical model introduced by Kutasov, compositional models by Peters and Hoberock and model by Sorelle et al. He found that the results from the empirical model were more accurate than the other models.

Rommetveit et al. [17] proposed two models including static model and dynamic model to show the effect of hydrostatic and frictional pressure losses in high pressure and high-temperature wells on equivalent circulating density (ECD). In static model, only vertical changes of temperature along the wellbore were considered, while in the dynamic one the changes in temperature over time are considered, too.

Peters et al. [18] introduced a program called "OILMUD" which predicted densities and hydrostatic pressures in oil-based mud at deeper parts of the well having higher pressure and temperature. The density was calculated using a multi-linear-regression analysis of experimental data. This program is applicable for diesel-oil-based mud and for four less-toxic mineral oil based mud.

Diaz et al. [19] compared three modeling methods of determination of equivalent circulating density (ECD) with experimental data. The ECD was calculated for a new drilling method called casing while drilling (CWD) [20]. In most casing drilling methods, ECD is higher than the ECD in conventional drilling method.

Baranthol et al. [21] compared two methods of ECD modeling: In the first method, a one-dimensional fluid flow for the Non-Newtonian fluid model was used. This method was easier but the results were not accurate. In the second one, a one-dimensional pressure model and a dynamic two-dimensional temperature model was used. Rheological data of the mud were used in this method and the results were accurate but more complex.

Some authors tried to investigate different factors affecting mud density modeling. Shale is one of the most important factors [22]. In some parts interstitial fluid pressure shales cause density reversal of normal shale compaction.

Some authors of Ref. [23] investigated the factors causing fluctuation of equivalent circulating density (ECD). They found that not only turning on and off mud pumps caused ECD fluctuation, but also repetition of drilling interruption for making a connection caused a fluctuation, too. So a schedule of hole cleaning and rate