Investigation of Plastering Effect in Casing-while-Drilling – A CFD Study

T N Ofei*, A N Jalaludin¹, A D Habte¹, T A Lemma² and J Ben-Awuah³

¹Department of Petroleum Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 32610 Perak, Malaysia.
²Department of Mechanical Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 32610 Perak, Malaysia.
³Department of Applied Geology, Curtin University, Sarawak, CDT 250, 98009 Miri Malaysia.

*Email: titus.ofei@utp.edu.my; titusofei@hotmail.com

Abstract. In conventional oil and gas well drilling, filter cake builds up on the wellbore wall due to overbalance pressure which forces the drilling fluid into the rock formation and leaves solid particles on the wellbore wall. The presence of a filter cake is beneficial since it reduces fluid loss and damage to the formation. Plastering or “smearing” effect is a mechanical conditioning of a wellbore which is believed to enhance wellbore stability by packing any fractured zone with drilled cuttings and fluid. This phenomenon is usually believed to occur in a narrow annular wellbore such as casing-while-drilling (CwD), where actual casing is used to drill and transmit both mechanical and hydraulic energy to the bit, rather than the usual conventional drillstring. In this study, a three-dimensional modelling and numerical simulation is carried out to examine the influence of particle size (drilled cuttings size) of 100 microns to 2000 microns and fluid type (water, oil-based mud, and water-based mud) on filter cake formation in a vertical wellbore. The simulation adopts the inhomogeneous Eulerian-Eulerian two-fluid model to solve the two-phase flow equations. The numerical model was set up to depict the subsurface conditions at moderate pressure and temperature of 13.8 MPa and 30°C respectively. The results showed that with the increase in particle size, the filter cake height increased marginally for all fluid types, where the percentage increment ranges from 1.3% to 2.6%. Furthermore, filter cake thickness was high when water was used as the drilling fluid, whereas, the least filter cake height was recorded when oil-based mud was used. The filter cake formation on the vertical wellbore was therefore non-uniform for all scenarios. This study shows how useful numerical simulation can capture the physical mechanisms affecting plastering effect and optimise drilling parameters during casing-while drilling.

Key words: casing while drilling; Eulerian-Eulerian model; filter cake; numerical simulation; plastering effect

1. Introduction

For decades, the oil and gas industry has been faced with many challenges when it comes to drilling operations. Amongst the common ones are non-productive time (NPT) due to tripping process and loss of circulation. The industry has been researching to provide improvements for drilling methods and wellbore activities. Amongst the practical ideas to minimise these challenges in drilling operation is by using casing-while-drilling (CwD) technique. This innovative technique allows the operator to drill and case the well simultaneously, as opposed to the conventional drilling approach where the
drillstring has to be pulled out of hole before the casing is installed. As the equipment compasses with the emergence of reliable parts such as top drive system, wireline retrievable bottom-hole assembly (BHA), polycrystalline diamond compact (PDC) and high rating rotating twisted casings, it is absolutely possible for the simultaneous process to be done [1]. CwD has proven that this method could actually reduce the NPT and loss of circulation significantly, to date. CwD method is basically replacing the conventional drill pipes with the casing itself. Therefore, at the designated and targeted drilled depth, the casing could be installed right away without the needs of tripping the drill pipe out first before running the case down the wellbore [2].

As the casing size is much bigger compared to the conventional drill pipe, it results in smaller annulus size, which affect the wellbore geomechanically and drilling fluid dynamically. The ratio of casing outer diameter to hole size is certainly the primary factor for the occurrence of plastering effect which is believed to be more than 0.75 [3]. As a result, plastering effect, also known as, smearing effect occurs [4]. There are many factors impacting plastering effect, for instance, particle size distribution (PSD), rotations per minute (RPM), cuttings volume fraction, time, types of mud, rates of penetration (ROP) and casing-hole eccentricity [5].

Plastering effect could be compared to ‘stress caging’ which is advantageous to the upstream sector [6]. Due to low fracture gradient in CwD operation, crack may form at the wellbore. In this way, smearing impact compels drilled cuttings and mud particles into the crack, making an extension or wedge between the cracks that expand the hoop stress around the wellbore, thereby improving the fracture gradient of the wellbore and aids in strengthening the wellbore. The wellbore could be drilled by utilising higher equivalent circulating density (ECD) [6]. This phenomenon requires a special integration of pipe rotation, velocity of the fluid in the annulus as well as a series of casing juxtaposition to grind the borehole, crumble and spread wellbore cuttings around, which travel up the annulus [7]. This scenario produces a less permeable filter cake at the wall of the formation.

An experimental study was carried out to investigate the combined effects of contact stresses, pore size and rotary dynamics on mud plastering during casing drilling operation [8]. The authors observed that a low radial clearance with the ratio of outer casing diameter to hole size greater than 0.70 and a lower tangential contact angles increased plastering effect benefits. In addition, the casing eccentricity in the wellbore supported the filtrate hammering and deposition. It has also been reported that [9] smaller particle size with wide range of the drilled cuttings improves the chances of sticking onto the wellbore wall when plastering effect occurs, which assists to close the pore spaces, and inhibit further fluid loss into the porous formation during drilling operation. Besides, it helps to avoid formation damage caused by the incompatibility between fluid-fluid and fluid-rock contacts [5]. It was concluded that particle size distribution and lost circulation materials sizes are significant factors in sealing fractures [10].

For plastering effect to occur, the pipe should have a smooth contact with the wellbore wall. If the pipe angular velocity is high, the mud cake will be damaged since the pipe’s momentum will be transferred forcefully at the contact area. With the same rotations per minute, the pipe’s linear velocity in casing drilling is lower and therefore less likely to damage the mud cake [11]. Furthermore, in low casing rotation rate, an increase in cuttings volume fraction will result in an increase on the mud cake thickness on the wellbore while on high rotation rates the result is opposite [6].

Experimental study [10] has shown that mud type is a factor in inhibiting fracture growth that could result in lost circulation. Water-based mud typically produces 2-3 mm of filter cake with toothpaste or putty-like characteristics under atmospheric pressure. Filter cakes from oil-based mud are normally much weaker and thinner, the study showed.

Finite element analysis was used to study casing drilling smearing effect and revealed that the increase in hoop stress is proportional to rotations per minute when contact force is applied along maximum horizontal stress orientation [12]. Similarly, a study was conducted using a 2D computational fluid dynamics (CFD) technique to numerically simulate filter cake formation on the vertical wellbore wall at high-pressure (25,500 psi or 175.8 MPa) and temperature (170°C) conditions, as well as moderate pressure (2,000 psi or 13.8 MPa) and temperature (30°C) conditions. Here, the
drilling fluids were treated as a two-phase system of solid particulates suspended in a non-Newtonian fluid. Results showed that the mud cake formed during extreme drilling processes is thicker than that formed for shallow drilling processes. Filter cake formed on the vertical wellbore wall is nonuniform for both extreme and shallow drilling process [13].

The above reviews indicate that the mechanisms leading to plastering effect in CwD operations are very complex due to the interactions among the parameters involved, thus, there is the need for further investigation using numerical simulation technique, which has the capability of handling complex multiphase flow problems as well as unlimited number of physical and operational conditions. This study aims to examine the effects of particle size (drilled cuttings size) and drilling fluid types on plastering effect in a vertical well geometry using CFD method.

2. Materials and methods

2.1. Continuity equations
The Navier-Stokes continuity equations for liquid and solid phases with isothermal and transient conditions are respectively [16, 17]:

$$\frac{\partial}{\partial t}(h_l) + \nabla (h_l U_l) = 0$$

$$\frac{\partial}{\partial t}(h_s) + \nabla (h_s U_s) = 0$$ (2)

2.2. Momentum equations
The forces acting on each phase and interphase momentum transfer term that models the interaction between each phase are given for liquid and solid phases respectively [14, 15]:

$$\rho_l h_l \frac{\partial U_l}{\partial t} + U_l \cdot \nabla U_l = -k_l \nabla p + k_l \nabla \cdot \tau_l + k_l \rho_l g - M$$ (3)

$$\rho_s h_s \frac{\partial U_s}{\partial t} + U_s \cdot \nabla U_s = -h_s \nabla p + h_s \nabla \cdot \tau_s + \nabla \cdot \tau_s - \nabla P_s + h_s \rho_s g + M$$ (4)

The liquid and solid phase shear stress tensors are represented by the following equations respectively:

$$\tau_l = \mu_l [\nabla U_s + (\nabla U_s)^T] - \frac{2}{3} (\nabla \cdot U_l) I$$ (5)

$$\tau_s = (-P_s + \zeta_s U_s) I + \mu_s \left[\nabla U_s + (\nabla U_s)^T\right] - \frac{2}{3} (\nabla \cdot U_s)$$ (6)

The bulk solid viscosity that includes the resistance of granular particles is defined as [16]:

$$\zeta_s = \frac{4}{3} h_s^2 \rho_s d_p g_o (1 + e) \sqrt{\frac{\theta}{\pi}}$$ (7)

Likewise, $P_s$ is the solid pressure which depicts the solid phase normal forces caused by interactions between the particles and given as [15]:
\[ P_s = \rho_s h_s \theta_s + 2 h_s^2 \rho_s \theta_s (1 + \varepsilon) g_o \]  

(8)

2.3. Drag force model

For spherical particles, the drag force per unit volume is given as:

\[ M_d = \frac{3 C_D}{4d_s} \rho_l |U_s - U_l| (U_s - U_l) \]  

(9)

For densely distributed solid particles, where the solid volume fraction \( k_s < 0.2 \), the Wen and Yu [17] drag coefficient, \( C_D \), model may be utilised. This model is modified and implemented in ANSYS-CFX to ensure the correct limiting behaviour in the inertial regime as:

\[ C_D = \frac{1.65}{k_l} \max \left[ \frac{24}{N_{Re_p}^4} \left( 1 + 0.15 N_{Re_p}^{0.687} \right), 0.44 \right] \]  

(10)

where \( N_{Re_p}^4 = k_l N_{Re_p}^4 \) and \( N_{Re_p} = \rho_l |U_l - U_s| d_s / \mu_l \)

For large solid volume fraction, \( k_s > 0.2 \), the Gidaspow drag model may be used with the interphase drag force per unit volume defined as [18]:

\[ M_D = \frac{150 (1 - k_l)^2 \mu_l}{k_l d_s^2} + \frac{7 (1 - k_l) \rho_l |U_l - U_s|}{d_s} \]  

(11)

2.4. Lift force model

For spherical solid particles, ANSYS-CFX employs the Saffman and Mei lift force model as:

\[ M_L = \frac{3}{2 \pi d_s \sqrt{\mid \nabla \times U_l}} C_L' k_s \rho_l (U_s - U_l) \times (\nabla \times U_l + 2 \Omega) \]  

(12)

Saffman [19, 20] correlated the lift force for low Reynolds number past a spherical solid particle where \( C_L' = 6.46 \), and \( 0 \leq N_{Re_p} \leq N_{Re_\omega} \leq 1 \). For higher range of solid particle Reynolds number, Saffman’s correlation was generalised by Mei and Klausner [21] as follows:

\[ C_L' = \begin{cases} 
6.46 \cdot f \left( N_{Re_p}, N_{Re_\omega} \right) & \text{for: } N_{Re_p} < 40 \\
6.46 \cdot 0.0524 \cdot \left( \beta N_{Re_p} \right)^{1/2} & \text{for: } 40 < N_{Re_p} < 100 
\end{cases} \]  

(13)

where \( \beta = 0.5 \left( N_{Re_\omega} / N_{Re_p} \right) \),

\[ f \left( N_{Re_p}, N_{Re_\omega} \right) = \left( 1 - 0.3314 \beta^{0.5} \right) e^{-0.1 N_{Re_p}} + 0.3314 \beta^{0.5} \]

and \( N_{Re_\omega} = \rho_l \omega_l d_s^2 / \mu_l, \quad \omega_l = |\nabla \times U_l| \)

2.5. Turbulence model

The \( k - \varepsilon \) turbulence model offers a good compromise in terms of accuracy and robustness for general purpose simulations. It is a semi-empirical model based on transport equation for the estimation of
turbulent length scale and velocity scale from the turbulent kinetic energy \( k \) and dissipation rate \( \varepsilon \) [22]. In multiphase flow, the transport equations for \( k \) and \( \varepsilon \) are phase dependent and assumes a similar form to the single-phase transport equations respectively as:

\[
\frac{\partial}{\partial t}(C_\alpha \rho_\alpha k_\alpha) + \nabla \cdot \left( C_\alpha \rho_\alpha U_\alpha k_\alpha - \left( \mu + \frac{\mu_{\tau\alpha}}{\sigma_k} \right) \nabla k_\alpha \right) = C_\alpha \left( P_\alpha - \rho_\alpha \varepsilon_\alpha \right) + T^{(k)}_{\alpha\beta} \tag{14}
\]

\[
\frac{\partial}{\partial t}(C_\alpha \rho_\alpha \varepsilon_\alpha) + \nabla \cdot \left( C_\alpha \rho_\alpha U_\alpha \varepsilon_\alpha - \left( \mu + \frac{\mu_{\tau\alpha}}{\sigma_\varepsilon} \right) \nabla \varepsilon_\alpha \right) = C_\alpha \frac{\varepsilon_\alpha}{k_\alpha} \left( C_{\varepsilon 1} P_\alpha - C_{\varepsilon 2} \rho_\alpha \varepsilon_\alpha \right) + T^{(\varepsilon)}_{\alpha\beta} \tag{15}
\]

where \( C_{\varepsilon 1} = 1.44, \ C_{\varepsilon 2} = 1.92, \ C_\mu = 0.09, \ \sigma_k = 1.0, \) and \( \sigma_\varepsilon = 1.3 \) are standard constants. \( T^{(\varepsilon)}_{\alpha\beta} \) and \( T^{(k)}_{\alpha\beta} \) are the interphase transfer for \( \varepsilon \) and \( k \) respectively.

Diffusion of momentum in phase \( \alpha \) is governed by an effective viscosity as:

\[
\mu_{\text{eff}} = \mu + \mu_{\tau\alpha} \tag{16}
\]

The \( k - \varepsilon \) model assumes that the turbulence viscosity is linked to the turbulence kinetic energy and dissipation by the relation:

\[
\mu_{\tau\alpha} = C_\mu \rho_\alpha \frac{k_\alpha^2}{\varepsilon_\alpha} \tag{17}
\]

The governing sets of partial differential equations were discretized using finite volume technique. The discretized equations together with initial and boundary conditions are solved iteratively for each control volume of cuttings volume fraction using ANSYS CFX R18.2 solver.

2.6. Physical model, initial and boundary conditions

The 3D geometry of the wellbore setup was modelled using ANSYS workbench design modeler for concentric vertical cylindrical pipes. The 3D model consists of a porous domain, wellbore wall, casing wall, rock debris, and three bit nozzles as shown in Figure 1. The model has the following dimensions: total height of 1000 mm, casing length of 810 mm, wellbore diameter of 400 mm, casing outer diameter of 320 mm, and bit nozzle diameter of 40 mm. The plan view of the model is shown in Figure 2 where the bit nozzles are arranged with 120° apart. The domain was discretized with tetrahedral grid where the flow domain was divided into finite surfaces. To ensure a fully developed flow, the hydrodynamic length was defined using the expression below:

\[
L_h = 4.4 \times N_{Re}^{1/6} \times D_h \tag{18}
\]

At the bit nozzle inlet, a static pressure of 13.8 MPa was imposed, whereas at the outlet, a pressure of 10.3 MPa was specified. A no-slip condition was specified on the casing and wellbore walls. The solid volume fraction for the rock debris is 0.80 with initial cuttings bed height of 20 mm, while the porous domain was imposed with permeability and porosity of 0.001 m² and 0.2 respectively. Similarly, the bottom-hole pressure was specified as 10.3 MPa.
2.7. Rheological parameters of fluid types

Three fluid types were used in this study, namely: water, water-based mud (WBM), and oil-based mud (OBM). For water, the parameters used are apparent viscosity of 0.001 Pa·s, and density of 1000 kg/m$^3$. The WBM was modelled using power law model with consistency index of 1.0362 Pa·s$^n$, and flow behaviour index of 0.4298. A density of 1190 kg/m$^3$ was also used. Likewise, the Herschel-Bulkley fluid model was used to characterize the OBM with the following properties: consistency index of 0.113 Pa·s$^n$, flow behaviour index of 0.784 and a yield stress of 3.192 Pa. A density of 1260 kg/m$^3$ was used for OBM.
kg/m³ was also used. Table 1 summarises the rheological models and their constants of the various fluid types.

Table 1. Rheological models and constants for various fluid types.

| Fluid type           | Rheological model          | Rheological constant         |
|----------------------|----------------------------|-------------------------------|
| Water                | $\tau_w = \mu_a \dot{\gamma}$ | $\mu_a = 0.001 \text{ Pa s}$ |
| Oil-based mud (OBM)  | $\tau_{HB} = \tau_o + K \dot{\gamma}^n$ | $\tau_o = 3.192 \text{ Pa}$  |
|                      |                            | $n = 0.784$                  |
|                      |                            | $K = 0.113 \text{Pa s}^n$    |
| Water-based mud (WBM)| $\tau_{PL} = K \dot{\gamma}^n$ | $n = 0.4298$                  |
|                      |                            | $K = 1.0362 \text{Pa s}^n$   |

2.8. Filter cake height

To measure the filter cake height, the cuttings volume fraction was recorded for different height of the wellbore at intervals of 0.2 m, 0.4 m, 0.5 m, 0.6 m, 0.8 m, and 0.9 m as shown in Figure 3. The mean value of the cuttings volume fraction was obtained. The equilibrium suspension height, $h_e$, was computed using the equation below [23]:

$$h_e = \left( \frac{h_o}{\alpha_e} \right) (\alpha_{so})$$  \hspace{1cm} (19)

where, $h_o =$ initial suspension height, $\alpha_e =$ equilibrium cuttings volume fraction, and $\alpha_{so} =$ initial cuttings volume fraction.

Figure 3. Locations of cuttings volume fraction at different wellbore height.
2.9. Parametric study
Table 2 presents the parameters that were varied in the simulation study. Other parameters that were set constant are fluid density, cuttings density, and ratio of casing diameter to wellbore diameter (diameter ratio).

Table 2. Simulation parameters.

| Particle size ($\mu$m) | 100, 1000, 2000 |
|------------------------|-----------------|
| Fluid type             | Water, WBM, OBM |

2.10. Numerical solution
The momentum and mass equations were discretized with the control volume method while time is discretized by first-order implicit technique and space discretized using second-order implicit technique. The transient analysis type was used for the simulation with an initial timestep of 0.001 second and total time of 20 seconds were used for all the simulation cases. Once the root mean square (RMS) of the simulation becomes $1 \times 10^{-4}$, the solution is assumed to be converged.

3. Results and discussion

3.1. Effect of particle size on filter cake height
The influence of different particle sizes (drilled cuttings size) of 100, 1000 and 2000 $\mu$m were evaluated on the filter cake height development for each constant fluid type. Figures 4, 5, and 6 show the cuttings volume fraction profile measured from the simulation study for particle sizes of 100, 1000 and 2000 $\mu$m when the fluid type is water. The profile in each figure shows three distinct regions which also represent the cuttings volume fraction at a specific distance in the wellbore. Region 1 (R1) describes the cuttings volume fraction within the porous domain, whereas region 2 (R2) represents the sharp rise in the cuttings volume fraction from the wellbore wall. Region 3 (R3) illustrates the annulus between the surface of the filter cake and casing where there is a gradual decline in the cuttings volume fraction. The average filter cake heights measured using equation 19 are recorded as 20.43 mm, 20.97 mm, and 20.94 mm for particle sizes of 100, 1000 and 2000 $\mu$m respectively.

Figure 4. Cuttings volume fraction for 100 $\mu$m for water.
Figure 5. Cuttings volume fraction for 1000 μm for water.

Figure 6. Cuttings volume fraction for 2000 μm for water.

Figure 7, 8 and 9 presents the measured average filter cake heights for all particles sizes for each fluid type of water, WBM, and OBM respectively. These results show that for water, a particle size of 1000 μm recorded the highest filter cake height, whereas, the lowest filter cake height occurred for 100 μm particle size. Nevertheless, at 2000 μm particle size, the highest filter cake height was recorded when both WBM and OBM were used. This indicate that when the fluid type is non-Newtonian, larger particle sizes promote high formation of filter cake. This is possible because larger particles bigger than the formation porosity tends to accumulate on the surface of the wellbore. However, small particle sizes with dimension less than the formation porosity could be flushed into the porous domain, thus reducing the formation of the filter cake height.
Figure 7. Filter cake height for varying particle sizes using water.

Figure 8. Filter cake height for varying particle sizes using WBM.

Figure 9. Filter cake height for varying particle sizes using OBM.
3.2. Effect of fluid type on filter cake height

Figure 10 depicts the average filter cake height as a function fluid type. Three fluids namely: water, WBM, and OBM were examined for a constant particle size of 1000 μm. Results indicated an increase in filter cake height when water was used, representing 2.7% and 2.9% compared to both WBM and OBM respectively. This is because, water with the least viscosity is lost in great amount into the porous media during circulation thereby depositing much drilled cuttings on the wellbore wall resulting high filter cake. Nonetheless, there is a marginal difference in the filter cake height between WBM and OBM.

![Figure 10. Filter cake height for varying fluid types using 1000 μm.](image)

4. Conclusion

This study examined that influence of particle size and fluid type on the filter cake height in vertical narrow annulus using computational fluid dynamics technique. The conclusion for the study can be summarized as follows:

1. The particles appear to initially fill the porous domain, after which the filter cake height begins to build up on the wellbore wall.
2. Larger particle sizes contributed to forming high filter cake height with non-Newtonian fluids (WBM and OBM) as opposed to Newtonian fluid (water).
3. For smaller particle sizes, the filter cake height was predominantly high with Newtonian fluid (water) as compared to non-Newtonian fluids (WBM and OBM). This phenomenon reverses for larger particle sizes.

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