NUMERICAL EVALUATION OF FRACTURE LENGTH INFLUENCE ON LOST CIRCULATION EMPLOYING PARTICULATE MATERIALS

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RESUMO – During the drilling process, the fluid loss is one of the major problems associated with operation and stability of the wellbore. The eventual presence of fractures combined with pressure gradients in the wellbore-formation set can intensify the fluid loss and, when no foreseen, the phenomenon must be controlled in order to reestablish the circulation in the wellbore. In this work, the association of particles in the drilling mud to reduce or eliminate the fluid loss is analyzed. The numerical simulation of the problem is divided into two approaches: the first one focus on the correct characterization of the invasion phenomena and the second one target the fracture filling process using particles with selected granulometry. The numerical formulation and the numerical modelling for the liquid-solid two phase flow are described using an Eulerian-Lagrangian approach. The phase coupling and particle-particle collisions are achieved through the combination of the Dense Discrete Phase Model (DDPM) and the Discrete Element Method (DEM). The filling process is characterized taking into account the time required to fill the fracture, the fluid loss monitoring over time and the pressure on the fractured channel inlet.

Palavras-Chave: particulate flow, fractured channel, lost circulation

INTRODUCTION

The drilling process to access an oil and gas reservoir is defined using an operation window. Such window is determined by, in the lower limit, the pore pressure of the formation – which is the pressure of fluids inside the rock. The upper limit of the operation is given by the fracture pressure of the formation that is the pressure in which the mechanical failure of the formation occurs (Selley and Sonnenberg, 2014).

Observing the pore pressure and the pressure configuration in the wellbore during the drilling process, two prejudicial phenomena may occur: the kick and the lost circulation.

The kick phenomenon occurs whenever the pressure in the wellbore is lower than the pore pressure, inducing the movement of fluids inside the formation towards the well. The kick is a rather undesirable condition in the drilling process, and may cause, in extreme circumstances, the blowout – which is the uncontrolled fluid flow of hydrocarbons towards the surface (Cook et al. 2012).

On the other hand, the lost circulation is considered a phenomenon inverse to the kick: during the lost circulation, the drilling mud circulating inside the wellbore invades the formation. This can occur whenever the pressure inside the borehole is higher than the pore pressure of the formation (Abbas et al. 2004).

The lost circulation may cause a decrease on the ability of the mud to remove cuttings, one of the main functions of the drilling mud, compromising the drilling operation (Bugbee, 1953).

It is estimated that the costs involved with the lost circulation phenomenon are of the order of US$ 2 to 4 billion annually in lost time, lost drilling mud and materials used to stem the losses (Cook et al. 2012).

The intensity of the phenomena described before depends, among other things, on the pressure configuration in the wellbore and on the permeability of the formation being drilled. Besides that, both phenomena may be intensified if fractures are present in the formation.

Usually, the presence of fractures in the drilling operation can occur by two forms: by drilling a naturally fractured formation or when the fracturing of the formation is induced during the drilling operation.

In the last configuration, the fracture pressure of the formation (the upper limit of the drilling operation) is surpassed by the pressure inside the wellbore.

When the lost circulation takes place, associated with the presence of a fracture, one of the techniques used to remedy the problem consists in adding materials of selected granulometry to the mud in order to promote the filling of the fracture. Such materials are often
referred to as lost circulation materials – LCM (Cook et al. 2012).

With the addition of the LCM it is expected that the mud will be capable of transporting such materials throughout the fractured channel, up to the fracture inlet. Once the material has reached the fracture, it will start to deposit inside the fracture and form a bed which will seal the point of fluid loss. A special form of LCM is solid particles.

This methodology have been recently studied by Oliveira et al. (2012) in which the authors use Computational Fluid Dynamics to analyze the problem. The particle to particle collisions are calculated using the DEM method. The authors observed a continuous rolling of particles inside the fracture, which can indicate a high pressure condition in the fracture or a poor choice for the friction coefficient.

In order to correct describe the pressure gradient due to the fluid loss associated with a fracture in a numerical domain, De Lai (2013) proposed the division of the fluid loss and the subsequent fracture filling process into three steps: simulation of the fluid loss with prescribed mass flux, simulation of the fluid loss with prescribed pressure conditions and the injection of particles with prescribed pressure conditions. In this work, the fracture in question was relatively short causing the particle bed to form itself right in the fracture outlet.

Barbosa (2015) performed an parametric analysis of the filling process of fractures. The main control variables were the fracture length, the flow’s Reynolds number the particle to fluid density ratio and diameter, the amount of particle injected and the fluid’s viscosity.

Although the lost circulation phenomenon has been widely studied, the lost circulation associated with the presence of fractures lacks further understanding. In the light of that, in this work the influence of the fracture length (hFR) over the particle bed and the fluid loss is studied.

The response variables associated with the particle injection process are the fluid loss monitored over time Qloss and the pressure on the fractured channel inlet, pCH.

The particle bed formed inside the fracture is characterized through its initial position hini, length hFR, and by its ability to vertically fill the fracture eFR. Besides that, the time dispended to perform the filling of the fracture (tfill) is also measured.

PROBLEM CHARACTERIZATION

As said before, the drilling operation is quite complex and represent the borehole-formation set is a rather difficult task. Therefore, for the analysis of the proposed problem, some considerations have to be made.

Figure 1 – Representation fo (a) wellbore-fracture set (Matex, 2011); (b) geometric domain and (c) numerical domain
The first one regards the geometry of the wellbore. In Figure 1(a) it is presented and schematics for the borehole-formation set with the presence of a fracture. The geometry considered in this work eliminates irregularities of the set and is represented as shown in Figure 1(b). Also, in Figure 1(b), it is possible to notice the symmetry plane inside the drilling rig can be used to reduce computational costs.

In this work, only the particle transport inside the annulus is of interest to the proposed problem. Therefore, the geometry can be reduced by the area indicated in the dashed line on Figure 1(b).

The 3D numerical domain is shown in Figure 1(c), in which the fracture is defined by its length \( l_{FR} \) and thickness \( e_{FR} \). The fracture channel upstream and downstream length is given by \( l_{UP} \) and \( l_{DW} \), respectively. The annulus is characterized by its thickness \( h_{CH} \) and the whole system have an z-component \( z_{FR} \).

Besides the geometric simplifications, there is an intrinsic necessity of correctly characterizing the invasion problem. In order to do so, the methodology proposed by De Lai (2013) is applied.

The methodology consists in dividing the problem into three parts: the subproblem (I) defines the amount of fluid being lost due to the presence of the fracture as boundary condition. Once a fully developed flow is attained, the results for the suproblem (I) are the pressure on the fracture outlet and on the channel outlet.

The subproblem (II) consists in using the pressures obtained in subproblem (I) as new boundary conditions. Once a fully developed flow is obtained, the subproblem (III) begins, in which the particle injection process takes place using the same boundary conditions of subproblem (II).

For all three subproblems, the boundary condition for the surface (1) is constant velocity \( U_{BC,CH} \), defined using the flow’s Reynolds number \( Re_f \), as showed in Eq. (1).

\[
U_{BC,CH} = \frac{Re_f \mu_f}{\rho_f h_{CH}}
\]  

in which \( \rho_f \) and \( \mu_f \) is the fluid’s density and dynamic viscosity, respectively.

**NUMERICAL MODEL**

The numerical model used in this work to perform the coupling of the phases is the Dense Discrete Phase Model (DDPM), developed by Popoff and Braun (2007). The description of the continuous phase (fluid) is performed using an Eulerian approach and the discrete phase (particles) is described by a Lagrangian one.

The mathematical formulation for the method is divided into two sets of equations: one for the fluid and one for the particles. In this study, the fluid is considered Newtonian and incompressible. The equations for the continuous phase are the mass, Eq. (2), and momentum conservation, Eq. (3).

\[
\frac{\partial (\varepsilon_p \rho_p u_p)}{\partial t} + \nabla \cdot (\varepsilon_p \rho_p u_p u_p) = -\varepsilon_p \nabla p_p + \nabla \cdot (\varepsilon_p \mu_p \nabla u_p) + \varepsilon_p \rho_p g + F_{DPM} + S_{DPM}
\]

in which \( t \) is the time, \( \varepsilon_p \) is the volume fraction of the continuous phase, \( u_p \) is the velocity vector, \( p_p \) is the pressure gradient and \( g \) is the gravity acceleration. \( F_{DPM} \) represents the coupling force between the phases and \( S_{DPM} \) is the source term due to de displacement of fluid caused by the particle entering in a control volume.

As for the discrete phase, the position of each particle is given by the particle velocity, Eq.(4). Newton’s second law of motion, Eq. (5), is applied to calculate the particle velocity.

\[
\frac{dx_p}{dt} = u_p
\]

\[
m_p \frac{du_p}{dt} = F_d + F_{gb} + F_{ps} + F_{vm} + F_e + F_{DEM}
\]

In Eq. (4) e (5) the particle position and velocity is given by \( x_p, u_p \), respectively. The particle mass is given by \( m_p \), \( F_d \) is the drag force, \( F_{gb} \) is the balance between the gravitational and buoyance forces, \( F_{ps} \) is the pressure gradient force, \( F_{vm} \) is the virtual (added) mass, \( F_e \) is the Saffman’s lift force and \( F_{DEM} = F_e + F_l \) is the particle collision force.

Table 1 shows a summary of the above mentioned forces in which \( \rho_p \) is the particle density, \( C_p \) is the drag coefficient, calculated using Morsi and Alexander (1972) model, \( Re_p \) is the particle Reynolds number, given by \( Re_p = \rho_p |u_p - u_r| d_p / \mu_f \), \( C_s \) is the Saffman constant (Li e Ahmadi 1992) e \( C_{vm} \) is the virtual mass coefficient (Kendoush et al. 2007).
Table 1 - Expressions for the forces acting upon the particles

<table>
<thead>
<tr>
<th>Force</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational and buoyance</td>
<td>$F_{gb} = m_p \frac{\rho_b - \rho_p}{\rho_p} g$</td>
</tr>
<tr>
<td>Drag</td>
<td>$F_d = \frac{3}{4} m_p \rho_b \mu_p C_d \mathrm{Re} \left( \frac{u_0 - u_p}{\rho_p} \right)$</td>
</tr>
<tr>
<td>Saffman lift</td>
<td>$F_{\lambda} = C_b m_p \frac{\rho_p}{\rho_p} \left( \nabla \times u_p \right) \times \left( u_0 - u_p \right)$</td>
</tr>
<tr>
<td>Virtual mass</td>
<td>$F_{vm} = C_{vm} m_p \frac{\rho_p}{\rho_p} D \left( u_0 - u_p \right)$</td>
</tr>
<tr>
<td>Pressure gradient</td>
<td>$F_{pr} = m_p \frac{\rho_p}{\rho_p} \left( u_0 \nabla \cdot u_p \right)$</td>
</tr>
<tr>
<td>Collision</td>
<td>Normal $F_n = k \delta + \gamma \left( u_0 \cdot \lambda_{12} \right) \lambda_{12}$</td>
</tr>
<tr>
<td>Collision</td>
<td>Tangential $F_t = -\mu_e \left</td>
</tr>
</tbody>
</table>

The collision force $F_{DEM}$ is a combination of the normal ($F_n$) and tangential ($F_t$) forces generate by the particle collisions. The normal force is calculated using a spring-dashpot model (Lundin, 1998), in which $k$, $\delta$, $\gamma$, $u_0$ e $\lambda_{12}$ are the spring constant, the particle overlap, the damping coefficient, the relative velocity between the particles and the normal direction of collision. The damping coefficient is calculated through Eq. (6), based on a restitution coefficient $\eta$. In Eq. (6), $m_{12}$ represents the reduced mass and $t_{col}$ is the collision time.

$$\gamma = -\frac{m_{12}}{t_{col}} \ln \eta$$

The tangential force is calculated using the Coulomb friction model, based on the friction coefficient $\mu_e$ and on the tangential direction of collision $\zeta_{12}$.

**VERIFICATION PROBLEMS**

The analysis of the capability of the numerical model chosen is necessary to ascertain its ability to correct describe the particulate flow.

The first set of problems consists in the terminal velocity of a particle. The parameters used in each simulation are the same as those of Mordant and Pinton (2000) work and are shown in Table 2.

In Figure 2 is presented the results for the terminal velocity of case 1, glass particle, and the respective comparisons with the numerical and experimental results of Mordant and Pinton (2000).

**Figure 2 - Terminal velocity for case 1**

It is possible to notice that there is a good agreement for both numerical models up until the acceleration phase. After this region, there is a little difference between the numerical and experimental data.

In Figure 3 it is presented the terminal velocity for case 2, in which a steel particle is considered. In this case, there is an excellent agreement between the numerical and experimental data from Mordant and Pinton (2000).

The next verification problem consists on the collision between a single particle and a static wall. This problem is used to ascertain the capabilities of the Discrete Element Method, used to calculate the particle-particle and particle-wall collisions.
The collision analysis uses the experimental data of Gondret et al. (2001). The particle has a density \( \rho_p = 7800 \text{ kg/m}^3 \), diameter \( D_p = 3.0 \text{ mm} \), and the fluid density and viscosity are \( \rho_f = 1187.6 \text{ kg/m}^3 \) and \( \mu_f = 0.01 \text{ [Pa.s]} \), respectively.

Table 2 - Parameters employed to the terminal velocity analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Representation [Unity]</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density</td>
<td>( \rho_p ) [kg/m³]</td>
<td>2560</td>
<td>7710</td>
</tr>
<tr>
<td>Particle diameter</td>
<td>( D_p ) [mm]</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Terminal velocity - experimental</td>
<td>( u_t ) [m/s]</td>
<td>0.0741</td>
<td>0.315</td>
</tr>
<tr>
<td>Fluid density</td>
<td>( \rho_f ) [kg/m³]</td>
<td>998.2</td>
<td></td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>( \mu_f ) [Pa.s]</td>
<td>1.003 \times 10^{-3}</td>
<td></td>
</tr>
</tbody>
</table>

To characterize the collision moment, the restitution coefficients are set as \( \eta = 0.78; 0.66; 0.45; 0.25 \). The results can be seen in Figure 4.

There is no significant change in the first collision time, with the subsequent ones presenting a time shift caused by the rebound velocity obtained after the first collision. Besides that, the results are in good agreement with the available literature.

RESULTS

The lost circulation phenomenon was analyzed using the amount of fluid being lost due to the presence of the fracture. In order to do so, three configurations were studied using the flow and pressure field: \( Q_{inr} = 5, 10 \) and 15%.

The fractured channel has the following dimensions: \( l_{hF} = 1800 \text{ m} \), \( l_{pW} = 0.225 \text{ m} \), \( h_{CF} = 0.045 \text{ m} \). The fractured studied has a length \( h_{FR} = 720 \text{ m} \) and thickness of \( e_{FR} = 0.010 \text{ m} \). The fluid studied has a density of \( \rho_f = 1187.6 \text{ kg/m}^3 \) and viscosity of \( \mu_f = 27.973 \times 10^{-3} \text{ Pa.s} \).

Observing the velocity field in Figure 5, it is possible to notice that there is a significant increase on the fluid flow velocity on the fracture inlet region as the fluid loss due to the presence of the fracture increases. This behavior is justified by the redirection of fluid from the annulus to the fracture.

As consequence of this redirection, the pressure field also changes, as shown in the right side of Figure 5. Both, the velocity field and pressure field in the fracture inlet can contribute to the fracture filling process, making it easier or difficult to plug the fracture.

In order to analyze the rate of penetration of the fracture and its influence over the fluid loss, the pressure on the fracture inlet and the geometric characteristics of the particle bed formed inside the fracture, four fracture lengths were established: 180, 360, 540 and 720 mm, which corresponds to 4, 8, 12 and 16 times the channel thickness.
The numeric parameters applied in the evaluation of the fracture length analysis are showed in Table 3.

The results obtained for the particle bed formed inside the fracture, for each configuration, are shown in Figure 7. As it can be seen, the fracture length has a direct influence on the geometry of the particle bed. In that sense, for fractures relatively short ($h_{fr} = 180$ mm) it is possible to see that the bed formed has no regularity, presenting an elongation in its end. As the fracture length increases, a similarity between the beginning and the end of the particle bed, presenting a trapezoid-like shape.

Also, in Figure 7, it is possible to infer that, for a certain fracture length, the length itself will not show any influence over the geometric characteristics of the particle bed.

To understand this behavior, the geometric characteristics for each fracture length is shown in Table 4. One can notice that there is no significant variation on the initial position of the bed, $h_{ini}$. This can be explained by the particle injection process: the particles used in each simulation and the rate of injection is the same.
Table 3 - Numeric Parameters applied to the fracture length analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Representation [Unity]</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control volumes</td>
<td>VC</td>
<td>19600</td>
</tr>
<tr>
<td>Fluid time step</td>
<td>( \Delta t_{\beta} ) [s]</td>
<td>( 2 \cdot 10^{-2} )</td>
</tr>
<tr>
<td>Particle time step</td>
<td>( \Delta t_p ) [s]</td>
<td>( 2 \cdot 10^{-4} )</td>
</tr>
<tr>
<td>Restitution coefficient</td>
<td>( \eta ) [-]</td>
<td>0.9</td>
</tr>
<tr>
<td>Particle spring constant</td>
<td>( k ) [N/m]</td>
<td>2.0</td>
</tr>
<tr>
<td>Particle diameter</td>
<td>( D_p ) [mm]</td>
<td>0.5</td>
</tr>
<tr>
<td>Density ratio</td>
<td>( \rho_{p/\beta} ) [-]</td>
<td>2.25</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>( Re ) [-]</td>
<td>250</td>
</tr>
</tbody>
</table>

As for the particle bed length, it is possible to notice the stabilization tendency mentioned before occurs for \( h_{FR} = 720 \) mm. This stabilization can be observed in both the bed length and vertical filling of the fracture \( e_{h,FR} \). Also, the time necessary to promote the fracture filling also shows the same indication of stabilization.

Table 4 - Geometric characteristics of the particle bed for each fracture length

<table>
<thead>
<tr>
<th>( h_{FR} ) [mm]</th>
<th>( h_{opt,i} ) [mm]</th>
<th>( h_{opt} ) [mm]</th>
<th>( e_{h,FR} ) [mm]</th>
<th>( t_{iop} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>24</td>
<td>142</td>
<td>59</td>
<td>45</td>
</tr>
<tr>
<td>360</td>
<td>25</td>
<td>143</td>
<td>61</td>
<td>45</td>
</tr>
<tr>
<td>540</td>
<td>23</td>
<td>112</td>
<td>62</td>
<td>55</td>
</tr>
<tr>
<td>720</td>
<td>24</td>
<td>109</td>
<td>62</td>
<td>57</td>
</tr>
</tbody>
</table>

The monitoring of the fluid loss due to the presence of the fracture \( Q_{loss} \) is defined as the ratio between the fluid loss during the particle injection process, \( q_{loss} \), and the initial fluid loss during associated with the appearance of the lost circulation problem, \( q_{\beta,FR,o} \), as shown in Eq. (7).

\[
Q_{loss} = \frac{q_{loss}}{q_{\beta,FR,o}} \quad (7)
\]

Figure 6 shows the results for the fluid loss monitoring for each fracture length.

Figure 6 - Results for \( Q_{loss} \) for each fracture length analyzed

Figure 7 - Results for the particle bed for each fracture length
As can be seen, there is an initial increase in the fluid loss, an overshoot, caused by the particles added to the fluid that surpasses the fracture region, staying in the annulus, and do not contribute to the fracture filling process. This enhances the fluid loss due to the associate pressure increase in the annulus. Also, the stabilization time $t_{st}$ for long fractures is higher than for short ones, as already discussed.

The fluid loss reduction obtained in the end of the filling process does not present a significant variation, with a difference of 4% between the fractures of $h_{FR} = 180$ and 720 mm.

The pressure on the fractured channel inlet $P_{inlet}$ is defined as the ration between the pressure during the particle injection process, $p_{inj,CH}$, and the pressure gradient generated due to the presence of the fracture $\Delta p_{loss}$ (taken as the difference between the pressure on the fracture outlet and on the fractured channel outlet), as shown in Eq. (8)

$$P_{inlet} = \frac{p_{inj,CH}}{\Delta p_{loss}} \quad (8)$$

The goal of this definition is to take into account the changes on the geometry of the fracture.

Through the monitoring of $P_{inlet}$, showed in Figure 8, one can notice that fractures with short length present a higher sensibility to the particle injection process. This happens because shorter fractures generates a lower $\Delta p_{loss}$ than longer fractures.

The same sensibility analysis can be applied to the overshoot observed in the fluid loss monitoring: the pressure generated by the particles that surpasses the fracture and do not contribute to the filling process is more pronounced in short fractures due to the sensibility observed in Figure 8.

**FINAL REMARKS**

In this work the lost circulation phenomenon associated with the presence of a fracture and its respective remediation using lost circulation materials (particles) was analyzed.

First, the lost circulation phenomenon was studied from the point of view of the amount of fluid being lost due to the presence of a fracture. In this process, it was possible to observe that when the fluid loss is higher, there is an associated increase on the fluid velocity and on the pressure in the fracture inlet region. This increase can collaborate to the fracture filling process.

With the analysis, it was possible to observe that there is an initial increase on the fluid loss, called overshoot that is directly related to the fracture length: shorter fractures presents a more pronounced overshoot when compared to longer fractures.

The capacity to reduce the initial fluid loss also changes with the changes on the fracture length, especially on the time required to perform the fracture filling.

Also, there is an apparent limit on which the particle bed formed inside the fracture does not present significant variations on its geometric characteristics.

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**REFERENCES**


Barbosa, M. V, 2015. Parametric Analysis of the Particulate Flow Applied to Filling Fractures,
Federal University of Technology, Curitiba, PR, Brazil.


