INTRODUCTION

Lost circulation has always been a serious and expensive problem when drilling through fractured formations (George & Scott 1951). A common cure of this problem is the introduction of granular lost circulation materials (LCM) into the drilling fluid system. Granular LCM are then carried and forced into fractures by drilling fluid under differential pressure. Proper LCM may establish an efficient bridge plug inside fracture formations (Dick et al. 2000; Kaageson-Loe et al. 2009; Whitfill & Hemphill 2003). A right and clear understanding of the fracture-plugging performance of granular LCM is essential to design the LCM and the treatment for circulation losses into fractured formations with a higher success rate.

In the past, various researchers have carried out a series of theoretical analyses and experiments to investigate the fracture-plugging performance of granular LCM and many valuable viewpoints have been obtained from these existing researches (Dick et al. 2000; Fathi et al. 2004; Gatlin & Nemir 1961; Moazzeni et al. 2012; Nayberg 1987; Pilehvari & Venkata 2002; Whitfill & Hemphill 2003). However, due to the absence of analytical solution and the difficulties of monitoring the full complicated movement and interaction process, the cognizance of the fracture-plugging performance of granular LCM remains limited. In order to make clear plugging behaviour of granular LCM in fractured formations, numerical simulation method ought to be considered. However, because of the difficulties encountered to this kind of simulation, there hardly exists a numerical attempt for this intricate problem yet.

Amongst all numerical approaches, distinct element method (DEM) may handle such a complicated process as it has the capability of modelling the movement and interaction of discrete particles (Fortin et al. 2005). In order to facilitate the simulation of the complex plugging process of granular LCM in a vertical fracture, the three-dimensional particle flow code (PFC3D), a numerical simulator developed by Cundall and Strack (1979), was adopted directly in the present work. The effects of particle shape, size distribution and concentration on the fracture-plugging performance were analyzed according to the simulation results.
MODEL DESCRIPTION

PFC3D PROGRAM

PFC3D is a program used to perform research into the element behaviour of granular material. It models the movement and interaction of spherical particles by the distinct element method. It is also possible to create particles of arbitrary shape by attaching two or more particles together, such that each group of particles acts as an autonomous object (Cundall & Stack 1979; Itasca 2003).

The calculations performed in PFC3D alternate between the application of Newton’s second law to the particles and a force-displacement law at the contacts (Itasca 2003). Contacts, which may exist between two balls or between a ball and a wall, are formed and broken automatically during the course of simulation. The calculation cycle is shown in Figure 1.

For particle i, as shown in Figure 2, the translational and rotational motion can, respectively, be described by:

\[
F_i = m_i \frac{d\mathbf{v}_i}{dt} = \sum \left( F_i^p + F_i^c \right) + F_{\text{drag},i} + F_{\text{buoy},i} + m_i \mathbf{g},
\]

and

\[
T_i = I_i \frac{d\mathbf{\omega}_i}{dt} = \sum \left( \mathbf{R}_i \times F_i^c - \mu \mathbf{R}_i \right) \left( F_i^p \right) \left( \mathbf{\hat{n}}_i \right),
\]

where \( F_i \) and \( T_i \) are the total forces and torques acting on the particle, \( m_i, v_i, \omega_i, \) and \( I_i \) are, respectively, the mass, translational velocity, angular velocity and moment of inertial of particle \( i \); \( \mathbf{g} \) is the gravitational acceleration; \( \mathbf{R}_i \) is the vector pointing from the center of particle \( i \) to the contact point with particle \( j \); \( \mu \) is the rolling friction coefficient and \( \mathbf{\hat{n}}_i = \mathbf{v}_i / \| \mathbf{v}_i \| \) and \( F_i^p \) and \( F_i^c \) are the normal and tangential contact forces, respectively, which can be given as:

\[
F_i^p = \frac{2}{3} E R_i \left( \mathbf{R}_i \times \mathbf{R}_j \right) \left( \mathbf{R}_i + \mathbf{R}_j \right),
\]

\[
F_i^c = \mu F_i^p \left( 1 - \sin(\xi_{\text{max}}) \right) / \xi_{\text{max}}^{\frac{1}{2}},
\]

where \( E \) is Young’s modulus and \( \xi_{\text{max}} \) and \( \xi_{\text{max}}^2 \) are, respectively, the maximum and total tangential displacements of particles during contact.

In order to extend the DEM model to the particle-fluid system, the interactions between fluid and particles should be incorporated. Although there are a range of forces in such system, not all are important in a particular application. In the present work, three forces are considered, i.e. the buoyancy force, pressure gradient force and drag forces, respectively, given by:

\[
F_{\text{buoy},i} = \frac{4 \pi}{3} \rho \mathbf{g},
\]

\[
F_{\nabla p,i} = 3 \rho \mathbf{g} \nabla p,
\]

\[
F_{\text{drag},i} = \frac{C_d}{Re} \mu \left| \mathbf{v}_i - \mathbf{v}_j \right| \left( \mathbf{v}_i - \mathbf{v}_j \right),
\]

where

\[
f_{\text{buoy}} = 0.5 C_d \rho \pi R_i^2 v_i^2 \left| v_i - v_j \right| \left( v_i - v_j \right),
\]

\[
Re = \frac{2 \rho \mathbf{R} \left| v_i - v_j \right|}{\mu_i} \text{ and } \chi = 3.7 - 0.6 \exp \left( \frac{1.5 - \log_{10} Re - 0.5}{2} \right).
\]
\( p, \nu, \rho, \) and \( \mu \) are, respectively, the fluid pressure, velocity, density and viscosity.

**Simulation Parameters**

In this work, vertical fracture is considered to represent the majority of fractures encountered (George & Scott 1951; Kaageson-Loe et al. 2009). The simulated fracture consists of two vertical jagged walls with height \( H_f \), length \( L_f \), inlet width \( W_i \) and outlet width \( W_o \). The detail geometrical conditions are listed in Table 1.

The particulate-treated drilling fluid flow is assumed to be one-dimensional along the fracture length direction with the base fluid viscosity \( \mu_f \) and density \( \rho_f \) at the differential pressure \( \Delta p \). The fixed coarse-grid fluid scheme has been used to implement the particle-fluid coupling in simulation (Apostolou & Hrymak 2008).

Table 1 gives the material properties used in the simulation, which are based on the properties of calcium carbonate particles. This work considers the irregularity of LCM particle, because many granular LCM, such as nut shells and calcium carbonate particles, are always rigid particles with shapes of angular rather than circular or spherical (Pilehvari & Venkata 2002). In this study, the granular particles larger than 0.45 mm are represented by irregular particles of equal volumes, while the other granules were represented by spherical particles. The bridge particles with irregular shape are modeled using the so-called overlapping discrete element cluster (ODEC) algorithm, as shown in Figures 3 and 4. In ODEC method, the representative assemblies of angular particles are generated by inscribing a number of overlapping spherical balls within the particle outline (Fortin et al. 2005; Garcia et al. 2009; Lu & McDowell 2006).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture height, ( H_f )</td>
<td>10 mm</td>
<td>Particle density, ( \rho_p )</td>
<td>2.7 g·cm(^{-3})</td>
</tr>
<tr>
<td>Fracture length, ( L_f )</td>
<td>150 mm</td>
<td>Particle size, ( d )</td>
<td>0.25-2.0 mm</td>
</tr>
<tr>
<td>Fracture inlet width, ( W_i )</td>
<td>2.0 mm</td>
<td>Young’s modulus of particles, ( Y )</td>
<td>45×10(^9) Pa</td>
</tr>
<tr>
<td>Fracture outlet width, ( W_o )</td>
<td>1.0 mm</td>
<td>Poisson’s ratio of particles, ( \sigma )</td>
<td>0.25</td>
</tr>
<tr>
<td>Fluid density, ( \rho_f )</td>
<td>1.05 g·cm(^{-3})</td>
<td>Damping coefficient, ( \gamma )</td>
<td>5×10(^{-3})</td>
</tr>
<tr>
<td>Fluid viscosity, ( \mu_f )</td>
<td>100 mPa·s</td>
<td>Sliding friction coefficient, ( \mu_s )</td>
<td>0.3</td>
</tr>
<tr>
<td>Differential pressure, ( \Delta p )</td>
<td>6×10(^6) Pa</td>
<td>Rolling friction coefficient, ( \mu_r )</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**FIGURE 3.** Schematic diagram of ODEC procedure

**FIGURE 4.** Definition of clump geometry
RESULTS AND DISCUSSION

PARTICLE SHAPE EFFECT
As the manner of passing through a sieve mesh is quite different between irregular particles and spherical particles, the size of irregular granular LCM in certain direction often grows up than the sieve mesh side (Pilehvari & Venkata 2002; Whitfill & Hemphill 2003).

In order to investigate the effect of particle shape on the fracture-plugging performance of granular LCM, this work simulated the fracture-plugging performances of nonspherical particles with equal volume to the spherical particles, which have the same equivalent diameter of 2 mm. The simulated outcomes of spherical and nonspherical particles of the equal volume are shown in Figure 5.

As can be seen from Figure 5, when the equivalent particle diameter equals to the fracture opening width, the spherical particles can plug inside fracture near the mouth, whereas the nonspherical particle of an equal volume can only block outside. The latter case is an unexpected plugging type in drilling industry, because the LCM will become dislodged easily as a result of drilling stem rotating or colliding as well as drilling fluid flushing. Hence the irregularity of particle should be taken into account to avoid plugging outside fracture. Moreover, it was observed at a particle scale during the simulation process that the granular LCM particle blocked fracture in the type of single-particle rather than multiple-particle bridging, which leads us to further believe that the granular LCM particles plug the fracture width larger than its sieving grain size due to the irregularity of shape.

PARTICLE SIZE DISTRIBUTION EFFECT
Particle size distribution (PSD) is always thought to be the most important factor impacting the plugging performance of granular LCM in fractured formations (Dick et al. 2000; Gatlin & Nemir 1961; Loeppke et al. 1990; Moazzeni et al. 2012; Pilehvari & Venkata 2002). For ease of presentation and study, the list of grain size grade for granular LCM is shown in Table 2.

In this study, the granular particles larger than 0.45 mm (40 mesh) were represented by irregular particles of equal volumes, while the other granules were represented by spherical particles. The simulation results for the four selected typical PSD of LCM are shown in Table 3 and Figure 6.

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TABLE 2. Grain size grade for granular LCM

<table>
<thead>
<tr>
<th>Grade</th>
<th>A</th>
<th>B</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm)</td>
<td>0.25-0.45</td>
<td>0.45-0.9</td>
<td>0.9-1.2</td>
<td>1.2-1.4</td>
<td>1.4-1.7</td>
<td>1.7-2.0</td>
</tr>
</tbody>
</table>

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TABLE 3. Simulation results for different PSD of the same concentration

<table>
<thead>
<tr>
<th>Case</th>
<th>Formulation of LCM</th>
<th>$d_{50}$ (mm)</th>
<th>$d_{25}$ (mm)</th>
<th>$d_{90}$ (mm)</th>
<th>Plugging depth (mm)</th>
<th>Time spent ($10^{-3}$ s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6% A+1% B</td>
<td>0.15</td>
<td>0.45</td>
<td>0.8</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>2</td>
<td>1.5% A+4% B+1.5% C1</td>
<td>0.25</td>
<td>0.7</td>
<td>1.05</td>
<td>130-150</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>1.5% A+1.5% B+3% C1+1% C2</td>
<td>0.25</td>
<td>1.0</td>
<td>1.25</td>
<td>80-100</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>1% A+1% B+1% C1+1% C2+2% C3+1% C4</td>
<td>0.25</td>
<td>1.3</td>
<td>1.75</td>
<td>0</td>
<td>13</td>
</tr>
</tbody>
</table>

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FIGURE 5. Snapshots showing the fracture-plugging performances of (a) spherical and (b) nonspherical particles of the equal volume.
From the simulation results, it can be clearly seen that both the plugging depth and time spent before plugging are related closely to the particle size distribution of LCM. The larger the value of \(d_{50}\) and \(d_{90}\), the shallower the plugging depth and the shorter time before plugging. However, too large \(d_{50}\) and \(d_{90}\) values of LCM are harmful to plugging inside fractures, because too coarse particles in LCM cannot enter fracture effectively and in consequence plug outside the fracture as case 4 shown in Figure 6(d). Although the calculation time is about half an hour, the actual physical time spent before plugging needs only several milliseconds. The milliseconds time, decreased with the \(d_{50}\) and \(d_{90}\) values of LCM, indicated that the fracture plugging process was instantaneous. Therefore, appropriate particle size distribution, especially the values of \(d_{50}\) and \(d_{90}\), is critical to plugging inside the fractures effectively and efficiently.

**PARTICLE CONCENTRATION EFFECT**

Besides particle shape and size distribution, the particle concentration also has significant impact on the plugging performance of granular LCM in a fracture (Moazzeni et al. 2012; Nayberg 1987). In order to investigate the effect of particle concentration, this study simulated the fracture-plugging performance at different concentration of 3.5, 7, 14 and 21% by weight, respectively. The simulation results showed that the effect of particle concentration on the plugging depth is negligible, whereas the effect of particle concentration on the time need to plug is significant. The particle concentration effect on time spent before plugging is shown in Figure 7.

From Figure 7, a nonlinear relation is obviously seen to prevail between the particle concentration and the time spent before plugging. The time spent before plugging decreases sharply until a certain concentration value, which may be called the *optimum concentration*. Many other researchers have also reported that there exists an optimum particle concentration for maximum effect of the LCM additive through their experiments (Dick et al. 2000; Moazzeni et al. 2012), which leads us to believe the accuracy of simulation result is high enough. It is concluded that the plugging efficiency can be improved

![Figure 6](image1.png)

**FIGURE 6.** Snapshots showing the plugging outcomes of different PSD: (a) not plug (case 1), (b) plug at tip (case 2), (c) plug at middle part (case 3) and (d) plug outside (case 4)

![Figure 7](image2.png)

**FIGURE 7.** The time spent before plugging for different particle concentrations
significantly by increasing the concentration up to the optimum value and any increase of LCM concentration over the optimum concentration will not improve its plugging performance significantly.

CONCLUSION

Due to the irregularity of particle, granular LCM are able to plug a fracture width larger than the sieving granulation by the type of single-particle bridging. The $d_{50}$ and $d_{90}$ values of the LCM’s particle size distribution dominate the plugging depth and efficiency in fractured formations. There exists an optimum concentration for maximum effect of granular LCM.

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