Effect of Mud Rheology on Cuttings’ Transport in Drilling Operations

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Abstract: Settling of solid particles in drilling fluids represents a major problem, necessitating effective removal of drilled cuttings to the surface of the well to maintain safe and profitable drilling operations. Experiments were conducted using two group of drilling fluids, Newtonian (water, gas-oil, kerosene, and ethyl-glycol) and Non-Newtonian (Carboxyl Methyl cellulose (CMC)) in four different concentrations. Four cutting sizes were used, with diameters 0.212, 0.445, 0.672, and 0.853 cm, taken from the Garraf area of the Nasirya oil fields. The test results showed lower Reynolds numbers within the laminar flow region compared with the Turbulent flow region. The drag coefficients decreased with increasing particle Reynolds number, and small particle sizes gave higher drag coefficients and lower Reynolds numbers, while large particles gave lower drag coefficients and higher Reynolds numbers in both Newtonian and Non-Newtonian fluids. The results indicate that an increase in CMC concentration will decrease NRep and increase the drag coefficient for different particle sizes. For non-Newtonian fluids, the settling velocity decreases with increases in CMC concentration due to increases in the viscous forces that oppose settling of particles, while in Newtonian fluids, the settling velocity increases with increasing particle size due to gravity forces increasing. The low CMC concentrations (low n, and high k) offer higher settling velocities, while larger particle sizes give lower drag coefficients than smaller ones.

Key Words: Drag coefficient, Reynolds number, Newtonian fluid, Settling velocity.

1-Introduction:

The most important function of drilling fluid is to remove the cuttings formed beneath the drill bit to the surface. Insufficient cuttings transport will impede drilling operations, and increased flow rate or mud effective viscosity may cause a decrease in the cleaning action under the bit, causing reductions in penetration rate.

Problems encountered due to insufficient cuttings removal and hole cleaning include stuck pipes, lost circulation, high torque and drag, poor cement jobs, reduced rate of penetration, excessive bit wear, and bottom hole pressure control failure.

For vertical wells, [1] first studied the problem of cuttings transport, though several authors had experimentally studied drilling fluid carrying capacity. [2] offered laboratory and field measurements on mud carrying capacity, recommending that 100 ft/min as a suitable annular velocity for hole cleaning. [3] offered a minimum annular velocity of about 50 ft/min to provide satisfactory cuttings transport for a typical drilling fluid, though the problem is acknowledged as being more complicated in directional and horizontal oil well drilling [4].
Settling velocity estimation, which assists the efficiency of transport of cuttings in vertical wells, is dependent on particle size, density and shape, rheology, density and velocity of drilling fluid, hole/pipe configuration, and eccentricity and pipe rotation [5]. Empirical correlations for calculating settling velocity have been proposed by several investigators, such as Moore, Chein, and Walker; the Mayes correlations have the most widespread acceptance [6].

Cuttings transport phenomena refers to the resultant forces acting on the particles, which are drag force due to settling of particles and lift force where the drilling fluid can lift cutting particles. Factors affecting particle transport include flow speed, shape of particles, flow regime (degree of turbulence), and annular space.

Calculating flow around a sphere (particles) requires a hydraulic analysis system to determine the relationship between the drag coefficient (DC), as a function of particle’s Reynolds number, and particle settling velocity (Vp), which is a parameter required to describe cuttings transport and settling in pipelines.

In turbulent flow, the relationship can be determined experimentally in the form of charts and tables; due to complicated phenomena seen in a turbulent flow regime, several attempts have been made to express the relationship and to estimate the drag coefficient versus particle Reynolds number accurately.

This research focuses mainly on the drag coefficient versus particle Reynolds number being measured experimentally.

2. Theory:

2.1 Settling Particle Correlations:

Stoke considered very slow flows of compressible fluids about a solid sphere [7], determining the resultant force as

\[ F_n = \frac{4}{3} \pi R^3 \rho_f + 6 \pi \mu_f RV_{sl} \]

Stokes then introduced the drag coefficient (DC), a factor for power law fluids, as a function of the modified particle Reynolds number, NR_{ep} , and the flow behaviour index (n):

\[ DC = f (NR_{ep}) \]

where

\[ NR_{ep} = \left(\frac{10^{-3} d_p \rho_p^{(2-n)} V_p^{(10^3 \rho_f)}}{\kappa}\right) \]

In a laminar flow Regime, Stokes offered the drag coefficient correlation for spherical particles within Newtonian fluids by theoretical analysis as

\[ DC = \frac{24}{NR_{ep}} \quad \text{for} \quad (NR_{ep} < 0.1) \]

The correlation representing the relationship between Reynolds number and drag coefficient used in general [8] for laminar and turbulent flow is
\[ DC = \frac{24}{NR_{ep}} + \frac{6}{1 + NR_{ep}} + 0.4 \]  

-------(5)

while another correlation for drag coefficient and particle Reynolds number is

\[ DC = \frac{24}{R_{ep}} + \frac{3}{16} \quad \text{for} \quad NR_{ep} < 0.01 \]  

-------(6)

As a sphere falls, at some point, the resistance balances the force of gravity and the sphere falls at a constant velocity, known as the terminal velocity of the particle; this is defined as

\[ V_t = \frac{d_s^2 \rho_s (\rho_s - \rho_f)}{18 \mu} \]  

-------(7)

Particles’ drag coefficient and particle Reynolds number are important when dealing with particle settling behaviour. The particle Reynolds number in a Non-Newtonian fluid is defined as [9].

\[ NR_{ep} = \frac{0.1617 \rho_p V_p (2-n) d^n}{36 (n-1) k} \]  

------- (8)

For Newtonian Fluids, \( NR_{ep} = \frac{0.1686 \rho_p V_p d_p}{0.001 + C_p} \)  

------- (9)

For \( R_{ep} < 0.2 \), the flow is called Stokes flow, and Stokes showed that

\[ DC = \frac{24}{NR_{ep}} \]  

------- (10)

For \( 0.2 < NR_{ep} < 500 \), the flow is called Allen flow, and

\[ DC = 18.5 NR_{ep}^{-0.6} \]  

------- (11)

While for \( 500 < NR_{ep} < 10^5 \), \( CD = 0.44 \).

Experiments have been conducted to simulate drilled cuttings transport and drag coefficients from different types of fluids. [10] conducted work that showed that laminar flow usually provides better transport than turbulent flow for cuttings, while the work in [11] clearly reflects the dependence of drag coefficients on both n and \( NR_{ep} \). [12] studied the drilling parameters affecting hole cleaning for vertical, directional, and horizontal wells, calculating the carrying capacity index, which represents an indicator for good hole cleaning in different sections of a borehole. [13] performed experimental work that showed that an increase in annular mud density improved hole cleaning; the cuttings transport ratio also experienced an improvement under turbulent flow from that seen in laminar when using polypropylene beads as cuttings.

### 2.2 Drag coefficient versus Particle Reynolds Number:

Stokes law is applied when \( R_{ep} < 0.01 \); for increasing Reynolds numbers, Stokes law fails due to fluid inertia, however. [8] concluded that, for \( 1 < Re < 100 \), a transitional flow region
exists. The major equations that describe the settling velocity of the particles depends on the Reynolds number:

\[ DC = \frac{M}{R_e} \quad \text{at } R_e < 1 \quad \text{Which indicates Laminar Flow.} \quad \text{(12)} \]

\[ DC = N, \quad \text{at } 10^5 < R_e < 2 \times 10^5 \quad \text{Which indicates Turbulent Flow.} \quad \text{(13)} \]

where \( DC = \) drag coefficient, and \( M \) and \( N \) are constants.

Thus, the settling velocity for laminar flow regimes is

\[ V_s = \frac{4gd}{3Mv} \quad \text{(14)} \]

while for turbulent flow, the settling velocity is expressed as

\[ V_s = \sqrt{\frac{4agd}{3N}} \quad \text{Where } M = 24, \text{ and } N = 0.4. \quad \text{(15)} \]

3. Experimental Work:

3.1 Particle Data:

The specifications of the particles used in this research are given in Table 1:

| Source     | Cutting Size | Cutting diameter (cm) | Density (g/cc) |
|------------|--------------|-----------------------|----------------|
| Garraf Field | Very small   | 0.212                 | 2.000          |
| Garraf Field | Small        | 0.455                 | 2.183          |
| Garraf Field | large        | 0.672                 | 2.310          |
| Garraf Field | Very large   | 0.853                 | 2.631          |

The particle densities were determined by measuring the mass of each cutting particle using an electronic balance, then dividing this by the volume of each sphere. Water, Kerosene, Gas-oil and Alcohol (Ethyl) are the Newtonian fluids used, as seen in table 2.

| Fluid Type     | Viscosity (cp) | Fluid Density (gm/cc) |
|----------------|----------------|-----------------------|
| Water          | 1              | 1                     |
| Gas-Oil        | 1.82           | 0.83                  |
| Kerosene       | 1.6            | 0.79                  |
| Alcohol (ethyl)| 1.095          | 0.74                  |
The Non-Newtonian fluid was represented by CMC Polymer (Hydroxyl methyl cellulose) in different concentrations (5 wt%, 3 wt%, 1.5 wt%, and 1wt% ).

3.2 Experimental Apparatus:

The apparatus used to perform the experiments included a graduated glass cylinder (1 m in length, 5 cm in diameter), a mud balance, a mixer, a stirring rod, a measuring cup, a sieve, a VG viscometer, a Venire calliper, and a stop watch as shown in Figure 1.

![Experimental Apparatus](image)

Figure 1. Experimental Apparatus

3-3 Test Procedures:

The experiments were conducted as follows:

1- Cutting sizes were determined using various mesh sieves with Venire callipers used for diameter length.

2- The 5 cm diameter glass tube was carefully calibrated from 0 to 100 cm and filled with fluid to the 100 cm mark.

3- Cutting particles were dropped through the glass tube gently and carefully.

4- The time that cuttings took to settle was assessed using a stopwatch.

5- Each test was repeated ten times to avoid error for each particle size; the average time taken was recorded.

6- The terminal velocity for each particle size was calculated by dividing the 100 cm length by the average time recorded in step 5.

7- The test procedure was repeated for all particles in all fluids.

4 - Settling Velocities:
4.1. Results for Newtonian Fluids:

The settling time and terminal velocities in Newtonian fluids for the different cutting diameters are given in table 3:

**Table 3. Settling Velocities for Newtonian Fluids**

| Cutting Diameter (cm) | Newtonian Fluids | Settling Time (sec) | Settling Velocity (cm/sec) |
|-----------------------|------------------|---------------------|---------------------------|
| 0.212                 | Gas Oil          | 5.0                 | 20.0                      |
|                       | Kerosene         | 3.65                | 27.4                      |
|                       | Alcohol (ethyl)  | 3.32                | 30.12                     |
|                       | Water            | 3.27                | 30.58                     |
| 0.455                 | Gas Oil          | 3.46                | 28.9                      |
|                       | Kerosene         | 3.24                | 30.86                     |
|                       | Alcohol (ethyl)  | 3.04                | 32.9                      |
|                       | Water            | 2.88                | 34.72                     |
| 0.672                 | Gas Oil          | 3.55                | 28.20                     |
|                       | Kerosene         | 3.04                | 32.90                     |
|                       | Alcohol (ethyl)  | 2.88                | 34.72                     |
|                       | Water            | 2.69                | 37.17                     |
| 0.853                 | Gas Oil          | 3.15                | 31.70                     |
|                       | Kerosene         | 2.80                | 35.71                     |
|                       | Alcohol (ethyl)  | 2.50                | 40.00                     |
|                       | Water            | 2.31                | 43.30                     |

4.2 Results for Non Newtonian fluids:

The settling time and terminal velocities in non-Newtonian fluids for the different cutting diameters are given in table 4:

**Table 4. Settling Velocities for Non-Newtonian Fluids**

| Cutting diameter (cm) | Non-Newtonian fluids (% CMC) | Settling Time (sec) | Settling velocity (cm/sec) |
|-----------------------|------------------------------|---------------------|---------------------------|
| 0.212                 | 1% CMC                       | 3.53                | 28.33                     |
Power law solution behaviours were simulated by preparing four CMC Polymer solutions with different concentrations (5 wt%, 3 wt%, 1.5 wt%, and 1 wt%). This was achieved by mixing specific quantities of CMC and water in vessels and agitating these for one hour; each solution was then left for 24 hrs, to continue hydration. The rheological results for CMC solutions were measured using a VG-Meter, as seen in Table 5, below:

Table 5. Viscometer readings for CMC % Polymers fluids

| Fluid Type | Speed (RPM) | Dial Reading (∅) | Shear Rate, Sec⁻¹ | Shear Stress (τ) (P_a) |
|------------|-------------|------------------|-------------------|-----------------------|
| 1wt% CMC   | 600         | 30.2             | 35                | 15                    |
|            | 300         | 22.4             | 23.5              | 12.7                  |
|            | 200         | 21               | 17.4              | 10.5                  |
|            | 100         | 12.5             | 14.9              | 6.8                   |
|            | 6           | 6                | 7.5               | 3.5                   |
|            | 3           | 3.5              | 5                 | 2.9                   |
| 1.5wt% CMC | 600         | 35.4             | 37.2              | 18.2                  |
|            | 300         | 26.4             | 27.8              | 13.5                  |
The rheological parameters for the power law fluids are given in Table 6. All tests were conducted at room temperature (25 °C).

Table 6. Values of Rheological Model for Power Law Fluids

| Non-Newtonian Fluid Type | Fluid Behaviour Index, n | Consistency Index, K (lb/100 ft²) |
|--------------------------|--------------------------|-----------------------------------|
| 1 wt % CMC               | 0.428                    | 0.910                             |
| 1.5 wt % CMC             | 0.441                    | 0.907                             |
| 3 wt % CMC               | 0.850                    | 0.560                             |
| 5 wt % CMC               | 0.875                    | 0.547                             |

5 - Results and Discussion:

The experimental results are classified into two sets for Newtonian and Non-Newtonian fluids. Table 7 shows the drag coefficient versus particles Reynolds Numbers for Newtonian Fluids.

Table 7 Drag Coefficient versus Reynolds Number for Newtonian fluids
at Various Particle Diameters

| Fluid Type | Particle Diameter, cm | Particle Reynolds Number | Drag Coefficient |
|------------|-----------------------|--------------------------|------------------|
| Water      | 0.212                 | 1311                     | 0.428            |
|            | 0.455                 | 3489                     | 0.409            |
|            | 0.672                 | 5836                     | 0.405            |
|            | 0.853                 | 9830                     | 0.403            |
| Gas Oil    | 0.212                 | 471                      | 0.464            |
|            | 0.455                 | 1596                     | 0.419            |
|            | 0.672                 | 2433                     | 0.412            |
|            | 0.853                 | 3954                     | 0.408            |
| Kerosene   | 0.212                 | 735                      | 0.441            |
|            | 0.455                 | 1938                     | 0.415            |
|            | 0.672                 | 3229                     | 0.409            |
|            | 0.853                 | 5067                     | 0.406            |
| Alcohol(ethyl) | 0.212        | 1415                     | 0.421            |
|            | 0.455                 | 3019                     | 0.410            |
|            | 0.672                 | 4915                     | 0.406            |
|            | 0.853                 | 8293                     | 0.404            |

The results for Non-Newtonian Fluids for all cuttings diameters are shown in Table 8:

Table 8 Drag Coefficient versus Reynolds Number For Non-Newtonian Fluids

| Fluid Type | Particle Diameter, cm | Particle Reynolds Number | Drag Coefficient |
|------------|-----------------------|--------------------------|------------------|
| 1% CMC     | 0.212                 | 139.7                    | 0.955            |
|            | 0.455                 | 485.0                    | 0.453            |
|            | 0.672                 | 673.4                    | 0.445            |
|            | 0.853                 | 969.4                    | 0.431            |
| 1.5% CMC   | 0.212                 | 84.7                      | 1.29             |
From the experimental results, the settling velocity for different Newtonian fluid types increases as particle diameter increases, due to increases in gravity forces, while the settling time decreases, as shown in table 3. For the 0.212 cm particle diameter, the settling velocity was 20 to 30.58 cm/sec, and for 0.853 cm diameter, it was 31.7 to 43.3 cm/sec.

For Non-Newtonian fluids, the results are shown in table 4. For the different CMC concentrations, maximum settling velocity was observed in the 1% concentration (24.87 to 35.46 cm/sec as compared to the 15.2 to 21.98 cm/sec seen in the 5% CMC concentration). This is due to increases in the viscous forces that affect settling velocity of the particles in high concentration fluids.

The drag coefficient is a function of the Reynolds number for Newtonian fluids and a function of (NR, n) in Non-Newtonian fluids. Thus, as shown in table 7, for the different Newtonian fluids, the drag coefficients are low, ranging from 0.428 to 0.403. For water with the large diameter particles (0.853 cm), the drag coefficient is equal to 0.403, and it is 0.428 for very small particle diameters as estimated by eq. 5 and 11, based on the Calculated Reynolds number values in equation 8 for Newtonian fluids, as shown in Figure 2. The drag coefficients decrease with increasing particle Reynolds number for non-Newtonian fluids.
Figure 2. Relationship between particle Reynolds number and drag coefficient for non-Newtonian fluids.

Drag coefficients appear to be smaller for Newtonian fluids in low viscosity than in non-Newtonian fluids, as shown in figure 3.

Figure 3. Relationship between particle Reynolds number and drag coefficient for Newtonian fluids.
The results in table 8, in particular the comparison between 1% CMC and 5% CMC concentrations, indicate that when increasing CMC concentration decreases the particle Reynolds number and increases drag coefficients for different particle size diameters, which indicates a good cleaning effect and increases cuttings transport during vertical drilling operations. This is due to increases in viscous forces that tend to lift and carry the particles and prevent cuttings settlement. The results for Non-Newtonian fluids are as calculated by eq. 11 for drag coefficients and eq. 8 for Reynolds number, based on the values of $m$ and derived from table 6, with the rheological properties for each fluid measured by VG viscometer as tabulated in table 5.

All experimental results showed particle Reynolds number values less than $10^5$, which reflects the existence of laminar flow regimes due to restrictions in the apparatus used in the laboratory, such as the mud column being only 5 cm in diameter and 100 cm long.

In Newtonian fluids, drag, the inertia effect, represents a greater effect on the fluid, being responsible for the majority of forces the particles are subjected to. The drag coefficients for smaller particle sizes are higher than those obtained from larger sizes in both fluid types as the slower settling rate of particles creates larger drag effects due to forces affecting the settling ratio.

A comparison between fluid types (Newtonian and non-Newtonian fluids) suggests that the Newtonian fluids’ settling velocity increases as the viscosity increasing for all particle sizes, while for non-Newtonian fluids, there is an increase in settling velocity with decreases in CMC concentration due to viscosity reduction. For Newtonian fluids, the drag coefficients decrease with increases in particle diameters for all types of Newtonian fluids. In non-Newtonian fluids for each CMC concentration (% CMC), the drag coefficient decreases with increases in particle diameter. An increase in drag coefficient with increases in CMC concentration for different particle diameters is also shown in Table 8. In general, the drag coefficient for non-Newtonian fluids is greater than for Newtonian fluids for all particle diameters, as shown in Figure 4.
6- Conclusions:

The results from this research support the following conclusions:
1- Low Reynolds number values, which represent laminar flow, were found due to restrictions in the experimental configuration.

2- Increases in particle Reynolds numbers give low drag coefficient values.

3- Settling velocities increase with increases in particle diameter.

4- Larger particles give lower drag coefficients than smaller ones.

5- Higher fluid density gives a higher settling velocity, with lower velocities for lower fluid densities at all particle sizes.

6- Higher concentrations in Non-Newtonian fluids offer the lowest settling velocities and low concentration give the highest.

7- Lower (n) and higher (k) values (low concentration) offer higher settling velocity.

8- Non-Newtonian fluids offer higher drag coefficients than Newtonian fluids, which indicates the potential for better cuttings transport and good hole cleaning.

**7- Recommendations:**

For future research, the authors recommend

1- The examination of other types of polymer fluids such as hydroxyethyl cellulose (HEC), polyethyl oxide (PED) and partially hydrolysed polyacryl amide (PHPA).

2- Investigating the correlation between laminar and turbulent flows, the Reynolds number, and drag coefficient.

**Nomenclature:**

\( V_p \) – Particle Velocity, cm/sec.

\( R \) - Radius of Particle, cm.

\( \rho_f \) - Fluid Density, gm/cc.

\( DC \) - Drag Coefficient.

\( \text{NR}_{cp} \) – Particle Reynolds Number.

\( d_p \) – Particle diameter, cm.

\( n \) - Flow behaviour Index.

\( K \) - Consistency Index.

\( \rho_s \) – Solid Particle Density, gm/cc.

\( \mu \) - Viscosity, cp.

\( V_t \) – Terminal velocity, cm/sec.

\( g \) – Acceleration of Gravity, cm/sec\(^2\).

\( V_s \) – Settling Velocity, cm/sec.

\( F_n \) – Resultant force acting on the particle, lbf.

\( \mu_f \) - Fluid viscosity, cp.

\( V_{sl} \)– Settling velocity, cm/sec.

\( d_s \) – Solid particle diameter, cm.

\( \rho_p \) - Particle density, gm/cc.

\( V \) - Velocity, cm/sec.

\( M \) and \( N \) - Constants.

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