A STUDY ON CUTTINGS TRANSPORT IN DRILLING FLUIDS WITH INCLINED ANNULUS

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ABSTRACT
This paper examines the migration of solid particles in a high-mixing flow inside an inclined annular pipe. An experimental study of non-Newtonian fluids in the layer region through annular tubes with axial flow and rotation of the inner cylinder was carried out. It was demonstrated that the gravitational force acting on the particle stream plays a very important role in directional drilling, cuttings particle movement, and cuttings transport. The pressure drop and the particle velocity of the drilling fluid (CMC and Bentonite solution) corresponding to the inclination and rotation of the drill pipe were measured. The hydraulic pressure drop owing to the mixture flow increased because of the friction between the wall and the solid particles. Further, a high particle feed concentration increased the pressure drop because of the friction between the solid particles in the fluid stream. The advantages of a rotating and an inclined annulus pipe, for the particle transport phenomena, were confirmed in this study.
Keywords: cuttings transport, drilling fluids, directional drilling, pressure drop.

1 INTRODUCTION

Several experimental studies have focused on cuttings transport, including the slope and rotation of drilling pipes applied under low-pressure conditions by conventional drilling methods. A previous study confirmed that pipe rotation is the main factor that controls the hole-cleaning efficiency of large inclined pipes and also of the horizontal boreholes. In addition to pipe rotation, the particles transport ratio depends on the inclination of the annular pipe, the viscosity of the drilling fluid, the size of the cuttings, and the flow rate.

Ford et al. [1] and Peden et al. [2] conducted a cuttings transportation experiment in an inclined annular tube using internal pipe rotation. The pipe rotation had great influence on the cuttings transportation using high-viscosity fluids; however, it did not have much influence on the cuttings transportation under low-viscosity fluids such as water. In addition, the pipe rotation had a greater influence on the large-annular-gap pipes, compared with the small-annular-gap pipes.

Lockett et al. [3] introduced Taylor vortices in their numerical analysis and demonstrated the importance of pipe rotation for effective cuttings removal. The vortices prevent the formation of a cuttings bed and assist in lifting cuttings from the cuttings bed. However, the actual simulation was conducted without the cuttings bed, and, therefore, the results are considered inconclusive.

Sanchez et al. [4] studied the effect of pipe rotation on cuttings transportation in directional drilling, through a large number (~600) of experiments at actual drilling scale. They reported that the rotation of the drill pipe could decrease the residue concentration by up to 80%. They also observed that at low flow rates during horizontal drilling at high rotational speeds (that is, above 100 rpm), the decrease in the cuttings volume was large.

Saasen [5] studied the effect of the pipe rotation on the cuttings bed. In an oil well located in the North Sea, Saasen observed that for oil-based mud, if the cuttings bed is formed, the pipe rotation has very little effect on the particle transport. Further, very high rotation speeds must be applied to increase the cuttings during the drilling. It was also reported that the effect of pipe rotation is even more important in the case of water-based mud when the cuttings bed is formed.

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However, these studies focused only on the cuttings transportation of conventional drilling and not on drilling operations at inclined boreholes. In addition, the experimental study of the annuli flow was not possible owing to the mechanical difficulties of drill pipe rotation. Even the researchers who studied the problem experimentally experienced difficulty in meeting the steady-state condition of annuli flow. As a result, there is a lack of research on the important phenomena that predict the particle transfer rate, and also on the cuttings bed formed radially due to the sliding velocity of solid particles from the inclined annular tube.

Therefore, the objective of this study was to solve the problem of clogging of the boreholes caused by the accumulation of cuttings in the inclined boreholes, by developing a cuttings mathematical transfer model that can predict cuttings movement characteristics during inclined drilling. The solid particles transportation characteristics in an annulus inclination in a directional drilling, such as the particle feed rate, axial rotation, and axial velocity, were identified as important parameters for this study.

2 RELEVANT VARIABLES

2.1 Fluid property

In this study, since the non-Newtonian fluid used as the working fluid is a shear thinning fluid, the Brookfield DV-III+ coaxial cylindrical viscometer was used to identify the rheological characteristic in shear conditions with shear rates up to 200 s^{-1}. All measurement units of the instrument are based on the CGS (centimeter–gram–second) unit system: viscosity is specified in cP, shear stress in dyne/cm^2, shear rate in 1/s, and spring torque in dyne-cm as %.

The viscosity of the fluids is measured by changing the temperature from 10°C to 38°C in increments of 1°C. The value is measured by setting the rotation speed and hole time at each stage in the program incorporated into the viscometer at each temperature; thus, it can adapt to various models of the non-Newtonian fluid.

When the power-law model was applied to all non-Newtonian fluids, the reliability was more than 97%, but it was under 90% when Bingham and other similar models were applied. Therefore, the power-law model was applied to all the working fluids. The properties of the non-Newtonian fluids used in this study are listed in Table 1.

2.2 Particles transport ratio

Researchers have traditionally developed theoretical and experimental equations for the slip velocity V_s of a particle, starting from eqn (1):

Table 1: Fluid properties (temperature 15°C).

Non-Newtonian fluids	Density (kg/m^3)	Rheological index (n)	Consistence value (k)
A	885.0	0.70	6.0
B	1005.0	0.71	7.0
C	996.9	0.64	13.0
D	1010.0	0.45	24.0

$$V_p = V_a - V_s \,, \tag{1}$$

where V_s is a function of the type of fluid and the properties of the particle. If the circulating rate of the mud is known, V_a can be determined easily, and V_p is determined using eqn (1).

The transfer ratio of the cuttings during the drilling and the effectiveness of the drilling fluid are best described by the transfer ratio discussed by Sifferman et al. [6]. The particle transfer ratio R_t can be expressed by eqn (2) as follows.

$$R_t = \frac{V_p}{V_a} = 1 - \frac{V_s}{V_a} \,. \tag{2}$$

2.3 Particle volume fraction

The particle volume fraction (C_{VT}) inside the annulus pipe is an important variable that is used to evaluate the particle transfer efficiency of the solid-fluid flow. A small C_{VT} represents excellent transfer performance, and can be obtained by dividing the overall annulus pipe volume by the solid particle occupied volume [7]:

$$C_{VT} = \frac{\text{Volume occupied by solids}}{\text{Volume occupied by mixture}} \times 100 \,. \tag{3}$$

A device to sample the flow at the exit area of the test zone was installed. The volume fraction of the particle was directly measured, and an equation for the independent variable, the volumetric ratio, was derived that uses the dimensionless numbers representing the measured values of various test flow rates, angles of inclination of the pipe, and the pipe rotation speeds.

3 EXPERIMENTAL METHOD

The experimental setup used in this study is composed of the particle input part, annular tube part, and the measuring part, as shown in Fig. 1. The annular tube was made of transparent acrylic pipe and was manufactured with the inner diameter of the outer pipe as 44 mm, and the outer diameter of the inner pipe as 30 mm, yielding a radius ratio of 0.7 for the annulus. In this experimental set up, it was possible to measure the pressure by boring a tab at intervals of 0.5 m on the upper part of the annular pipe. In addition, the particles could be injected steadily by installing a particle injector at the lower part of the annular tube.

4 RESULTS AND DISCUSSION

Fig. 2 shows the phenomenon for various inclination angles of the annular tube, which denote an important variable in this study. The figure shows that as the inclination angle of the annular tube increases, the radial sliding speed also increases, causing increasingly more solid particles to concentrate on the lower part of the annular tube. Eventually, at lower fluid speeds, the solid particles begin to form the cuttings bed.

The thickness of the solid particle cuttings bed was generally small at a small angle of inclination, and when the rotation of the inner axis or the velocity of fluid increased, it became very unstable and tended to disappear. For different types of fluid flow, and for an increasing angle of inclination, the development process of the cuttings bed can be categorized into four types [8].

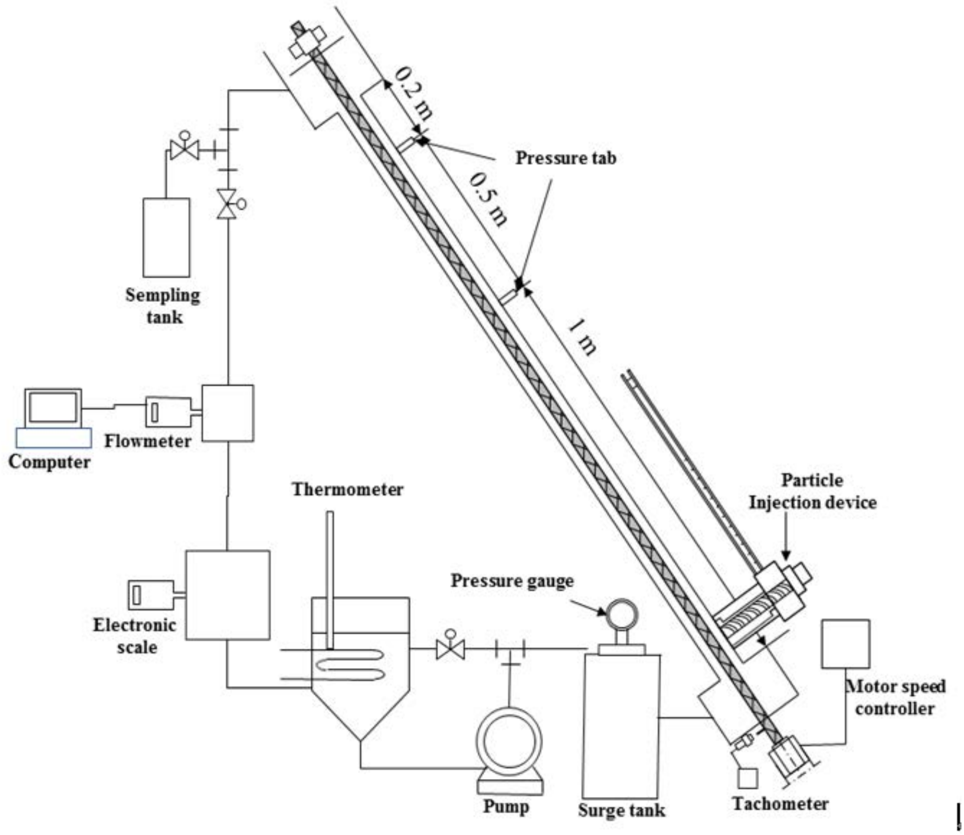
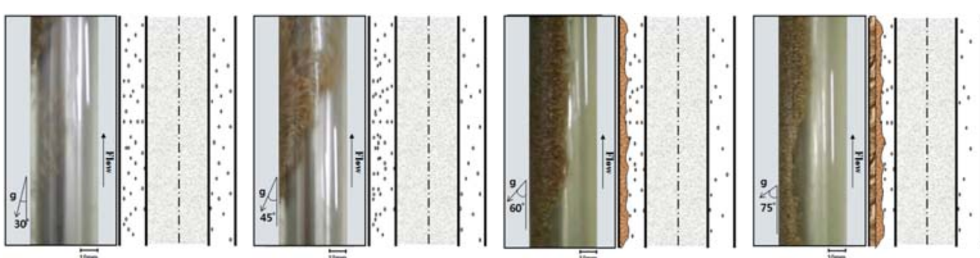


Figure 1: Schematic diagram of the experimental setup.



(a) (b) (c) (d)

Figure 2: Photograph of sand particle movement in the Fluid A. (a) Suspended asymmetric; (b) Suspended asymmetric; (c) Moving bed; (d) Stationary and moving bed. (φ = 8%, Vf = 0.48 m/s, Ω = 0 rpm.)

4.1 Particle transport ratio

Fig. 3 shows the particle transfer rate of the non-Newtonian fluid used in this study. To compare different working fluids, the particle transfer rates for various values of the inner axis rotational speed and for different inclination angles are shown for different fluids. The particle transport ratio was highest for Fluid D, and this is due to the fact that Fluid D had the highest viscosity and density. Therefore, it can be concluded that not only the viscosity but also the density of the fluid has a positive effect on the particle transport.

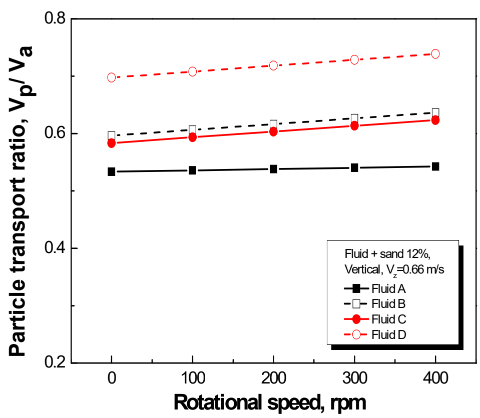
For Fluid A, which had the smallest viscosity and density in this study, the results showed a significant change in the particle transport ratio depending on the changes in the angle of inclinations. In the 0–30° section, the decrease in the particle transfer rate appeared smaller than in the other fluids, and it showed a relatively stable particle transfer level. However, in the section after the 30° inclination, the particle transfer rate significantly decreased compared with the cases of the other fluids.

4.2 Particle volume fraction

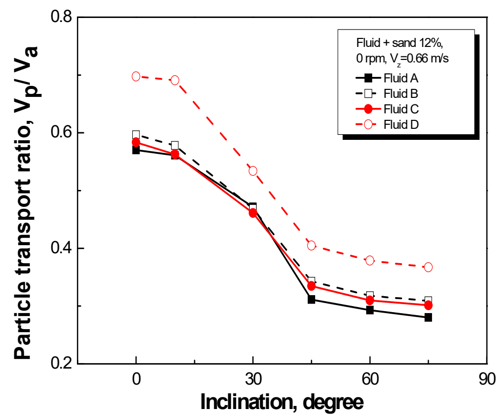
Fig. 4 shows the particle volume fraction value of the non-Newtonian working fluids. As the inclination angle in all fluids increased, the volume fraction of solid particles also increased. This phenomenon was more significant in Fluid A, which had the smallest viscosity and density. However, this increase in the volume fraction of the solid particles for Fluid D was relatively small because of its high viscosity and density. Therefore, it can be concluded that the lower the particle transfer rate, the greater the particle volume fraction, which corresponds to an opposite tendency to the results presented in Fig. 3.

5 CONCLUSIONS

In this experimental study on the two-phase concentric annular flow of high-liquid non-Newtonian fluids, the characteristics of the high-liquid two-phase flow of the inner part of the annular tube were identified. The experiments were conducted on different drilling fluids



(a)



(b)

Figure 3: Comparison of particle transport ratio with non-Newtonian fluids. (a) Rotational speed; (b) Inclination.

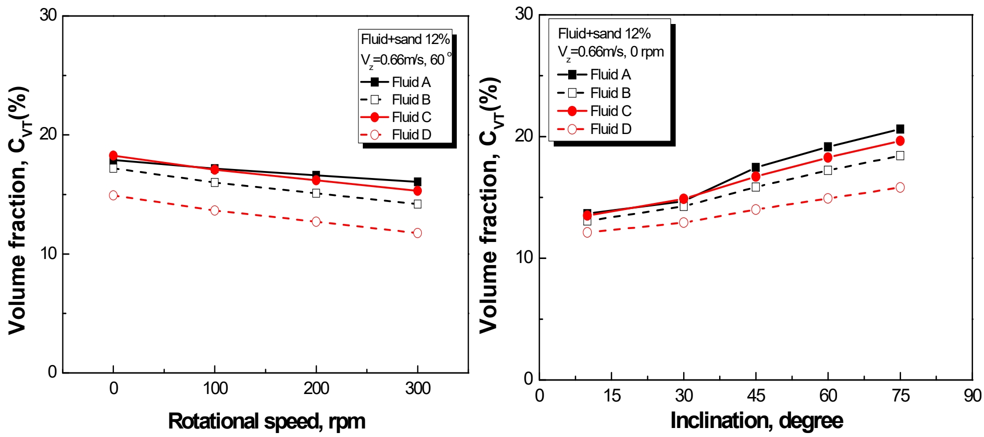


Figure 4: Comparison of volume fraction with non-Newtonian fluids. (a) Rotational speed; (b) Inclination.

by changing the main flow variables such as the annular angle, particle feed rate, axial rotation, and axial velocity.

The main factors that affect the carrying capacity of the drilling fluid in the inclined annular tube are the flow velocity, rotation speed, inclination angle, and rheological characteristics of the fluid. The particle transfer rate and the particle volume flux were observed to improve in proportion to the flow velocity, rotation speed of inner axis, and fluid viscosity. Moreover, it was observed that as the particle injection rate and the inclination angle increased, the transfer capability decreased.

At more than a 30° inclination, the solid particle cuttings bed that is transferred to the pipe was found to develop in the direction of gravity inside the annular tube, and the thickness of the cuttings bed was formed largely by the increase in the inclination. It was also observed that as the cuttings bed developed, the particle transfer rate decreased, and the cuttings bed forming period was dependent upon the rheological properties of the fluid and the flow variables.

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