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Mini-hydrocyclones applied to the removal of solids from non-Newtonian fluids and analysis of the scale-up effect

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ABSTRACT

In the solids control system, the removal of fine solids from drilling fluid is performed by decanter centrifuges. The use of these centrifuges is limited not only by the costs involved but also by the available space on the oil rig, so they cannot process the entire volume of fluid circulating in the drilling system. This paper proposes the use of hydrocyclones to support decanter centrifuges, aiming to increase the removal rate of fine material from the fluid to be reinjected into the well. To this end, a highly efficient with low flow ratio hydrocyclone geometry was tested, using non-Newtonian fluids with a particulate matter size distribution similar to the conditions encountered in the field. Empirical expressions were obtained to predict the total separation efficiency, flow ratio, capacity and cut diameter of the equipment as a function of the operating conditions. The hydrocyclone scale-up results indicated that the larger device maintains practically the same separation performance as the original device, but provides an evident improvement in processing capacity.

1. Introduction

It is known that during the oil well drilling process, drill cuttings are produced as the drill bit advances towards the oil deposit. These solids must be quickly withdrawn from the bottom of the well so that drilling can continue. This is done by using drilling fluid which is injected directly into the drill string and returns to surface through the annular space between the drill pipe and the borehole wall. From this fact arises then the need of these drill cuttings be removed from the drilling fluid as soon as it reaches the surface, so that the fluid can be reinjected into the well (Bicalho et al., 2016; Escudier et al., 2002; Meuric et al., 1998).

Drill cuttings are separated from drilling fluid by means of a set of equipments and operations, which together are commonly referred to as the solids control system (Eow et al., 2007; Liu et al., 2015; Petri Junior et al., 2015). Solids from oil well drilling present a wide range of sizes, with particles that fall into the categories of sand (0.06–2 mm), silt (0.002–0.06 mm) and clay ($< 2\ \mu m$), thus requiring different types of devices to separate them (Yong et al., 2012). The devices commonly used in these systems range from vibrating screens, hydrocyclones (desander and desilter) and decanter centrifuges to high-speed cuttings dryer (Marins et al., 2010; Marthinussen et al., 2014; Njobuenwu and Wobo, 2007).

The decanter centrifuges play an important role in solids control system in the cleaning of the fine drilled solids. Although they efficiently remove fine particles from drilling fluid, decanter centrifuges have some disadvantages, e.g., relatively low processing capacity, especially when compared to other devices used for solids control and considering the large volume of fluid circulating in the drilling system; high cost of installation, operation and maintenance; and the need for a large space for installation, which limits their use in offshore rigs (Mognon et al., 2015b).

The relatively low processing capacity of centrifuges is a problem in the early stages of drilling. In these stages, the large diameter of the shaft requires an increase in the fluid flow, which overloads the solids control system. Thus, most of the drilling fluid is ultimately not treated in the centrifuges. This causes fine particles to accumulate in the fluid, creating a variety of problems as the fluid recirculates between the solids control system and the well that is being drilled. Quantitatively, it can be stated that in critical operating conditions, only about 10% of the circulating fluid is directed to decanter centrifuges, while the remainder is redirected by bypass, mixed with the already treated stream, and then reinjected into the well.

In view of these problems, there is a need for alternatives to handle the volume not processed by the centrifuges, considerably reducing the amount of dispersed fine particulate material in the fluid recirculated into the well. Hydrocyclones offer an alternative that involves low installation, operation and maintenance costs, and whose operation requires little space (Nascimento et al., 2013; Pinto et al., 2013; Young et al., 1994).

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Nomenclature

C_i	Infeed mass concentration (%)
C_{cmc}	Carboxymethyl cellulose concentration (%)
$\overline{C}_{cmc}$	Carboxymethyl cellulose concentration in coded form (–)
C_{sol}	Solids concentration (%)
$\overline{C}_{sol}$	Solids concentration in coded form (–)
C_u	Underflow mass concentration (%)
d_{50}	Diameter of the particle collected with 50% efficiency (μm)
D_c	Diameter of hydrocyclone cylindrical section (mm)
ΔP	Pressure drop (psi)
$\Delta X_i(d)$	Fraction of solids with diameter d fed to the hydrocyclone (–)
$\Delta X_u(d)$	Fraction of solids with diameter d discharged into the underflow (–)
D_u	Underflow conduit diameter (mm)
$\overline{D}_u$	Underflow conduit diameter in coded form (–)
Eu	Euler number (–)
$G(d)$	Granulometric efficiency (%)
η	Total separation efficiency (%)
η'	Reduced separation efficiency (%)
L_c	Length of the cylindrical region (mm)
L_v	Relative length of the vortex finder (mm)
θ	Angle of the conical region (°)
ρ	fluid density (g/cm^3)
R_f	Flow ratio or underflow-to-throughput ratio (%)
v_c	Velocity in the cylindrical chamber of the hydrocyclone (cm/s)
W_i	Mass flow rate of infeed (g/s)
W_u	Mass flow rate of underflow (g/s)
Y	Vector of coded variables
Y^T	Vector of transposed coded variables

Hydrocyclones belong to the most applied separation equipments in technology, being found in mineral processing, chemical industry, oil industry, pharmaceutical industry and others (Schubert, 2010). These devices are already used for the removal of sand and silt to control solids in drilling fluids, but their typical diameter of more than 4 in. makes them ineffective in removing finer particles (Svarovsky, 2000). However, optimization studies to evaluate the effects of the geometric configuration of the equipment, operating conditions, and the characteristics of the suspension (non-Newtonian fluid) and solids to be separated enable the desired removal or improvement of the hydrocyclone separation performance to be achieved (Bergström and Vomhoff, 2007; Fan et al., 2015; Kawatra et al., 1996; MacKenzie et al., 2014; Scheid et al., 2013; Tavares et al., 2002).

Marthinussen et al. (2014) investigate experimentally the separation of particles from highly viscous liquids in hydrocyclones. Data obtained in this study can be used for pointing the way to modifications of the hydrocyclone geometry to make it better suited for operating on viscous fluids. Ghodrat et al. (In press) has numerically shown that modifications on hydrocyclone design are useful to improve the performance of devices used to handle different sized particles with a wide density range. A considerable amount of research has been performed using computational fluid dynamics (CFD) to suggest optimization for improving hydrocyclone performance in the most varied applications (Hwang et al., 2013; Tang et al., 2015; Yang et al., 2015).

Thus, in this work, we studied the applicability of hydrocyclones in solids control systems (notably finer solids). A geometry designed specifically for this purpose was tested (Mognon et al., 2015b), in conditions resembling those observed in the field, using non-Newtonian fluids with solids distribution similar to that processed by decanter centrifuges. The scale-up of the hydrocyclone was also evaluated, aiming to come closer to meeting the needs of field processing.

2. Evaluation of the performance of the optimized hydrocyclone under field conditions

Based on a hydrocyclone geometry considered optimal in a previous work of this research group (Mognon et al., 2015b), a study was conducted to assess the effects considered paramount in the operation of this device in the field. These effects can be summarized in the following points:

- Use of non-Newtonian fluids: drilling fluids have shear-thinning rheological characteristics. Therefore, it is necessary to evaluate these effects on the performance of the device. To this end, water-based fluids containing different concentrations of carboxymethyl cellulose (C_{cmc}) were used in the tests.
- Variation in solids concentration: the well drilling process involves a series of stages that differ primarily in the volumetric rate of rock drilled, i.e., in the drill bit rate of penetration (ROP). Therefore, the concentration of solids (C_{sol}) dispersed in the fluid was also the target of this study.

Another important point that deserves comment is the maintenance of the underflow diameter (D_u) as a study variable. This choice is directly linked to the fact that this variable strongly influences the performance of the device and can be considered, in a peculiar way, as an operational variable rather than a design variable. The underflow diameter can be considered as an operational variable, which must be adjusted according to the conditions prevailing in the industrial plant (Silva et al., 2015).

Based on the abovementioned points, a 3^k experimental design was built, according to the levels described in Table 1.

According to the methodology used for the experimental design (Bicalho et al., 2012), the variables of interest will be commonly presented in their coded forms, denoted by $\overline{D}_u$, $\overline{C}_{cmc}$ and $\overline{C}_{sol}$:

$$\overline{D}_u = \frac{D_u[\text{mm}] - 6}{2} \tag{1}$$

$$\overline{C}_{cmc} = \frac{C_{cmc}[\%\ \text{mass}] - 0.4}{0.2} \tag{2}$$

$$\overline{C}_{sol} = \frac{C_{sol}[\%\ \text{mass}] - 3.5}{2.5} \tag{3}$$

Based on the levels shown in Table 1, the full set of 29 experiments (with two center point replicates) executed in this experimental design is described in Table 2.

Table 1
Variables selected for the experimental design.

Level	D_u (mm)	C_{cmc} (%)	C_{sol} (% mass)
1	8	0.6	6.0
0	6	0.4	3.5
−1	4	0.2	1.0