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Dynamical feature of particle dunes in Newtonian and shear-thinning flows: Relevance to hole-cleaning in pipe and annulus

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ABSTRACT

Cuttings transport under laminar and turbulent liquid flow in horizontal and deviated pipes were investigated. Several experiments were conducted both for single-phase liquid flow and liquid-particle flow in order to study the impact of rotation of a drill string, as well as fluid rheology and particle size on dynamic feature of particle dunes. Long time series of pressure gradients and flow patterns of the liquid-particle flow were obtained for off-line analysis. Fast Fourier Transform (FFT) was the methodology used to study the time series of pressure gradient signals. The time series were recorded as long continuous experimental sequences, while the flow conditions were changed in time stamped steps. The off-line analysis could then be carried out on each sequence which was easily extracted from the original based on the time intervals. The analysis indicated an existence of dominant frequencies corresponding to liquid and particle dynamics, and to the rotational speed of the drill string. It was found that the distribution and width of the frequency spectrum can be used as an indicator of the particle concentration at given flow conditions. Particle size has a large impact on the frequency spectrum, mostly when the drill string is rotating. The results of this study could help in real time prediction of downhole conditions in petroleum geology, exploration, and drilling operations.

1. Introduction

Efficient cuttings transport is an essential part of a drilling operation in order to avoid problems occurring as a result of poor hole-cleaning. The problems related to poor hole-cleaning include the stuck pipe situation, circulation loss and well instability which lead to higher operational costs. A proper study of the cuttings transport concept will reduce the operational cost involved by providing a more sensible picture of the parameters which affect the performance of the drilling fluid. There are other factors related to the wellbore size, the cross-sectional area and the rotation of drill string (DS) which affect the cuttings transport efficiency. The most critical section of the wellbore, where the cuttings removal is challenging, is the horizontal and slightly inclined sections. To investigate the problem more thoroughly, the main focus of this study is investigation of liquid-particle flow patterns and pressure gradient at horizontal and inclined (5°) test sections. The prediction of the liquid-particle flow patterns in the pipe for any given set of operational conditions is very important for diagnosing and also for stabilizing the pressure fluctuations. (Kökpınar and Göğüş, 2001; Peysson, 2004). Moreover, the pressure gradient differs from one liquid-particle flow pattern to another and this is crucial for drilling operations (see e.g. Chen et al., 2007; Corredor et al., 2016; Duan et al., 2010). It is desirable to minimize pressure fluctuations and stay within the "operational window" between reservoir pore and fracture pressure gradients during drilling operations. Various studies have been done for predicting liquid-particle flow patterns in the pipe (see e.g. Bello et al., 2011; Corredor et al., 2016; Doron and Barnea, 1993; Doron et al., 1987; Doron et al., 1997; Goharzadeh et al., 2013; Khan et al., 2016; Nossair et al., 2012; Savage et al., 1996) where they developed flow pattern maps to indicate liquid-particle flow patterns under various operational conditions. Savage et al., (1996), Nossair et al., (2012), and Goharzadeh et al., (2013) partly generalized the liquid-particle flow patterns in horizontal and inclined pipes using a wide range of experimental data, both from published literature and acquired data in their studies. They categorized liquid-particle flow patterns into two categories; three-layers flow patterns with stationary, moving and dispersed layers, and also two-layers where the moving and dispersed layers act together as a continuum. Nossair et al., (2012), based on visualization of dunes morphology, found that pipeline inclination has a significant influence on particle dynamics and characteristics of liquid-particle flow patterns. Corredor et al., (2016) determined the cuttings movement with bed load (having rolling particle motion), saltating, dunes, and suspension modes. In addition, they investigated the effect of fluid rheology on particle dunes and found that

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the critical velocity for initiation of particles movement is lower for water than that of using drag reducing fluid (Corredor et al., 2016). Despite detail investigation of flow patterns, the effect of DS rotation on changing of flow patterns has not been studied yet.

A long history of investigation of sediment transportation (e.g. Cardona Florez and Franklin, 2016; Coleman et al., 2003; Garcia, 2008; Kennedy, 1969; Raudkivi, 1997) has been done in both open and closed channels. The bedforms were classified by Raudkivi (1997) and Garcia (2008) mainly as "no-motion" plane bed, ripples (small triangular sand surface waves due to disturbances in the near bed boundary layer), dunes (large irregular sand waves), antidunes (dunes moving against the flow direction), and transition to suspension flow. Edelin et al., (2015) studied bedforms in the pipe, using floating particles, and obtained vortex ripples within a range of laminar to low turbulent flow. Using heavy particles in pipe/annular flow as in this study, the stationary plane bed at low flow condition formed irregularities. As the flow speed was increased the irregularities developed into dunes. However, the transition to moving dunes occurred abruptly with increasing flow rate, without ripples in the sense of clear wave structures.

The pressure gradient time-series were studied in detail using frequency spectral analysis in order to determine the dominating frequency of the pressure fluctuations. Pahk and Klinzing (2008) applied the spectral analysis of pressure gradient in pneumatic conveying, finding that the dominant frequency peaks corresponded to the variation in gas and particle flow rates, and to the mechanical rotating units in the flow loop. Singh et al., (2010) investigated the frequency spectral of near-bed velocity fluctuations and bed elevations to study the impact of bedform dynamics on the flow over a gravel bed. They interpreted that the high-frequency limit is associated with turbulence and the low-frequency limit corresponds to the scale of the smallest bedforms. Takahashi et al., (1989) found that the pressure fluctuation in liquid-particle flow could be related to the movement of dunes in the pipe, and also that the dominant frequency was increasing with an increase in the dune velocity. Felipe and Rocha (2004) found that the frequency spectral analysis is a viable method for identification of fluidization regimes. Brown and Brue (2001) devised sufficiently long sampling time in order to be able to capture all the variability that occurs in fluidized beds flows.

The presence of DS and with and without rotation was also applied to create various dynamic conditions in the annulus flow area. The cutting sizes used in the experiments are generally not in the same range as in the drilling operation. A variety of flow conditions exists in real pipe flows, depending on turbulence and shear layers, favoring the transport of either large particles or, more commonly, finer particles. The cuttings in this investigation were two classes of spherical glass beads having a median diameter of 0.3 and 1.2 mm, respectively. In this work, the aim is to investigate the pressure gradient data to predict the liquid-particle flow patterns under a given set of conditions.

2. Experiment

2.1. Experimental setup

The experiments were carried out in a medium-scale flow loop. A schematic of the flow loop is shown in Fig. 1. The flow loop included two main test sections: horizontal (0°) and inclined (5°). The total length of test sections is about 13 *m* with an inner diameter of 40 mm. The criteria used for scaling the experimental setup was for the borehole size 8.5 *in* (0.216 m) and drill pipe 5.0 *in* (0.127 m) in the field (see more detail in Busch et al., 2016) . The pipes in the test sections were made of transparent acrylic, thus allowing for visual observation of liquid-particle flow patterns.

The test fluid was stored in a 350 l liquid source tank. The fluid was circulated by means of a screw pump (PCM Moineau 2515, $P_{max} = 3$ bar, $\dot{Q}_{max} = 14$ m^3/h) equipped with a variable frequency inverter. A Coriolis flow meter (Promass 80F DN50) was installed before the mixing section for measuring the liquid flow rate and temperature. The particles (glass beads) were mixed into the liquid through a Venturi shaped injector. The flow of liquid with particles in a closed loop were separated and re-injected continuously to the test sections after collection in a hydrocyclone. There were two manual control valves for controlling the injection rate of particles into the test sections. The pressure gradient at each test section was measured over a pipe length of 1.5 m using a Rosemount 3051S transducer. The horizontal test section was located 4 m downstream of the injection point to minimize entrance flow effects and to let the liquid-particle patterns become fully developed. The inclined test section 5° had a DS inside the pipe with a possibility of controlling the rotational speed. The DS was a pipe with outer diameter OD = 25 mm filled with a colored water for better visualization. The rotating system connected to the drill string was a Maxon motor (DC 22*L* ϕ22 mm) with an encoder (EN 16) for reading the rotational speed and torque on the driving shaft.

Flow pattern images were recorded with Basler (A800-510) mono and color cameras (500 fps at full resolution 800 × 600 pixels). A strong uniform white light LED panel provided background illumination of the test sections and high contrasts between the particles and background (see more detail in Khatibi et al., 2016b).

2.2. Fluid and particle properties

Experiments were performed with water and an aqueous solution of Poly-Anionic Cellulose (PAC) with concentrations of 1 g/l (PAC1). Anton Paar MCR 302 apparatus with concentric cylinder modification (CC27) was used for rheology measurements (such as shear viscosity and small amplitude oscillation shear (SAOS) tests). Preparation of PAC solutions and rheology measurements were described in previous studies Khatibi et al., (2016a) and Khatibi et al., (2016b) . PAC was provided by M-I SWACO and had the molecular weight of 881 kDa measured by gel permeation chromatography (GPC). Fig. 2 represents the shear viscosity (μ) of water and PAC1 versus the shear rate ($\dot{\gamma}$). Water is a Newtonian fluid with a fairly constant viscosity, while PAC1 features shear-thinning characteristics as the viscosity decreases with increasing the shear rate. Power-law (PL) and Cross (Cr) models were used for curve fitting of the rheology data as shown in Eqs. (1) and (2), respectively. However, both models are focused on measuring the viscosities at both low and high shear rates, so that time-dependent and viscoelastic behavior are not considered in these models. In addition, the error of measurement was higher at low shear rate due to very mechanical noise at small angles of torque and angular displacement (see also Khatibi et al., 2016a).

$$\mu = \kappa \dot{\gamma}^{n-1} \tag{1}$$

Here κ and n are the consistency factor and the power–law index, respectively.

$$\mu = \frac{\mu_0 - \mu_\infty}{1 + (c\dot{\gamma})^m} + \mu_\infty \tag{2}$$

Here c and m are the Cr model parameters; μ_0 and μ_∞ are the zero-shear viscosity and the infinity-shear viscosity, respectively.

The viscoelastic properties of PAC1 were studied in SAOS tests. Strain amplitude sweep and frequency sweep were performed to determine the linear viscoelastic (LVE) region at low strain amplitude and also to indicate the viscoelastic properties of the sample. Fig. 3a shows the result of amplitude sweep for PAC1 over a given

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