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Utilizing Instrumented Stand Pipe for Monitoring Drilling Fluid Dynamics for Improving Automated Drilling Operations

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Abstract: This paper introduces a method to enable automatic updates of the density, compressibility and frictional effects of the drilling fluid during a drilling operation. By placing pressure sensors along the circulation path from the mud pump to the connection to the drillstring, the fluid dynamics can be examined more thoroughly at various flow rates and pressures. This will help filling the gap of reliable data on drilling fluid properties, which is of great importance in automated drilling operations.

Keywords: Drilling automation, pressure measurements, density measurements, flow measurements, pressure control

1. INTRODUCTION

A schematic of a conventional drilling system is shown in Figure 1. The system consists of a rotating drillstring with a drilling bit at the bottom. The volume that develops around the drillstring as the well is drilled is referred to as the annulus. Drilling mud is pumped from a pit tank, down the drillstring, through the bit, up the annulus, and back into the pit tank. The purpose of the drilling mud is to transport cuttings from the bottom of the well, and to create a certain pressure balance in the well. The pressure in the well during a conventional drilling operation is managed by the density and the flow rate of the drilling fluid.

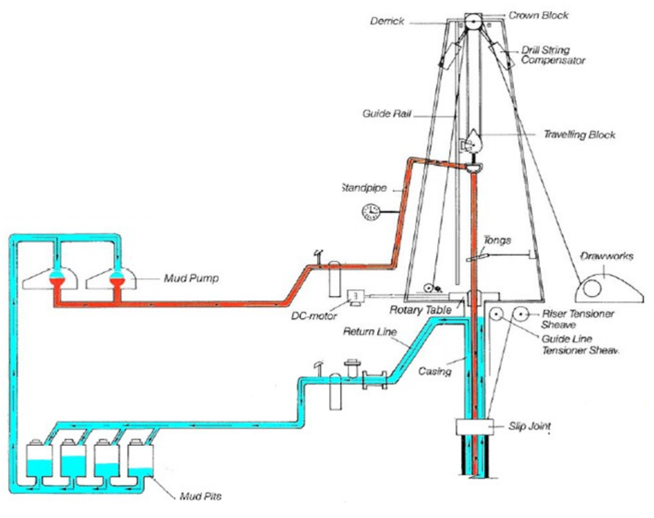

Fig. 1 A conventional drilling system

The drilling fluid is the primary barrier in the effort of avoiding unintended influx of hydrocarbons during drilling operations. Nevertheless, two of the main parameters of the drilling fluid, namely rheology and density, are typically only measured manually in intervals of 15 minutes. The reason for this is that it is deemed as standard practice both by drilling contractors and authorities. This might have been sufficient for traditional drilling operations performed some decades ago, but today's drilling operations utilizing specialized drilling fluid components such as balanced mud pills and drilling fluid spacers challenge the accuracy and timing for performing drilling fluid measurements.

The lack of drilling fluid dynamics data is a challenge for automated drilling operations involving pressure control, for example managed pressure drilling (MPD) operations. According to Godhavn (2009), if a hydraulic model is used real time to provide a choke pressure set point that will result in the desired downhole pressure, online updates of the mud properties is needed. Also advanced observers for downhole pressure estimation and kick detection (Zhou, 2010), and automated well control operations (Carlsen, et al, 2012) are dependent on online mud properties updates.

This work presents how more accurate and automatic measurements of the drilling fluids parameters can be collected and used, utilizing the instrumented standpipe using differential pressure transducers (Nygaard, 2011). The paper also tries to answer why these new measurements should become standard for defining the drilling fluid properties during drilling operations, allowing the drilling industry to make both the mud balance and the mud funnel superfluous.

Utilizing differential pressure for measuring flow rates and mud densities has been used in other industries for decades due to automation system requirements. Since drilling fluid operations to a large extent is performed manually, there has been less need for this online fluid measurement. As drilling operations now are becoming more automated this concept has emerged as a new tool for automating the drilling process (Nygaard, 2011). With exception of this publication, no previously published work has been found describing this measurement concept for drilling operations.

2. DRILLING FLUID INSTRUMENTATION

The pressure balance between the wellbore pressure and the formation pressure is one of the most important conditions being monitored during drilling operations. The pressure in the wellbore consists of two components, the hydrostatic pressure and the dynamic fluid pressure loss. The hydrostatic pressure P_h at a certain depth is calculated as

$$P_h = \rho g h \tag{1}$$

Here ρ is the density of the mud, g is the gravitational acceleration constant, and h is the vertical depth.

When calculating the frictional pressure loss in the drillstring and annulus, the viscosity of the drilling fluid is an important parameter. The viscosity μ of a Newtonian fluid is given by the ratio of the fluid shear stress τ and the shear rate γ (Mott, 2006) and and (API 2010).

$$\mu = \tau / \gamma \tag{2}$$

If the viscosity of a fluid is known, the Reynolds number, defined as

$$\mathrm{Re} = d \upsilon \rho / \mu \tag{3}$$

can be found. Here υ is the fluid velocity in the pipe, d is the diameter of the pipe, and ρ is the density of the fluid. Subsequently, the Reynolds number is used to calculate a friction factor for the fluid in the pipe for turbulent and laminar flow. The (fanning) friction factor for laminar flow is given by

$$f = 16 / \mathrm{Re} \tag{4}$$

For turbulent flow, the most common used method for evaluating the friction factor employs the Moody diagram, where the friction factor is plotted versus the Reynolds number. The pressure loss P_f in the pipe is finally calculated using the friction factor, according to

$$P_f = 2 f \rho \upsilon^2 L / d \tag{5}$$

Here L is the distance length of the pipe. In (Zamora, et al., 2005), (Subramanian, et al, 2000) and (Kelessidis, et al., 2011), the pressure loss in drillpipe and annuli when circulating a drilling fluid is examined thoroughly.

The rheology of drilling fluids is typically non-Newtonian. This gives additional challenges when trying to identify the drilling fluid rheology using measurements of shear stress and shear rate. A need for constantly evaluation of the viscous effect in a drilling fluid is therefore beneficial. The main viscous effect that should be monitored is the frictional pressure loss while the drilling fluid is flowing through the drillpipe. A direct measurement of the frictional pressure loss is therefore proposed instead of measuring shear stress and shear rate.

2.1 Current Instrumentation

Today, the density of the mud is calculated by measuring the weight of a known volume of a sample of the mud. The sample is collected from the mud pit and weighed at atmospheric pressure.

The rheology is measured using a Marsh funnel or a Fann Viscometer. The Marsh funnel, depicted in Figure 2, measures the time a sample of the mud takes to run out of the funnel. The recorded time is then used to identify the rheology of the fluid using a look-up table which correlates Marsh funnel flow duration and the rheology parameters. A more accurate rheology measurement is found using the viscometer, using a rotating device, measuring at various rotational rates.

Fig. 2. Marsh funnel and mud cup

The flow rate of the drilling fluid from the mud pump is measured by counting the strokes from the mud pump. The pump is typically a triplex pump with three pistons pumping the drilling fluid though the system. On each stroke, a fixed volume of fluid is pumped. The definition of a pump stroke is when the three pistons have stroked once. A stroke counter counts the number of strokes per minute, and with the known volume of each stroke, the fluid flow rate per minute is evaluated.

There are several uncertainties regarding this flow measurement. An example is that if one of the pistons stops working, the fluid flow rate will decrease with the volume of one piston stroke. The stroke counter will however still count as if all pistons are working, causing an incorrect mud flow rate reading. The internal valves inside the piston pumps may also leak due to wear and tear. This may cause reduction of the actual flow rate delivered by the pump.

2.2 Instrumented Standpipe

Differential pressure sensors, if properly tested and calibrated, are robust and reliable. The accuracy of these has evolved considerably the last two decades. The accuracy of an off-the-shelf differential pressure sensor is specified to be 0.045% FS (SMAR, 2006), and with a full scale (FS) of 1 bar, the accuracy will be 0.45 mBar. At these accuracies the analogue to digital signal conversion is important. The conversion should be handled using a 14 bit AD circuit giving a numerical resolution of less than 0.06 mBar.

The idea behind the instrumented standpipe is to place accurate differential pressure sensors along the circulation path from the mud pump to the connection to the drillstring. The frictional pressure drop across a pipe section with diameter *d* and length *L* can then be found and used to estimate the frictional pressure drop across a pipe section with arbitrary diameter *d* and length *L*.

Instead of measuring the rheology using a viscometer and then calculating the frictional pressure drop the fluid will have along a certain drillpipe section, it is both easier and more accurate to measure the frictional pressure drop directly.

Using the setup in Figure 3, the drilling fluid properties can be examined more thoroughly and also calibrated towards water. As the main rig pump is available during pipe connections, the valve in the top of the standpipe can be manipulated, sending the flow in the return line where an adjustable choke valve is placed. By pumping flow in this inner loop, the frictional pressure loss and density at different flow rates and pressures can be found. By having an automatic setting of the flow rate and automatic adjustment of the choke valve, then a pre-programmed sequence of flow rate and backpressure can be performed while measuring the pressure along the flow path. Based on these examinations, a table of frictional pressure loss and densities at various pressures and flow rates can be found.

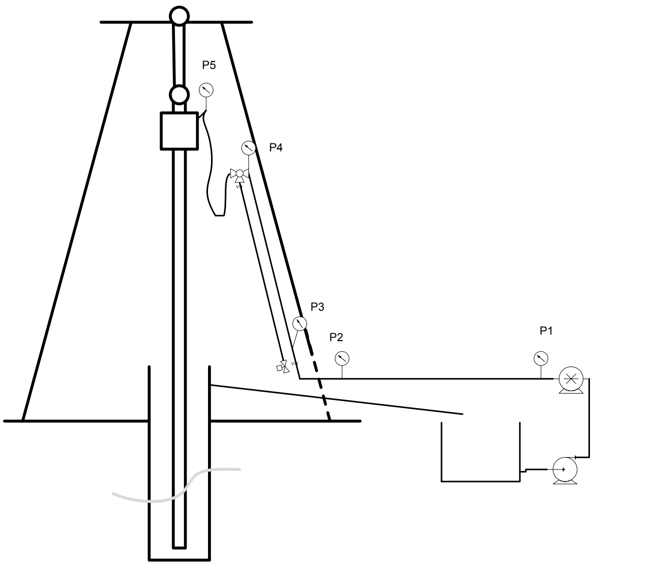

Fig. 3. Drilling rig schematic showing fluid flow loop. Pressure measurements installed on the standpipe. P1 is the pump pressure, P2 is the lower standpipe pressure, P3 is the upper standpipe pressure and P4 is the swivel pressure.

The frictional pressure drop across the horizontal section is the pressure difference $P_{h,f}$ = P1-P2 (see Figure 2). The frictional pressure drop across this section is given by (5), with L as the distance between P1 and P2, and d as the diameter of the pipe section. The (Fanning) friction factor f for the fluid in the pipe, given by

$$f = P_{h,f} d / 2\rho \upsilon^2 L \tag{6}$$

can be found for turbulent and laminar flow at various pressures, fluid densities and fluid velocities, and used to calculate the frictional pressure drop across a pipe segment with an arbitrary pipe length *L*, and diameter *d*.

In the vertical section, the fluid density ρ can be found as

$$\rho = (P_3 - P_4 - P_{v,f}) / hg \tag{7}$$

where P3 is the pressure at the bottom of the vertical section (see Figure 3), P4 is the pressure at the top of the vertical section, $P_{v,f}$, is the frictional pressure drop between P3 and P4, and h is the height between the two points. It is assumed that the friction factor f is equivalent in the horizontal and the vertical section so that $P_{v,f}$ can be found using equation 5 once the friction factor is known. By adjusting the fluid flow rate and the opening of the choke valve at the outlet, the density at various pressures can be found.

Differential pressure measurements can also be used to calculate flow rates. Typically, a flow meter is utilizing pressure drop across a restriction in the flow path to calculate the flow rate. By measuring the differential pressure across the elbow section of the piping, the flow rate may be calculated. In this set-up flow rate may be calculated by measuring the pressure drop across the elbow section P2-P3 (see Figure 2). This way of finding flow rate is indicated as a possibility, but has not been examined further in this paper. There exists several ways of measuring flow rate easily and accurately using flow meters, such as venturi meters. These flow meters can be placed on the suction side of the pump.

3. SIMULATION SETUP

The simulations performed in this paper are evaluated using a detailed multiphase fluid model (Nygaard et al., 2007), modeling both the wellbore dynamic pressure, temperature and velocity effects. This model has been tested during several offshore drilling operations.

To evaluate the potential of the instrumented standpipe concept, simulations of the instrumented standpipe flow loop in Figure 3 have been performed. A mud pump is pumping drilling fluid through a horizontal and a vertical pipe section with a choke valve at the outlet. By running the mud pump at various flow rates and varying the choke opening, the mud density and frictional coefficients have been found at various flow rates and pressures.

Simulations have also been performed using a full scale well to simulate the frictional effects in the drillstring when pumping a drilling fluid. The frictional pressure losses found in the drillstring during the full scale simulations when running with various pump rates are compared to the theoretical calculations of pressure losses found using the frictional coefficients found during the instrumented standpipe simulation.

3.1 Instrumented Standpipe Simulations

The simulations of the instrumented standpipe flow loop used to simulate the flow loop in Figure 3 have been performed using a pipe with a vertical and horizontal section with a total pipe length of 90 meters. The distance between the pressure sensors in the horizontal section and the vertical section is 20 meters. Drilling mud is circulated through the pipe with an adjustable choke at the outlet. The drilling fluid is an oil based mud with a density of 1580 kg/m^3. Table 1 summarizes the details about the instrumented standpipe geometry and fluid.

Table 1. Instrumented standpipe data

Parameter	Value	Unit
Pipe length	90	m
Vertical height	48	m
Length between P_1 and P_2	20	m
Length between P_3 and P_4	20	m
Pipe inner diameter	0.1	m
Mud density (atmospheric pressure, 40° C)	1580	kg/m^3

During the simulation, the mud flow rate is ramped down from 2000 l/min to 0 l/min in steps of 250 l/min. Flow rate noise, taken from a real full scale experiment using a rig pump, is added to the flow rate input in the simulator. The simulator calculates pressure along the pipe for the various flow rates. Figure 4 shows the flow rate, the pressure from sensors P1, P2, P3, P4, and the pressure difference between sensor P2 and P1 in the horizontal section. Special consideration must be taken into account when signal noise effects cause negative pressure difference.

The friction factor f_d in the pipe has been calculated at the various flow rates using (6), with $P_{h,f}$ as the difference between pressure P1 and P2 in the horizontal section, L=20 meter and d=0.1 meter. The friction factor has been found by averaging samples from each flow rate level. Figure 5 shows the result of f_d versus flow rate. The friction factor f_d versus pump pressure is also shown since the choke is adjusted to obtain equivalent pump pressure values as when pumping through the full scale well.

The fluid density derived from (7) using the friction factor f_d and the pressure measurements P3 and P4 is depicted in Figure 6 at various pressures, together with the true fluid density as given by the simulator based on PVT input data.

The viscosity and shear stress properties for the fluid has been calculated using equations (6), (4), (3), and (2), with $P_{h,f}$ as the difference between pressure P1 and P2 in the horizontal section. The results for laminar flow are shown in Figure 7, together with the real rheology values from viscometer measurements, measured at various rotational rates and used by the simulator.

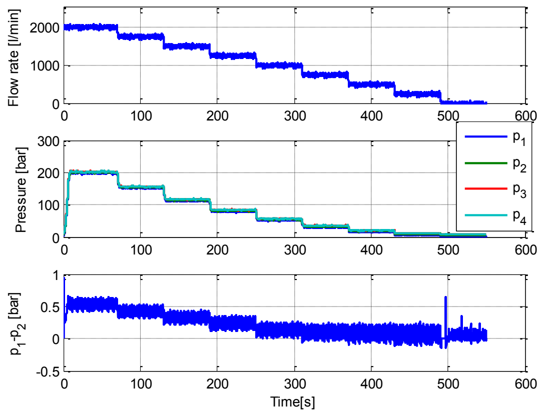

Fig. 4. Flow sweep in instrumented standpipe loop. Upper plot: Flow rate (l/min). Middle plot: Pressure (bar) from sensors P1, P2, P3, and P4. Lower plot: Pressure difference between P1 and P2.

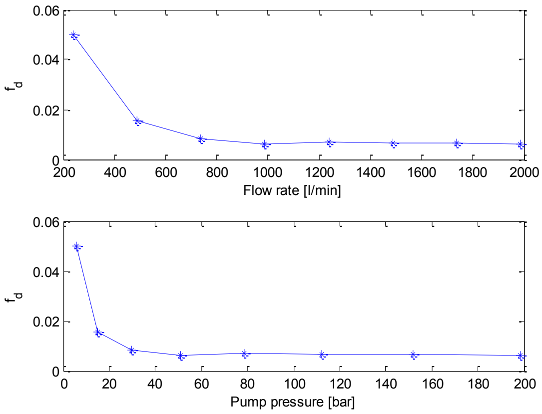

Fig. 5. Instrumented standpipe simulation. Upper plot: Friction coefficient f_d versus flow rate. Lower plot: Friction coefficient f_d versus pump pressure.

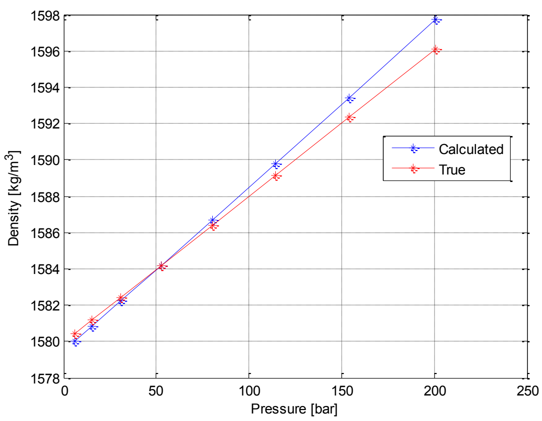

Fig. 6. Instrumented standpipe simulation. Mud density at various pressure values.

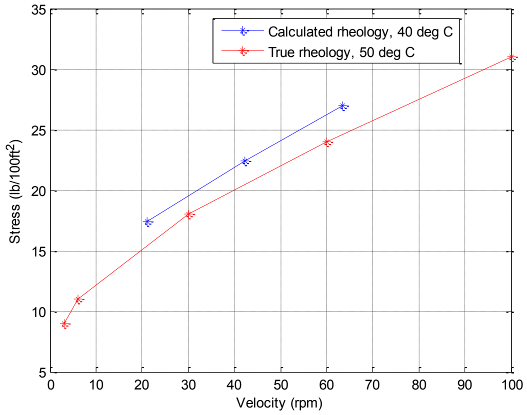

Fig. 7. Instrumented standpipe simulation. Mud shear stress versus rotational rate. True values at 50°C (red), and calculated values at 40°C (blue).

3.2 Full Scale Simulations

Simulations of a full scale well have been performed using drillpipe, well and mud data from a North Sea well. The drilling mud used in the simulation is identical to the mud used in the instrumented standpipe simulation. A pressure sensor P1 is placed in the interior at the top of the drillpipe and a sensor P2 in the interior at the bottom of the drillpipe. There is no BHA in the drillpipe. Details about the pipe and the drilling mud are given in Table 2 and the well trajectory is depicted in Figure 8.

Table 2. Full scale pipe

Parameter	Value	Unit
Pipe length	1951	m
Vertical height	1725	m
Length between P_1 and P_2	1800	m
Pipe diameter	0.1	m
Mud density (atmospheric pressure, 40° C)	1580	kg/m^3

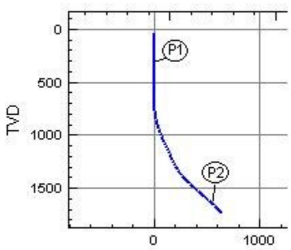

Fig. 8. Full scale simulation. Well trajectory.

During the simulation, the mud flow rate is ramped down from 2000 l/min to 0 l/min in steps of 250 l/min. The friction factor f_D in the drillpipe has been calculated at various flow rates using (6) with P_f as the difference between pressure P1 and P2, minus the hydrostatic pressure difference. The hydrostatic pressure difference is assumed to be known based on PVT dataset from the instrumented standpipe calculations. Figure 9 shows the result f_D versus flow rate and pressure.

The upper plot in Figure 10 shows the frictional pressure drop P_f in the full scale drillpipe resulting from the full scale simulation (blue) and the calculated frictional pressure drop $P_{f,calc}$ (red) for the full scale drillpipe calculated using (5) with the friction coefficients f_d found in the instrumented standpipe simulation for the various flow rates (depicted in Figure 5). The lower plot shows the difference between the calculated and real frictional pressure drop.

We are using the same simulator for the full scale simulation and the instrumented standpipe simulation. We argue that this will be equivalent to using the same drilling fluid in the instrumented standpipe and in the wellbore. In case a new drilling fluid is used, the calculations may have to be re-iterated. This would account for changes in mud rheology parameters, yield point and temperature effects. Effects of drillstring rotation will not be accounted for.

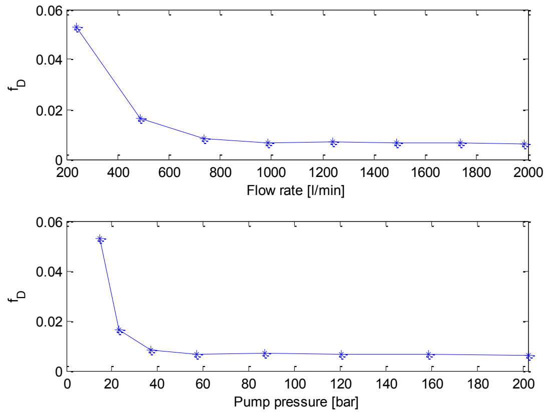

Fig. 9. Full scale simulation. Upper plot: Friction coefficient versus flow rate. Lower plot: Friction coefficient versus pressure

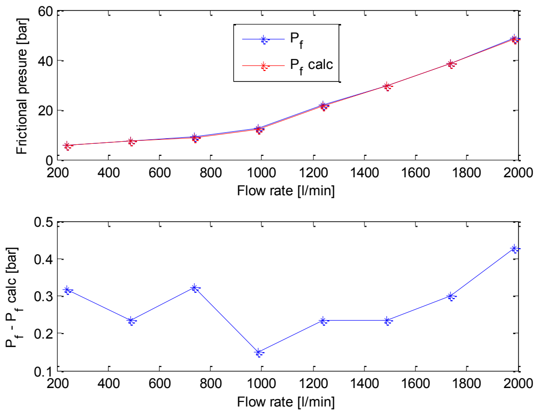

Fig. 10. Upper plot: Frictional pressure drop in full scale pipe from full scale simulation (blue) and calculated frictional pressure drop using friction factor from instrumented standpipe loop (red). Lower plot: Difference between real and calculated frictional pressure drop.

4. DISCUSSION

The results indicate that it is possible to find friction factors for the fluid in the instrumented standpipe loop at various flow rates and pressures. When the frictional pressure drop is known, the density of the mud can be calculated both during periods of zero flow, and also when circulating the fluid through the loop using (7). By adjusting the fluid flow rate and the opening of the choke valve at the outlet, the fluid compressibility effects are found, giving the density at various pressures.

Temperature effects and thixotropic properties must be taken into account when calculating the frictional pressure loss and density in the drillstring. The temperature in the drillstring increase with increasing depth. The rheology of the drilling fluid, and hence the frictional pressure drop in the pipe, usually decrease at higher temperatures, generally with a non-linear effect.

The inner diameter of a drillpipe is not known exactly, and will vary between different pipes. This will influence the correctness of the pressure loss calculations. Pipe roughness will also vary between pipes. In turbulent flow, pipe roughness will increase the friction factor and hence the frictional pressure drop. However, the relative roughness of most drillpipes are low (Zamora et al., 2005), and the Reynolds numbers rarely reach values where the effects of roughness are most significant.

The instrumented standpipe result indicates that it may be used for measuring additional drilling fluid rheology parameters, such as shear stress and viscosity. However, the results should be further compared with current instrumentation, such as the viscometer, in a more detailed study.

The use of instrumented standpipe would be to predict the downhole pressure. Even though the instrumented standpipe data are more accurate than manual recorded data, the model used to predict downhole pressures may still have to be calibrated in order to fit the measured downhole pressures.

5. CONCLUSIONS

In automated drilling, the accuracy and repeatability of the measurement of the drilling fluid properties is important. By using the differential pressure sensors between the pump and the swivel, more accurate density and frictional parameters for the fluid can be found, continuously.

This enables better tracking of viscous pill and other mud changing parameters. The sensor system can easily be calibrated by pumping a calibration fluid (water) in the inner loop during connections. The method also excludes the need for mud balance measurements, Marsh funnel readings and viscosity meter readings.

Results from simulations indicate that instrumented standpipe might have a potential for improved drilling fluid monitoring. The results need to be confirmed by running full scale tests. The full scale test should also include measurements using existing methods such as the mud balance and viscometer to allow a comparison analysis.

REFERENCES

American Petroleum Institute (2010), *Recommended Practice on Rheology and Hydraulics of Oil-well Fluids*, API Recommended Practice 13D, 6th edition, 2010.

Carlsen, L. A., Nygaard, G., and Nikolaou, M. (2012) Evaluation of Control Methods for Drilling Operations with Unexpected Gas Influx, Preprint submitted to *Journal of Process Control*.

Godhavn, J.M. (2009). Control Requirements for High-End Automatic MPD Operations. *SPE/IADC Drilling Conference and Exhibition.* Amsterdam, The Netherlands, 2009.

Kelessidis, V.C., Dalamarinis, P., and Maglione, R. (2011) Experimental study and predictions of pressure losses of fluids modeled as Herschel–Bulkley in concentric and eccentric annuli in laminar, transitional and turbulent flows, *Journal of Petroleum Science and Engineering*, 77 (3-4), 305-312.

Mott, R. L., (2006). Applied Fluid Mechanics. Pearson Education, Upper Saddle River, New Jersey.

Nygaard, G., and Gravdal. J.E. (2007), *Wemod for Matlab's user guide, Tech. Rep. 2007/234*, IRIS, Bergen, Norway, 2007.

Nygaard, G. (2011). Evaluation of automated drilling technologies developed for petroleum drilling and their potential when drilling geothermal wells. *GeoEnergi2011*, Bergen, Norway, 2011.

SMAR LD400 Series Pressure Transmitters, 2006. *SMAR.* [online]. Available at: http://www.smar.com. [Accessed 1 Dec 2011].

Subramanian, R. and Azar, J.J. (2000). Experimental Study on Friction Pressure Drop for NonNewtonian Drilling Fluids in Pipe and Annular Flow. 64647-MS *International Oil and Gas Conference and Exhibition in China,* China, 2000.

Zamora, M., Sanjit, R., and Slater, K. (2005). Comparing a Basic Set of Drilling Fluid Pressure-Loss Relationships to Flow-Loop and Field Data. *AADE National Technical Conference and Exhibition,* Houston, Texas, 2005.

Zhou, J. (2010). Adaptive Observer for Kick Detection and Switched Control for Bottomhole Pressure Regulation and Kick Attenuation during Managed Pressure Drilling. *American Control Conference.* Baltimore, USA, 2010.