DESIGN OF A SLURRY LOOP FOR CUTTINGS TRANSPORT STUDIES IN HARD ROCK DRILLING APPLICATIONS

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ABSTRACT

Transportation of the fluid and slurry (fluid and solid particles mixture) in the pipe and annulus space has been the focus of numerous studies. There are different parameters to be considered when studying slurry transportation. These include slurry velocity or flow rates; fluid properties such as density and rheology; and solid particles properties including concentration, density, shape and size. Also the angle of the flow conduit, rotation of the pipe and possible eccentricity of the annulus are other factors which influence slurry transport characteristics.

Although a number of analytical, numerical and empirical equations as well as numerical simulations have been developed for studying the flow and slurry transport, the results need to be validated against either field or lab data. As performing field tests is costly and time consuming conducting simulations at laboratory scale appears as a good alternative.

Different flow loops have been designed to study the slurry transport in different science and engineering disciplines including oil and gas and mining. However, few of these consider in particular cuttings transportation in small size annulus space. The flow characteristics appear to be very different when it travels within a small size annulus, in particular when the fluid velocity is high.

In this study, a review of some of the existing slurry flow loops will be conducted. Then the details of a slurry loop which has been designed and commissioned for the purpose of studying cuttings transport in a small size annulus space for applications in drilling mineral exploration wells using coil tube technology will be presented.

KEYWORDS

Slurry loop, Cutting transports, Annulus space, Mineral exploration, Lab scale

INTRODUCTION

In mineral exploration, which involves drilling multiple boreholes to map the extent of ore bodies, the operation should be completed as fast as possible and at the lowest possible cost. With this in mind, coiled tube (CT) technology has been proposed for drilling mineral exploration boreholes by the Deep Exploration Technologies (DET) Cooperative Research Center (CRC) (Hillis, 2012). CT is a continuous steel tube coiled over a drum which is straightened by an injector before it is inserted into the wellbore and is placed back onto the reel when recoiled. So, the drilling fluid has to pass through the entire coiled pipe on the reel as well as the straightened section in the well before going through the annulus section. It then carries the cuttings, produced by the bit, to the surface. Figure 1 shows a schematic of the main components of a coiled tubing unit (CTU) and also illustrates the flow path through the straitened pipe as well as cuttings transport inside the annulus space after exiting the bit.

This technology has been used in the oil and gas industry but mainly for work-over operations (Leising & Newman, 1993). However, past operations have successfully drilled with 2 7/8 inch (Littleton, Nicholson & Blount, 2010) and 2 5/8 inch (Perry, 2009) coiled tubes. In applications referred to in this paper coiled tubes of 1.5 to 2 inch diameter are considered for drilling purposes.

Kamyab, Rasouli, Cavanough and Mandal (2012) performed a study of the cuttings transport studies in microborehole coiled tubing drilling for mineral exploration drilling. They highlighted the various differences between oil and gas and mineral exploration drilling. Following this and in their recent laboratory studies they showed the significant effect of concentration of very small size cuttings on drilling fluid rheology. It is important to note that the cuttings expected from drilling hard rocks in mineral explorations are very small as opposed to large size cuttings generated in oil and gas drilling. The change in fluid rheology can consequently result in a larger pressure drop across the annulus.

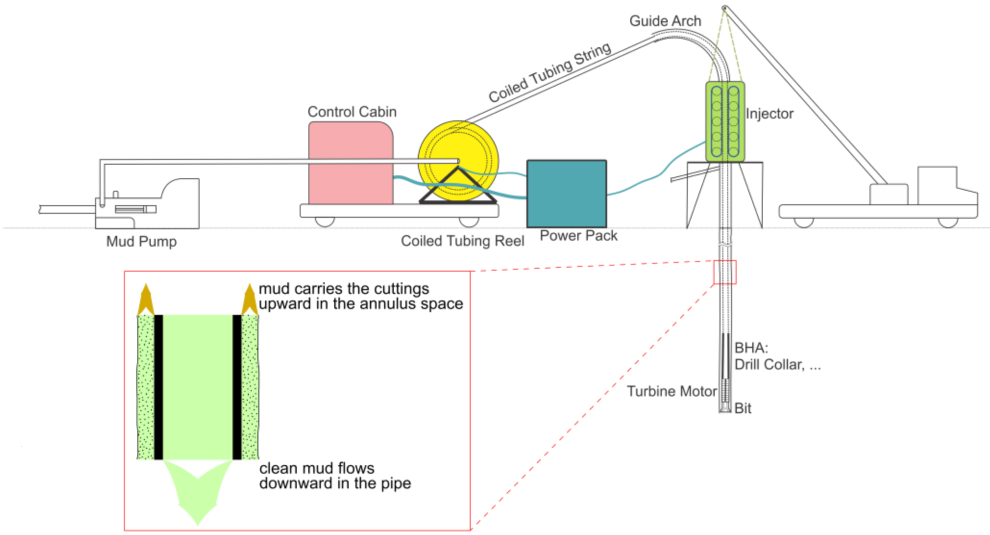

Figure 1 – The main sections of a CTU with diagram of fluid flow in the pipe and annulus space

Due to the importance of the above mentioned finding, performing laboratory experiments in order to investigate various characteristics of slurry containing small size cuttings in a micro-annulus space is an important exercise. In this paper, the details of a slurry loop designed for such studies will be explained. However, before that a brief overview of cuttings transport in microborehole and a review of some of the existing flow loops that have been used in the past are given.

CUTTINGS TRANSPORT IN MICROBORHOLES

In slurry transport, the liquid phase carries the solid particles. An example of this is the cuttings transport in the annulus space in wells drilled in oil and gas or mining industries. However, slurry transport has application in many other fields including foods, pharmaceuticals, chemicals, construction, and power generation industries (Doron, Granica & Barnea, 1987; Eesa & Barigou, 2009; Kelessidis, Bandelis & Li, 2007).

To understand the cuttings transport phenomena, it is crucial to know about the key elements of this process. Assuming no chemical reaction between the solid and the liquid phase, a number of parameters affect the slurry transport including (Doron & Barnea, 1993; Doron, et al., 1987; Hyun, Shah & Osisanya, 2000; Kelessidis & Bandelis, 2004; Li, Bjorndalen & Kuru, 2007; Nguyen & Rahman, 1998):

- transporting conduit: pipe, annulus;
- geometry of the transporting conduit: diameter sizes, roughness, inner pipe rotation speed, eccentricity of the inner pipe in the annulus;
- conduit inclination: vertical, deviated, horizontal;
- carrying fluid properties: density, rheology, amount of solid particles in the fluid;
- concentration of the solid in liquid phase;
- solid particle properties: density, shape, size;
- solid/liquid interaction: slip;
- solid/solid interaction: interaction in the bed layers;
- velocity (or flow rate) of the slurry and flow regime;
- pressure and temperature;

- time dependency of fluid flow: steady, transient.

In Microborehole CTD, the pondering transporting conduit is the annulus space which has a smaller gap than in the oil industry. In addition rotation of the inner pipe which is assisting the cuttings transport in conventional rotary drilling does not happen. Usually in oil and gas applications, the cuttings concentration is kept under 5% (Albright, Dreesen, Anderson, Blacic, Thomson & Fairbanks, 2005; Kelessidis & Bandelis, 2004). Cuttings sizes in mineral exploration drilling are smaller because the impregnated diamond bit which is used for hard rock drilling generates particle sizes in the order of microns as opposed to the petroleum industry where cuttings are of millimetre size order.

Among different annulus inclinations, horizontal wells are subjected to more challenges in carrying cuttings as the flow direction and gravitational force are acting perpendicularly. This means that the cuttings can settle down easily if the fluid flow does not provide enough energy to suspend the particles.

The major differences between fluid flow and cuttings transport in drilling oil and gas and mining wells are shown in Table 1. In the petroleum industry the annulus clearance (i.e. the space between the hole and the inner pipe) is usually larger than that of microborehole CTD (MBHCTD). In addition, high fluid rate is required to drive the turbine motor in MBHCTD to rotate the bit which in turn creates high speed, more turbulent fluid flow in the annulus space. As a result, the pressure loss is expected to be higher than what is observed in petroleum wells.

Table 1 – Difference between cuttings transport in oil and gas and micro borehole coiled tubing drilling (MBHCTD)

Criteria	Conventional Oil & Gas	Micro Bore Hole CT Drilling
Annulus space	⬤	•
Velocity	•	⬤
Flow regime	laminar	turbulent
Annular pressure loss	⬤	•
Cuttings size	•	⬤
Stokes number(order of magnitude)	1	10^{-3}

The Stokes number is the ratio of characteristic response time of the solid particles to that of the fluid. The particle response time is the characteristic time for the particles to adopt themselves to the abrupt variation in fluid flow (Ansys Fluent Theory Guide, 2011):

$$St = \frac{\tau_p}{\tau_f}, \tau_p = \frac{\rho_p d_p^{\,2}}{18\mu}, \tau_f = \frac{L_s}{V_s} \Rightarrow St = \frac{\rho_p d_p^{\,2}}{18\mu}\frac{V_s}{L_s} \tag{1}$$

In the above equation τ_p is the particles response time, τ_f is the Kolmogorov time scale which is defined as the ratio of the characteristic length (L_s) of a swirl to its characteristic velocity (V_s), ρ_p is the particles density, d_p is the particles diameter, and μ is the fluid apparent viscosity (Ansys Fluent Theory Guide, 2011). As can be seen from the equation (1), the particles size has a major effect on the Stokes number, i.e. smaller particle sizes significantly decrease the Stokes number. Smaller values of this number indicate that the particles are much adoptable to sudden changes to the flow, so easier to transport and do not settle as easily as larger particles tend to in petroleum wells.

Our experimental studies have indicated that in hard rock drilling the effect of small size cuttings on drilling mud rheological properties is noticeable and should be considered. This is contrary to the applications in oil and gas industry where the effect of large size cuttings on drilling fluid rheology is negligible. The results of lab experiments indicated that this effect is more pronounced at higher fluid velocities. This corresponds to the applications in hard rock drilling where high velocity is required to rotate the downhole turbine motor at very high speed for optimized drilling. Using the rheological parameters of the drilling muds obtained from a mineral exploration site, the calculations indicated that pressure drop along the annulus could increase by 15% when the cuttings concentration increases from 0 to 5% considering an annulus size of ID=5cm and OD=7cm.

The above discussions demonstrate the importance of studying flow behaviour of small size cuttings in microborehole annulus space. This was the trigger idea for designing a slurry loop for such studies at lab scale.

EXPERIMENTAL CUTTINGS TRANSPORT STUDIES

Fluid flow loops are designed to understand the single or multiphase flow through a conduit in which the continuous phase is a fluid either liquid or gas. Lab scale experiments for studying flow behaviour, comparing to field scale tests, are more useful as they are less costly and time consuming. A typical slurry loop consists mainly of a pump to circulate liquid, compressor to pressurize and circulate the gas, flow rate measurement unit, and pressure transducers to measure the pressure.

Many fluid flow loops have been designed and used in the past. One of the advanced multiphase fluid flow loops for oil and gas applications has been developed in Tulsa University. Their Advanced Cuttings Transport Facilities (ACTF) include a drilling section of 75 feet long that can be adjusted to inclinations from 0 to 90 degrees (Tulsa Fluid Flow Projects, 2012; Tulsa Drilling Research Projects, 2012).

Figure 2 – The drilling section of Advance Cuttings Transport Facilities (ACTF) of Tulsa University at inclination of 25 degrees (Miska et al., 2004)

Figure 2 shows a view of the ACTF. This set up is at a pilot scale and expensive to run for simple fluid flow studies. Other fluid flow loops have been developed at smaller scales, an example of which is shown in Figure 3 for applications in coiled tube drilling. It is seen that all of the flow loops have a similar design concept but with certain capabilities for the required applications. Table 2 summarizes various literatures related to fluid flow and slurry loop studies. These studies are those which modeled the transportation of the solid particles using a liquid, i.e. slurry transportation. In this paper we present the setup of a new slurry loop design which we developed for flow studies of small size cuttings in microboreholes for applications in mineral exploration drilling.

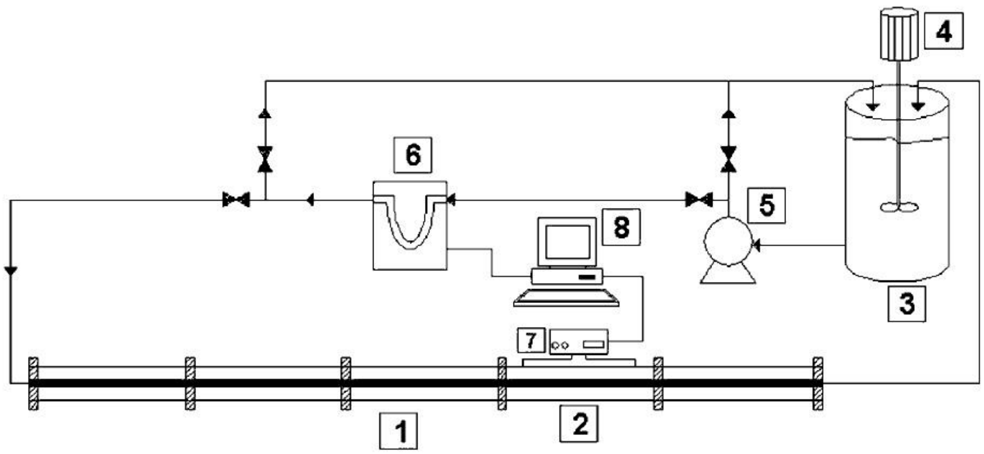

Figure 3 – Schematic of a slurry loop designed for oil drilling applications (Kelessidis and Bandelis, 2004)

Table 2 – Some literature studies on slurry flow in pipe and annulus space

reference	investigation method	V(m/s) or Q (l/s)	hole ID (mm)	inner pipe OD (mm)	particle specific gravity	particle size (mm)
(Doron, et al., 1987)	num, lab, comp	0-3.5 m/s	50	-----	1.24	3
(Nguyen & Rahman, 1998)	num, comp	0-1.22 m/s	48	127	2.62	6.35
(Hyun, et al., 2000)	num, comp	0-1.83 m/s	48	127	2.62	6.35
(Kelessidis & Mpandelis, 2004)	lab	NA	70	40	2.59	2
(Ramadan, Skalle & Johansen, 2003)	num, lab	1.5-4.2 l/s	70	-----	2.6	0.125-5.5
(Bandelis & Kelessidis, 2006)	lab	NA	NA	NA	NA	NA
(Li, et al., 2007)	num, comp	1.7-38 l/s	114	203	2.6, 2.7	1-24
(Kelessidis, et al., 2007)	lab	0-2.32 m/s	70	50	NA	2
(Eesa & Barigou, 2009)	CFD, lab	0.025-0.125 m/s	45	-----	1.02	2-9
(Al-Kayiem, Zaki, Asyraf & Elfeel, 2010)	CFD	38-57 l/s	250	127	2.57	2.54, 4.45, 7
(Xiao-le, Zhi-ming & Zhi-hui, 2010)	num	60, 80 l/s	NA	NA	NA	NA

Abbreviations: num: numerical; comp: compared with others' models.

DEVELOPED SLURRY LOOP

Figure 4 shows schematic of fluid flow loop designed for studying small size cuttings transport in microborehole annulus space. The flow loop is designed to be 1:1 scale to the field; therefore the same field annulus size will be tested in the lab.

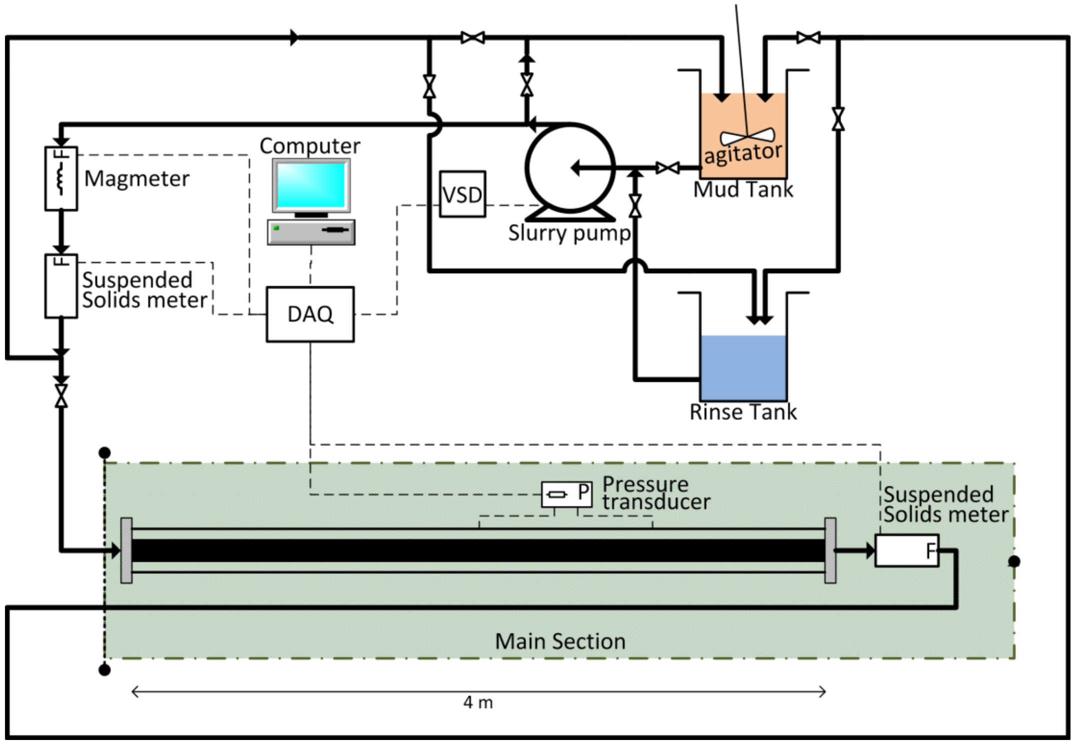

Figure 4 – Schematic of developed slurry loop

The liquid (drilling mud) is prepared at the mud tank with the capacity of holding 1380 litres of drilling fluid. To prepare the drilling fluid, firstly the tap water is used as the base liquid and solid or liquid additives are added to obtain required properties for the mud. Then, cuttings are added to the mud to prepare the slurry (liquid–solid mixture) with desired concentrations of cuttings. A rinse thank with the capacity of 745 litres is used to clean the loop in order to avoid accumulation of the cuttings and solid particles along the pipes and at the edges.

A Weir Mineral heavy duty slurry centrifugal pump with 22 KW power injects the slurry into the loop. It supplies 50 m^3/h of slurry at 70m head. Due to the erosive nature of solid particles, the impellers of the pump are coated with corrosion resistant materials. A Variable Speed Drive (VSD) is connected to the pump to control the output flow rate of the drilling fluid. This device changes the frequency and voltage required for the pump, and in turn the flow rate.

A Siemens magnetic flow meter (Magmeter) is used to measure the flow rate of the pump. The Magmeter works based on the Faraday's law: when a conductive fluid is passing through a magnetic field, it generates a voltage proportional to its speed. This type of flow measurement instrument gives more accurate values compared to other flow meters.

A WTW ViSolid solid suspended meter measures the amount of solids suspended in the flow stream and then the flow goes to the annulus section. A second suspended solids meter measures particle concentrations after it leaves the annulus; so it is possible to calculate the amount of cuttings settled in the annulus space.

The annulus space consists of two pipes: two 2-meter transparent Cast Plexiglass tubes with an inner diameter of 80 mm, and a PVC pipe as the inner pipe with outside diameter of 2 in (= 50.8 mm). The latter is replaceable with any real pipe if need be. The flow goes to inner pipe and enters to the annulus space through small holes designed in the pipe. It then goes back to the inner pipe when it reaches to the end of annulus space. The annulus section is shown in Figure 5. This section can be set in different angles from horizontal to vertical to test slurry flow behaviour at different hole inclinations. The transparent outer pipe is useful to visually trace the cuttings flow path along the annulus space

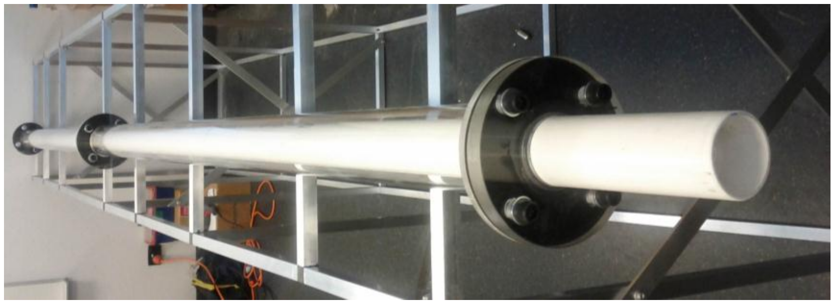

Figure 5 – The main section (annulus) of the flow loop

A Validyne variable reluctance differential pressure transducer measures the pressure difference between two points along the annulus space which are located at a distance of 1 meter from each other. The pressure range of the device is 14 KPa.

The size of cuttings which will be used for experiments varies from 1–100 micro metre with their density being approximately 2.7 gr/cc. However, other solid particle sizes and densities can be tested for comparison purposes.

Error! Reference source not found. shows the view of a small scale flow loop (aka mini flow loop) which was set up for some preliminary qualitative investigation of small size cuttings transport in microborehole CT drilling. In this arrangement the flow rate injected to the coiled tubing is controlled using a bypass line at the pump outlet. Increasing the flow rate helps cuttings to be transported easier through the annulus space. As it can be seen from **Error! Reference source not found.** (right) larger cuttings accumulated at the bottom and smaller cuttings floats to the top of the annulus. This is in agreement with the Stokes number concept which indicates smaller cuttings follow and adapt themselves to the main flow steam easier than larger cuttings.

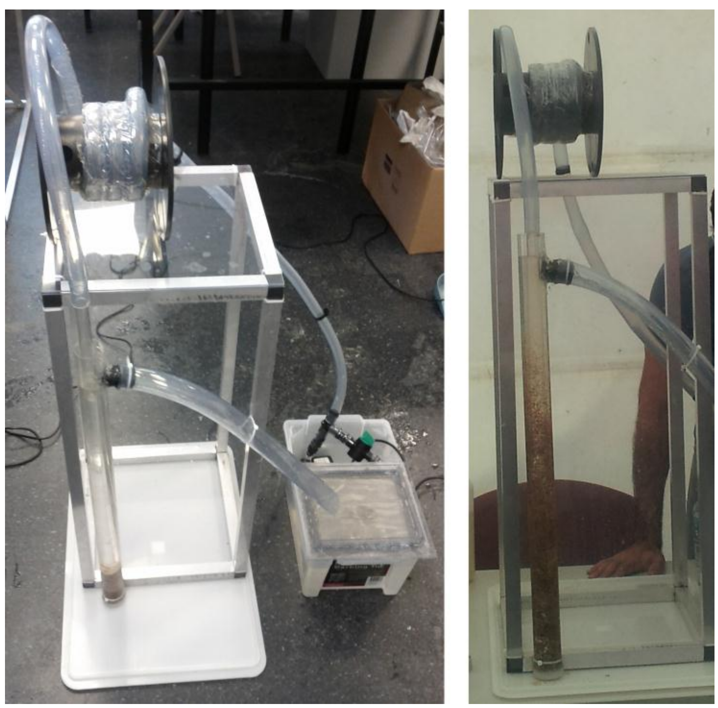

Figure 6 – Mini flow loop designed for qualitative demonstration of cuttings transport in microboreholes using coiled tubing (left). Smaller cuttings are easier to be transported in the annulus space as it can be seen the bigger particles are accumulated at the bottom (right).

CONTROLLING PARAMETERS

During the experiments using the designed slurry loop, the following parameters can be controlled in order to simulate the field situation more closely:

- Fluid: the properties of the drilling fluid (mud) such as weight and rheological properties in the mud tank.
- Cuttings: the properties of solid particles such as concentration, size, density and shape in the mud tank as well.
- Slurry flow rate: changing the frequency and voltage of the pump using a VSD can control the flow rate in the system. Then, the value of flow rate will be measured using the Magmeter.
- Annulus size and pipe type: the size of the annulus space and the material for the pipe can be changed wither by changing the inner or outer pipe properties.
- Hole inclination: the inclination of the hole can be changed from horizontal to vertical.

By changing the above controlling parameters, the pressure loss can be measured using pressure transducer. Also, the amount of cuttings deposited in the annulus space can be measured: this is proportional to the differences between the solid concentrations recorded at the two solid suspended meters.

CONCLUSIONS

In this paper the differences between fluid flow characteristics in petroleum and mineral exploration wells were discussed. It was explained that concentrations of small size cuttings in small size annulus space will change the fluid rheology when drilling hard rocks. To study the flow characteristics at lab scale the detail specifications of a slurry loop which has been designed were presented. The slurry loop allows measurements of pressure drop, volume of cuttings settlement and other parameters.

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REFERENCES

Al-Kayiem, H. H., Zaki, N. M., Asyraf, M. Z., & Elfeel, M. E. (2010). Simulation of the cuttings cleaning during the drillling operation. *American Journal of Applied Sciences, 7*(6), 800-806. doi: 10.3844/ajassp.2010.800.806

Albright, J., Dreesen, D., Anderson, D., Blacic, J., Thomson, J., & Fairbanks, T. (2005). Road map for a 5000-ft microborehole: Los Alamos National Laboratory.

Ansys Fluent Theory Guide. (2011).

Bandelis, G. E., & Kelessidis, V. C. (2006). Solid bed erosion by liquids flowing in horizontal concentric annulus.

Doron, P., & Barnea, D. (1993). A three-layer model for solid-liquid flow in horizontal pipes. *International Journal of Multiphase Flow, 19*(6), 1029-1043. doi: 10.1016/0301-9322(93)90076-7

Doron, P., Granica, D., & Barnea, D. (1987). Slurry flow in horizontal pipes-experimental and modeling. *International Journal of Multiphase Flow, 13*(4), 535-547. doi: 10.1016/0301-9322(87)90020-6

Eesa, M., & Barigou, M. (2009). CFD investigation of the pipe transport of coarse solids in laminar power law fluids. *Chemical Engineering Science, 64*(2), 322-333. doi: 10.1016/j.ces.2008.10.004

Hillis, R. (2012). Uncovering the future of drilling. *The AusIMM Bulletin*.

Hyun, C., Shah, S. N., & Osisanya, S. O. (2000). A three-layer modeling for cuttings transport with coiled tubing horizontal drilling.

Kamyab, M., Rasouli, V., Cavanough, G., & Mandal, S. (2012). *Challenges of cuttings transport in micro borehole coiled-tubing drilling for mineral exploration.* Paper presented at the Petroleum 2012, Koya, Kurdistan, Iraq.

Kelessidis, V. C., & Bandelis, G. E. (2004). Flow patterns and minimum suspension velocity for efficient cuttings transport in horizontal and deviated wells in coiled-tubing drilling. *SPE Drilling & Completion*, *19*(4), 213-227. doi: 10.2118/81746-PA

Kelessidis, V. C., Bandelis, G. E., & Li, J. (2007). Flow of dilute solid-liquid mixtures in horizontal concentric and eccentric annuli. *Journal of Canadian Petroleum Technology, 46*(5), 56-61. doi: 10.2118/07-05-06

Kelessidis, V. C., & Mpandelis, G. E. (2004). Hydraulic parameters affecting cuttings transport for horizontal coiled tubing drilling.

Leising, L. J., & Newman, K. R. (1993). Coiled-Tubing Drilling. *SPE Drilling & Completion*, *8*(SPE 24594-PA), 227-232. doi: 10.2118/24594-PA

Li, Y., Bjorndalen, N., & Kuru, E. (2007). Numerical modelling of cuttings transport in horizontal wells using conventional drilling fluids. *Journal of Canadian Petroleum Technology, 46*(7). doi: 10.2118/07-07-TN

Littleton, B., Nicholson, S., & Blount, C. (2010). Improved drilling performance and economics using hybrid voiled tubing unit on the Chittim Ranch, West Texas.

Miska, S. Z., Reed, T., Kuru, E., Takach, N., Ashenayi, K., Ahmed, R., ... Al-hosani, A. (2004). Advanced Cuttings Transport Study (pp. 57). Tulsa: The University of Tulsa.

Nguyen, D., & Rahman, S. S. (1998). A three-layer hydraulic program for effective cuttings transport and hole cleaning in highly deviated and horizontal wells. *SPE Drilling & Completion, 13*(SPE 51186), 182-189. doi: 10.2118/51186-PA

Perry, K. (2009). Microhole coiled tubing drilling: a low cost reservoir access technology. *Journal of Energy Resources Technology*, *131*. doi: 10.1115/1.3000100

Ramadan, A., Skalle, P., & Johansen, S. T. (2003). A mechanistic model to determine the critical flow velocity required to initiate the movement of spherical bed particles in inclined channels. *Chemical Engineering Science*, *58*(10), 2153-2163. doi: 10.1016/S0009-2509(03)00061-7

. Tulsa Fluid Flow Projects. (2012) Retrieved 14 December, 2012, from http://www.tuffp.utulsa.edu/facilities.html

. The University of Tulsa Drilling Research Projects. (2012) Retrieved 14 December, 2012, from http://www.tudrp.utulsa.edu/research_facilities.html

Xiao-le, G., Zhi-ming, W., & Zhi-hui, L. (2010). Study on three-layer unsteady model of cuttings transport for extended-reach well. *Journal of Petroleum Science and Engineering, 73*(1-2), 171-180. doi: 10.1016/j.petrol.2010.05.020