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Application of Particle Image Velocimetry (PIV) on Newtonian and Two-phase Slurry Flow through the Annulus

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Abstract - The objective of the study is to visualize the impact of fluid flow rate, fluid rheology, drill pipe rotation and eccentricity of drill pipe on cutting transport, transitional velocity profile, the effect of near-wall fluid turbulence and drag stress with and without the solid cuttings bed to mimic best drilling conditions for horizontal wells in ex-situ conditions. The analysis has conducted using combined techniques of Laser-induced Particle Image Velocimetry (PIV), Seeding/fluorescent tracers tracking, and Refractive Index Matching (RIM). Experiments have been performed on a plant-scale multiphase flow loop. The pipe sections of the flow loop and investigation area were made up of acrylic glass to imagine fluid flow patterns better. Biopolymer Flowzan® is used in different concentrations to obtain non-Newtonian characteristics of the liquid. For PIV analysis, seeding particles of a hollow glass material having a uniform diameter of 20 nm and fluorescent particles of size 20-30 µm were used to track and illuminate particles. A class IV LASER was used to illuminate the flow field inside the RIM box. The premixed seeding and fluorescent particles with the flow were tracked to evaluate the velocity field for the respective interested area by the PIV system. A high-speed CCD Phantom® v7.3 camera was utilized to capture flowing particles under the laser field. Both Laser and camera were placed in the normal position to capture PIV images. The refraction Matching Index (RIM) method was applied to calibrate the system by introducing the same fluid inside the RIM box to avoid the error of particle position in the annulus due to glass-liquid-glass refraction. To evaluate the statistics for the desired velocity field of the flow acquired, data was thoroughly investigated with DaVis 8.4 software. Additionally, the turbulent behavior of the slurry flow has also been identified with high preciseness, and the corresponding characteristics of the suspended particles were also observed at the same time. The velocity field outcomes will suggest that at the bottom of the annulus section, the velocity at the near-wall region deviates from the bulk velocity of the fluid because of the solid accumulation tendency. However, a higher flow rate of the slurry may introduce more suspended solid particles, which can eventually result in a uniform velocity field for the whole annulus section. The fluid flow patterns were altered due to drill pipe rotations and solid particles' helical motion. The rotation of the drill pipe resulted in the solid and tracer particles scattered more uniformly in the annular cross-section, which provided a constructive impression on the cutting transport. This technique provides a better prediction of mass and momentum transfer and identification of velocity profiles and pressure drop gradient in multiphase flow on a large scale.

Keywords: Annulus, PIV, Slurry Flow, Non-Newtonian fluid, Cuttings Transport.

1. Introduction

Exploration and Production of oil and gas deal with fluid flow behaviour, for example, drilling mud entering the drill pipe and transporting the drill cuttings to the surface. Over the past decade, horizontal and extended-reach wells, either toe-up or toe-down, have massively increased [1-2]. Drilling such unconventional off-shore and onshore wells produces stationery cutting beds. The drilling process produces solid cuttings which cannot be removed efficiently from the annulus and effectively taken out through the drilling mud. This may result in a thick bed of solid cutting particles accumulating on the bottom of the annulus [3]. The accumulation of this type of cuttings can cause different well drilling along with well completion operational issues (such as the pipe stuck, excessive torque and drag, wellbore cleaning, lost circulation, additional costs, etc.) [4-6]. Additionally, cuttings can be removed effectively and efficiently in extended-reach wells by pumping fluid at a high flow rate [7]. The effect of this methodology is apparent in short-reach wells. However, it is not feasible in extended-reach wells as a result of certain limitations, including dynamic pressure losses, high drag force, and slow drilling rates. To remove near-wall turbulence requires a complete investigation of the various near-wall turbulent factors.

Our research group has researched two-phase flow [8-13] and multiphase flow [14]. The purpose of the study is to visualize the impact of fluid flow rate[3], fluid rheology [15], drill pipe rotation and eccentricity on cutting transport [16], transitional velocity profile, the effect of near-wall fluid turbulence and drag stress with and without the solid cuttings bed to mimic best drilling conditions for horizontal wells in ex-situ conditions. The analysis has conducted using combined techniques of Laser-induced Particle Image Velocimetry (PIV), Seeding/fluorescent tracers tracking, and Refractive Index Matching (RIM) [17-19].

The purpose of the PIV method is to observe the velocity profile of moving particles with the help of fluorescent particles by taking pictures through a high-speed camera. The calculation of velocity relies on tracking the distance of the movement of a particle during its flow with respect to time. In the PIV system is the camera and the laser are kept perpendicular to each other and aligned correctly.

2. Method and Approach

The study was an experimental and visualization method using the plant scale multiphase flow loop system and the state-of-the-art Laser-induced Particle Image Velocimetry (PIV), Seeding/fluorescent tracers tracking, and Refractive Index Matching (RIM). The main equipment used includes a High-Resolution camera and a high-power diode laser. The Davis software was also used to investigate, process, and generate image profiles.

The window of observation and the use of a transparent fluid need to be implemented for the PIV technique. Our study used the Biopolymer Flowzan® as a non-Newtonian fluid, which is not 100% transparent. For PIV analysis, fluorescent particles of size 20-30 µm mixed with seeding particles of a hollow glass material of a uniform diameter of 20 nm were used to track and illuminate particles. A class High Power Class IV LASER was used to illuminate the flow inside the RIM box and obtain comprehensive visualization images for the research. Additionally, the same fluid was injected in the RIM box to keep the refractive index similar. Furthermore, 5% of solid seedings were used to avoid pipe sticking problems. Also, the agitator was rotated for 20 seconds before the experiment to ensure that equal amounts of solid cuttings reached the annulus. Lastly, 200 images were processed in the Davis 8.4 Software after the completion of every experiment.

2.1. Experimental Facility

Fig. 1 is the experimental setup includes the simple horizontal (that can be transformed into an inclined position) flow loop system installed at Qatar's Texas A&M University. The flow loop system illustrated consists of a 6.16 m long pipe with a 6.4 cm x 11.4cm (2 1⁄2 by 4 1⁄2 in.) inner pipe diameter and outer pipe diameter that acts like the annulus. The total annulus area of this flow loop system is 70.9 cm^2. The flow loop represents a real wellbore behaviour. The outer pipe acts like an annulus made from an acrylic pipe, and the inner rotating pipe acts like a drill pipe composed of PTFE pipe. The outer pipe comprises three sections of 1 m each made of transparent acrylic material to make visualization easy, and two 1 m steel pipes joined with aluminium flanges. The flanges have 180 x 2000 mm dimensions. Each section has the same inner diameter of 4.5 inches. The inner pipe is composed of five 1 m PTFE pipes that have a 2.5 inches outer diameter. The inner rotating pipe behaves like a drill string. It can be put in concentric or eccentric conditions by varying its rotation and position. The whole unit is built on a structure made of aluminium that can be subjected to inclination. The inclination angle can be altered to 150 degrees from the horizontal. It is built to examine the effects of inclination. Specially designed fasteners are incorporated into the unit to secure the frame's position while allowing the system to move in one axis. This allows the system to be manually positioned into an eccentric or concentric position. The system contains a 1000 L capacity (265 gallons) flow tank. It has an agitator fitted inside with an adjustable RPM, between 150-250 RPM. The tank also contains a sensor that sends notifications regarding the volumetric flow rate. A rotor is used for rotating the inner tube between 0-150 RPM. A high-quality and high-speed camera with a High-Power Diode Laser is also installed to capture the behaviour of solids beads.

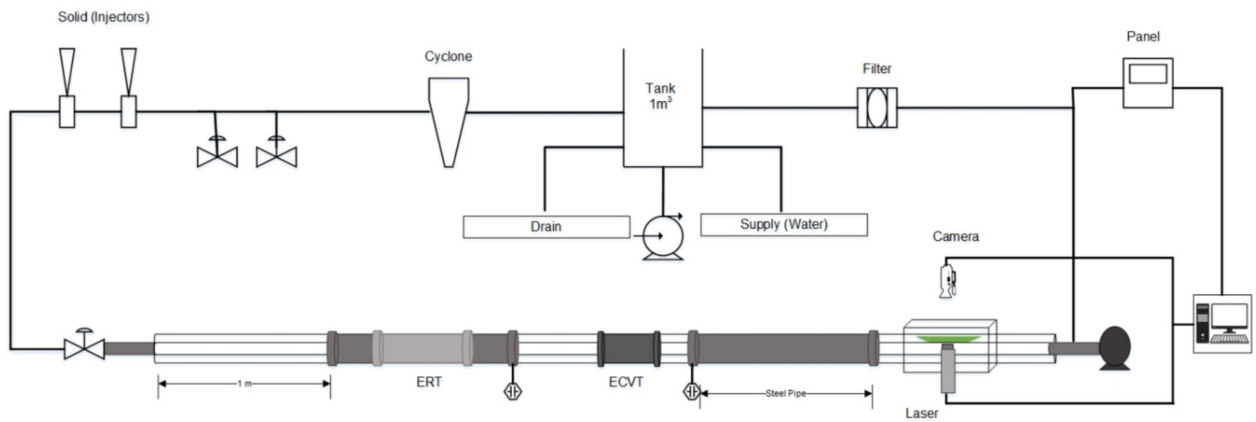

Fig. 1: Illustration of the Flow Loop Facility

Fig. 2 illustrates the RMI, Refractive Index Matching. It is a plexiglass box with a rectangular shape that is fitted around the glass sections' outer pipe to monitor and observe solid cutting behaviour. It is also used for calculating the velocity. The prime reason for using the RIM box is to reduce the effects of pipe curvature.

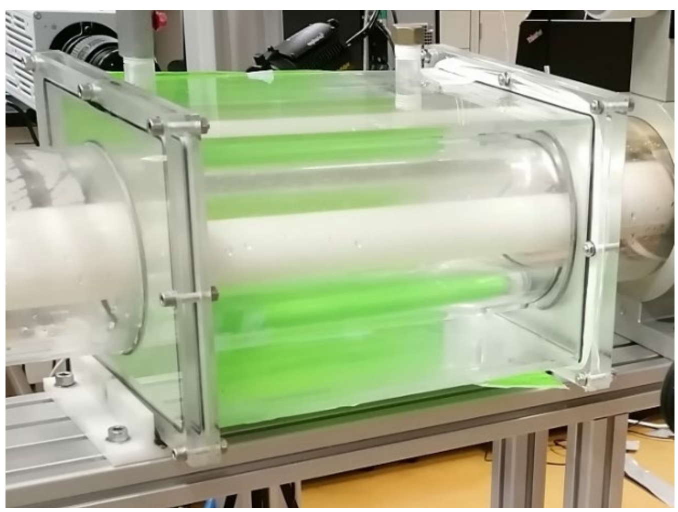

Fig. 2: Refractive Index Matching (RIM) Box

The maximum pressure in the annulus allowing the system to function is 1.0 Barg (15 psig) when air-liquid (two-phase) flows through it and 2.0 barf (30 psig) when only the liquid is flowing. A manual system using locking devices is placed at the top of the tubes is used for achieving eccentric and concentric positions. These experiments were primarily conducted for finding the velocity of the solid particles as they pass through the annulus. The investigation shows a real scenario of the hole cleaning procedure during drilling processes when cuttings solid beds begin accumulating at the bottom of the annulus [17-18]. The Flow Loop System is in a horizontal position at the beginning by default. Although the system can be inclined in either direction (upward or downward). The investigation only covered the annulus being uplifted to 5˚and 10˚from the horizontal.

The cutting concentrations are maintained below 5% to avoid pipe sticking problems. A 4% concentration of the liquid with 2600 Kg/m3 density solid glass beads. Each experiment requires 12 Kg glass beads with some fluorescent particles.

2.2. Experimental Procedure

A mixture of Flowzan and solid glass beads is added to the storage tank of flow loop system. The tank is filled with 300 L of water, then circulated at the desired flow rate. When using the Flowzan mixture, 125g is added for 0.05% concentration.

Solid glass beads with a total mass of 12 kg are passed through the annulus. The inclination motor, incline the flow loop annulus from 0˚to 2.5˚and 5˚(toe-up) and 2.5˚(toe-down). A high-resolution camera and a high-diode laser to visualize the solid beads movement in the bed.

The PIV equipment is kept in correct visualizing zone and the high-speed camera is calibrated to ensure that it focuses on the RIM box. The scaling of the imaging area covers the RIM box. The PIV-Davis software to calibrate the inner pipe area. The laser's diode current is set to 20 Ampere and to on 'ON' mode. The Cycle Rate and Cycling Image Rate is kept at 1 Hz and 1 kHz respectively. The behaviour is observed through the PIV Davis software to take images at all flow rates. During the whole experiment, 200 images were captured within a time span of 10 seconds. Then, during the investigation, as soon as the displacement is calculated, we move toward the instantaneous velocity vector field and generate it. Moreover, the images are pre-processed and then pro processed to understand the behaviour. An interrogating frame of size N×N pixels is chosen from the first image. Then while looking for comparisons, Direct Cross-Correlation Method (DCM) is used and finally identifying the illuminated points as in.

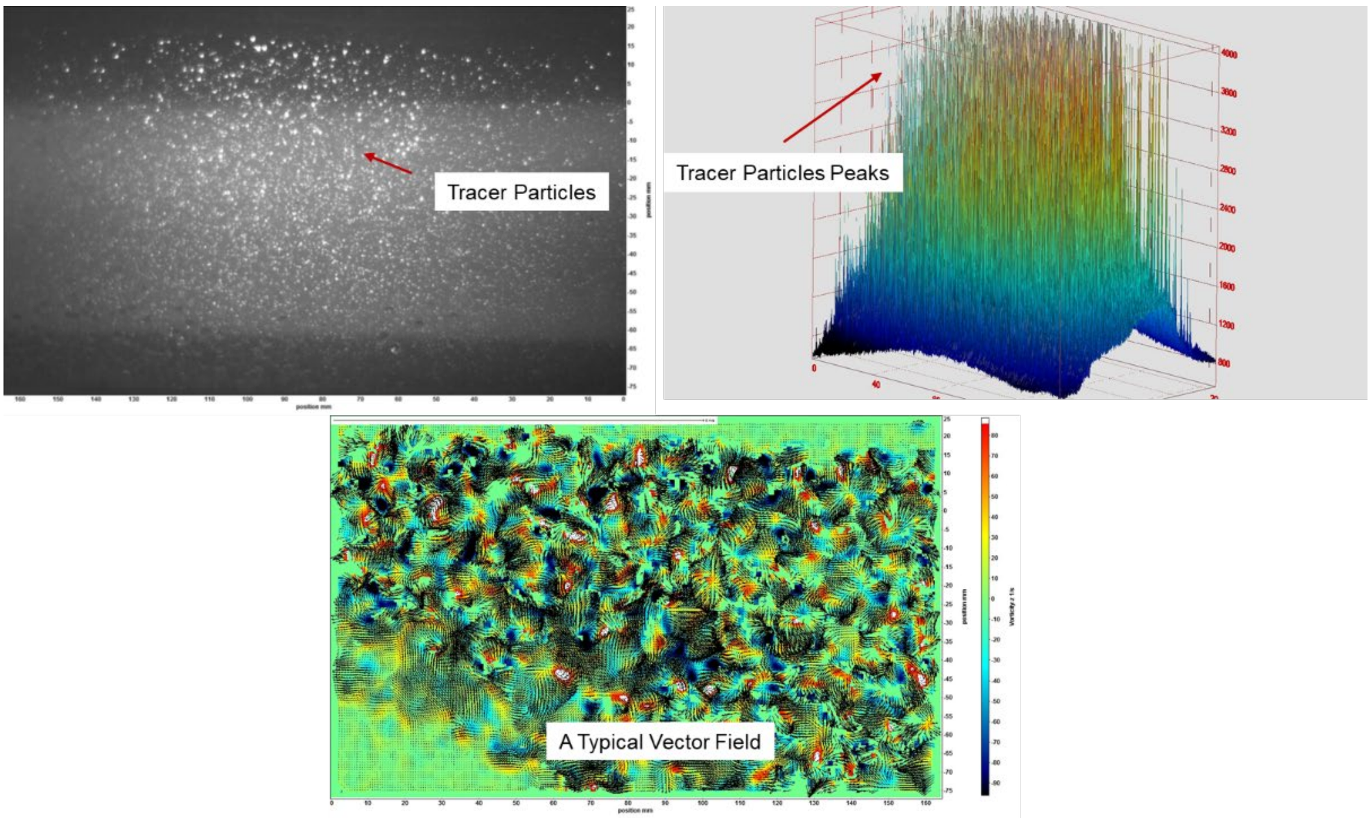

Fig. 3: Pre-Processing PIV Images

2.2. Experimental Matrix

The total of 144 experiments with additional repeat experiments to confirm the obtained results with the set of drilling parameters investigated during the experiment as in Table 1.

Table 1: Different set of drilling parameters investigated during experiment.

Parameters	Ranges
Fluids	Newtonian Fluid (Water) Non-Newtonian Fluid (Flowzan – 0.05% conc.)
Inclination Degrees	Horizontal (0°), Toe-up (2.5°, 5°), Toe-down (2.5°)
Pump RPM	800-1000
Mass Flow Rates (Kg/min)	225, 255, 285
Inner Pipe Positions	Concentric (0), Eccentric (0.3,0.6)
Solid Cuttings	Glass beads (2-3 mm)

The density of the Flowzan used was 995 Kg/m3. The values obtained for every pump RPM, the acquired flow rate, and annular velocity are highlighted in Table 2.

Table 2: Flow rates and annular velocities for Flowzan (0.05% conc.)

Pump RPM	Mass Flow Rate (Kg/min)	Volumetric Flow Rate (L/min)	Annular Velocity (m/s)
800	225	226.131	0.531
900	265	256.281	0.602
1000	285	286.432	0.673

The main interest of this study was velocity profiles. Hence, the Reynolds number value for Flowzan was obtained from Eq. (1) to know whether the result identifies the turbulent flow regime [20].

$$Re = \frac{\rho \mathrm{u} \mathrm{D}_H}{\mu} \tag{1}$$

Table 3: Reynolds Numbers Obtained

Flow Rate Q (L/min)	N_{Re}
226	26978
256	30575
286	34172

The minimum Reynolds number used for different flow rates is 26978 for a flow rate value of 226L/min. Fluids must have a minimum value of 2100 to fulfil the minimum requirement to be categorized as turbulent.

3. Results and Discussions

The black rectangular box represents the distance between the inner pipe and the annulus. At the same time, the red rectangular box represents the solid dune section. The velocity from the 35mm to 200mm section was analysed because the solid behaviour occurred in the 85 mm to 200mm section. As observed in the horizontal case in blue colour, the solid accumulation tended to decrease the velocity and started to make a thin bed. While in 2.5˚ toe-up condition. velocity increase in the initial window represents the uplift force of the particles. Whereas in 5˚ toe-up condition in yellow colour we observed little change in the velocity because the backflow and the uplift force were cancelling each other the bed length was getting longer. On the other hand, at 2.5˚ toe-down case represented with Gray colour in the initial point fluctuate velocity representing the gravitational force overcoming the viscous force.

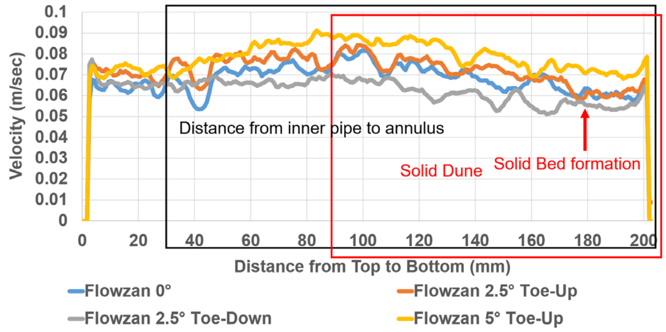

Fig. 4: At concentric condition with 800 RPM Pump Rate

The 900 and 1000 RPM showed prominent behaviour in the velocity change since the solid transport was little quicker. Toe down 2.5 degrees representing the gravitational force impact. While in toe-up 2.5-degree and 5-degree case solid bed was accumulating and showed a decrease in velocity. And high velocity near 80 mm represents the movement of the bed on top of the bed surface.

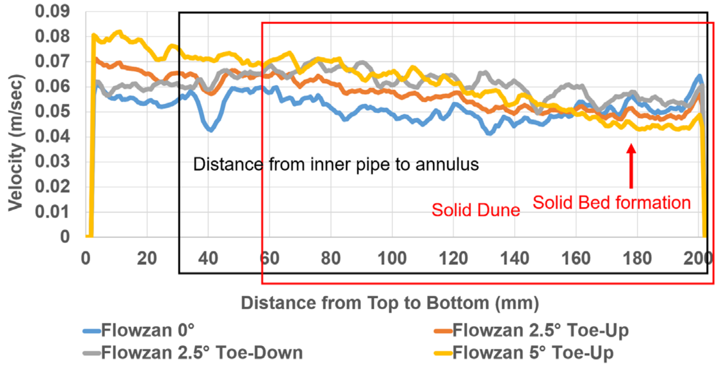

Fig. 5: At concentric Condition with 900 RPM Pump Rate

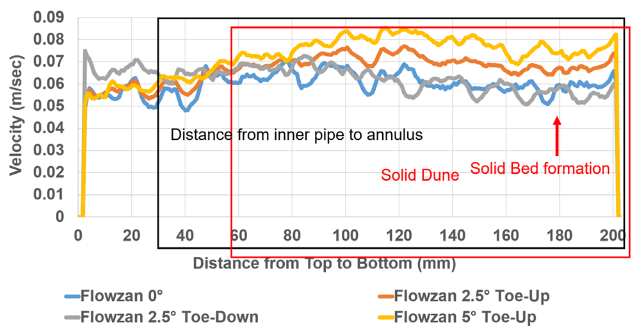

Fig. 6: At concentric Condition with 1000 RPM Pump Rate

At 30% eccentricity in 800 and 900 RPM we saw the bed formation and decrease in velocity near the bottom of the annulus. Additional uplift forces show the high velocity in a 5-degree toe-up case, while in 2.5 up and down, the trends were nearly the same however, additional gravitational force affected 2.5 toe-down to move faster. However, we observe high velocity at 1000 RPM in toe-down due to gravitational force and in 5-degree toe-up due to uplift force and backflow.

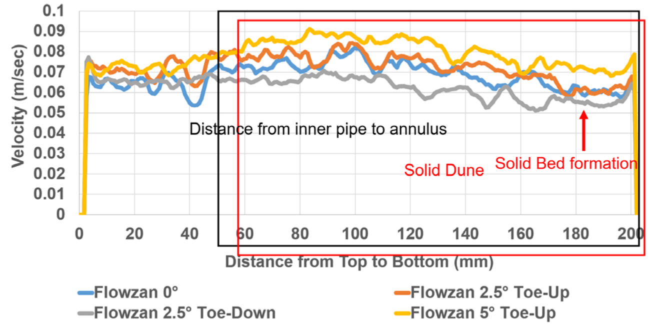

Fig. 7: At 30% Eccentric Condition with 800 RPM Pump Rate

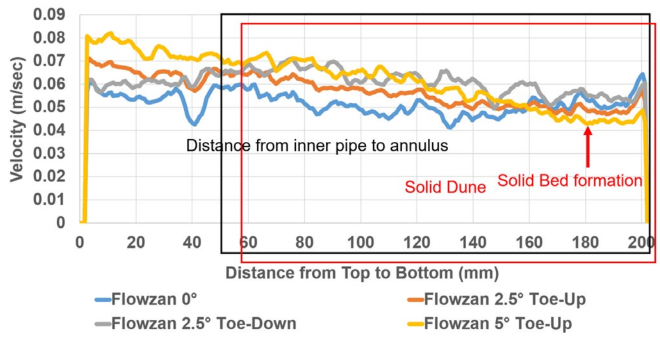

Fig. 8: At 30% Eccentric Condition with 900 RPM Pump Rate

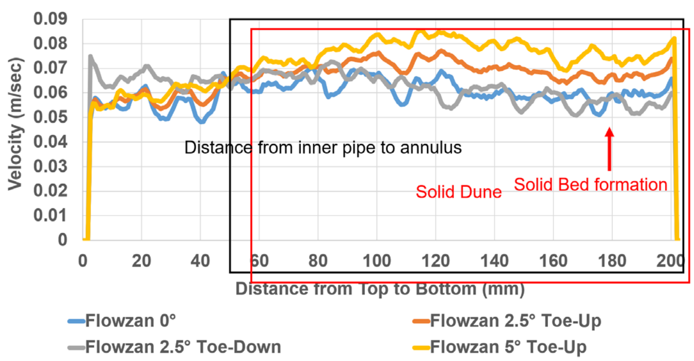

Fig. 9: At 30% Eccentric Condition with 1000 RPM Pump Rate

At 60 % eccentricity and 800 and 900 RPM we saw the bed formation but less bed forming due to the high flow rate. However, we observe high velocity in 900 RPM toe-down due to gravitational force and velocity trend on the top representing backflow creating the velocity less near the annulus. Moreover, we observed high-velocity trend in 1000 RPM 5-degree toe-up 2.5 degrees due to the drag force of the fluid.

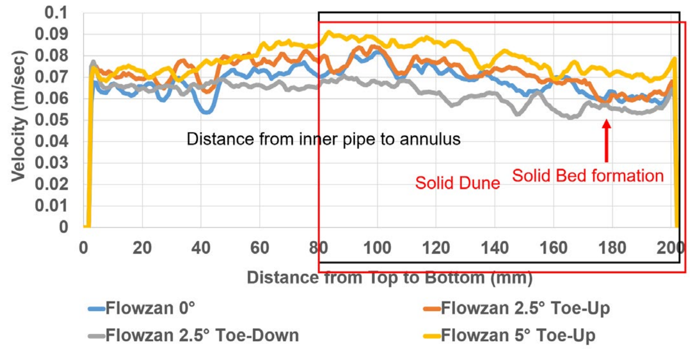

Fig. 10: At 60% Eccentric Condition with 800 RPM Pump Rate

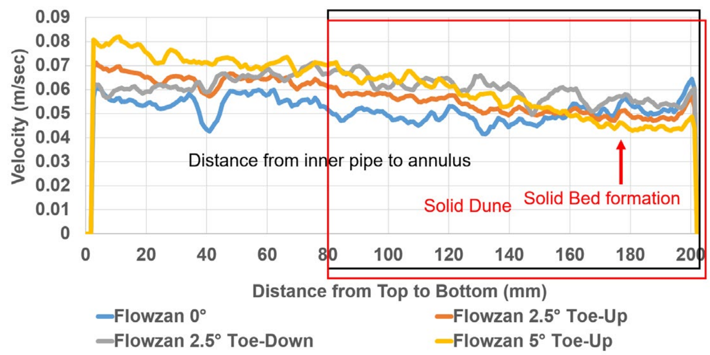

Fig. 11: At 60% Eccentric Condition with 900 RPM Pump Rate

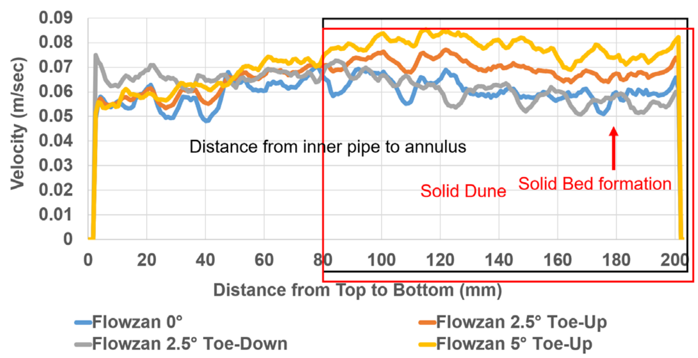

Fig. 12: At 60% Eccentric Condition with 1000 RPM Pump Rate

Conclusion

The difference of eccentricity in both, 30% and 60% eccentricity the cutting transport was faster. The reason for the fast transport was the high-viscous behaviour of the polymer. The gravitational forces possess an important role in the transport of solid cuttings concerning inclination. The solid cuttings transport was fast in toe-down condition as compared to toe-up because of the drag forces, viscous forces, and gravitational forces. In this flow loop system, the critical velocity was found to be at 500 RPM. This is the point at which the flowrate was not supporting the solid bed movement, and a stationary bed was forming.

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References

[1] L. Quintero, M. Azari, and F. Hamza, “Dynamics of Multiphase Flow Regimes in Toe-Up and Toe-Down Horizontal Wells ,” SPWLA 23rd Formation Evaluation Symposium of Japan. p. SPWLA-JFES-2017-M, Oct. 11, 2017.

[2] S. Browning and R. Jayakumar, “Effects of Toe-Up Vs Toe-Down Wellbore Trajectories on Production Performance in the Cana Woodford,” SPE/AAPG/SEG Unconventional Resources Technology Conference. p. URTEC-2461175-MS, Aug. 01, 2016. doi: 10.15530/URTEC-2016-2461175.

[3] S. K. Arnipally, M. M. Hirpa, M. Bizhani, and E. Kuru, “Effect of particle size on the near wall turbulence characteristics and the critical velocity required for the particle removal from the sand bed deposited in horizontal pipelines,” 11th North American Conference on Multiphase Production Technology. p. BHR-2018-443, Jun. 06, 2018.

[4] T. Nazari, G. Hareland, and J. J. Azar, “Review of Cuttings Transport in Directional Well Drilling: Systematic Approach,” SPE Western Regional Meeting. p. SPE-132372-MS, May 27, 2010. doi: 10.2118/132372-MS.

[5] J. Li and B. Luft, “Overview of Solids Transport Studies and Applications in Oil and Gas Industry – Experimental Work,” SPE Russian Oil and Gas Exploration & Production Technical Conference and Exhibition. p. SPE-171285-MS, Oct. 14, 2014. doi: 10.2118/171285-MS.

[6] J. Li and B. Luft, “Overview Solids Transport Study and Application in Oil-Gas Industry-Theoretical Work,” International Petroleum Technology Conference. p. IPTC-17832-MS, Dec. 10, 2014. doi: 10.2523/IPTC-17832-MS.

[7] M. Naegel, E. Pradie, T. Delahaye, C. Mabile, and G. Roussiaux, “Cuttings Flow Meters Monitor Hole Cleaning in Extended Reach Wells,” European Petroleum Conference. p. SPE-50677-MS, Oct. 20, 1998. doi: 10.2118/50677-MS.

[8] Manikonda, K., Hasan, A.R., Kaldirim, O., Rahmani, N., and Rahman, M.A. Estimating Swelling in Oil-Based Mud due to Gas Kick Dissolution. in ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering. 2020a.

[9] Manikonda, K., Hasan, A.R., Barooah, A., Rahmani, N.H., El-Naas, M., Sleiti, A.K., and Rahman, M.A. A Mechanistic Gas Kick Model to Simulate Gas in A Riser with Water and Synthetic-Based Drilling Fluid. in Abu Dhabi International Petroleum Exhibition & Conference. 2020b.

[10] Herath, D., Khan, F., Rathnayaka, S., and Rahman, M.A., Probabilistic estimation of hydrate formation. Journal of Petroleum Science and Engineering, 2015. 135: p. 32-38.

[11] Qureshi, M.F., Ali, M.H., Ferroudji, H., Rasul, G., Khan, M.S., Rahman, M.A., Hasan, R., and Hassan, I., Measuring solid cuttings transport in Newtonian fluid across horizontal annulus using electrical resistance tomography (ERT). Flow Measurement and Instrumentation, 2021. 77: p. 101841.

[12] Rasul, G., Qureshi, M. F., Ferroudji, H., Butt, S., Hasan, R., Hassan, I, & Rahman, M. A., Analysis of Cuttings Transport and Flow Pattern in Nearly Horizontal Extended Reach Well. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 71(2), 69–86, 2021.

[13] Rehman, Syed Raza and Zahid, Alap Ali and Hasan, Anwarul and Hassan, Ibrahim and Rahman, Mohammad A. and Rushd, Sayeed, Experimental Investigation of Volume Fraction in an Annulus Using Electrical Resistance Tomography, SPE Journal, 24 (5),1947-1956, 2019.

[14] Rahman, M.A., Adane, K.F., and Sanders, R.S., An improved method for applying the lockhart-martinelli correlation to three-phase gas-liquid-solid horizontal pipeline flows. Canadian Journal of Chemical Engineering, 2013. 91(8): p. 1372-1382. [15] S. S. Okrajni and J. J. Azar, “The Effects of Mud Rheology on Annular Hole Cleaning in Directional Wells,” SPE Drill. Eng., vol. 1, no. 04, pp. 297–308, Aug. 1986, doi: 10.2118/14178-PA.

[16] D. Nguyen and S. S. Rahman, “A Three-Layer Hydraulic Program for Effective Cuttings Transport and Hole Cleaning in Highly Deviated and Horizontal Wells,” SPE/IADC Asia Pacific Drilling Technology. p. SPE-36383-MS, Sep. 09, 1996. doi: 10.2118/36383-MS.

[17] M. U. Siddiqui, “Near Wall Turbulence Investigation of Solid Transport with Non-Newtonian Fluid Flow in an Inclined Annulus through Particle Image Velocimetry (PIV) Technique,” Politecnico di Torino, 2020. [Online]. Available: https://webthesis.biblio.polito.it/14743/

[18] A. Zahid et al., Effect of Multiphase Flow Behaviour on A Horizontal Annulus by Integrating High-Speed Imaging Technique. 2019. doi: 10.1615/TFEC2019.emt.028526.

[19] A. A. Zahid, S. R. ur Rehman, S. Rushd, A. Hasan, and M. A. Rahman, “Experimental investigation of multiphase flow behavior in drilling annuli using high speed visualization technique,” Front. Energy, vol. 14, no. 3, pp. 635–643, 2020, doi: 10.1007/s11708-018-0582-y.

[20] B. K. Menge, “Analysis of Turbulent Flow in a Pipe at Constant Reynolds Number using Computational Fluid Dynamics,” 2015.