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WELLBORE TRAJECTORY IMPACT ON EQUIVALENT CIRCULATING DENSITY

1. INTRODUCTION

Wellbore trajectory is one of the most basic and vital aspects of drilling operations. There are many different trajectory types, but nowadays in most cases vertical wells are displaced by directional drilling, which is essential to accomplish planned goals and to meet with economical requirements of modern, complicated projects. The path has to be designed in order to reach target location with regard to geological conditions and materials strengths. It appears that wellbore trajectory may not only have a major impact on well design but also hole cleaning and pressure losses, thus Equivalent Circulating Density management as well. For that reason, throughout computer simulations and laboratory tests, correlation between the wellbore trajectory modifications and ECD value changes was investigated.

2. RESEARCH METHODOLOGY

At the beginning it is vital to mention that the research consists of two main parts: computer simulations and laboratory tests. Research methodology is illustrated on Figure 1 and described below.

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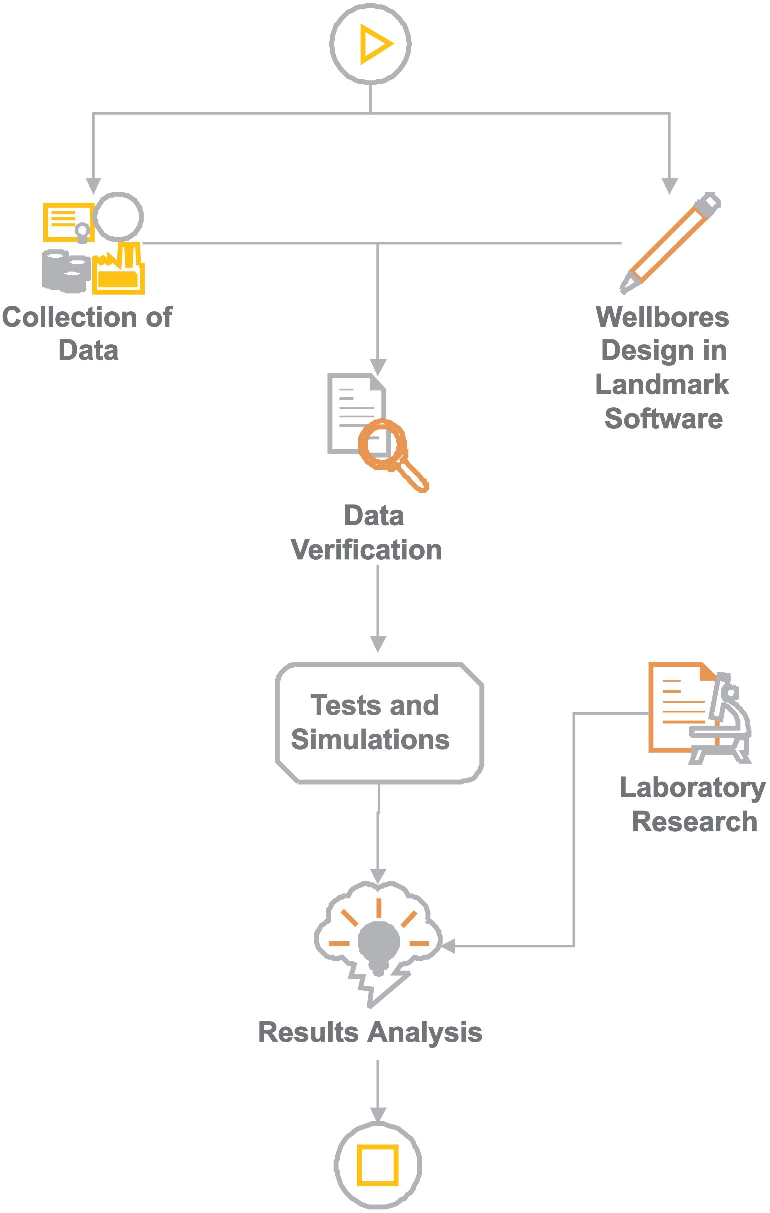

Fig. 1. Research methodology

The first step of the research was aimed to collect relevant information [1]. Therefore, the first part is based on real, field data from six previously accomplished wells: four horizontals (A, B, C, D) and two verticals (E, F). Both groups were chosen in a way to have similar design, trajectory, completion, drilling and hydraulics parameters. All wellbores were drilled by of the contractors operating in Lublin Basin (Poland) in order to estimate potential of shale hydrocarbons accumulations in this area. For that reason wellbores have also similar lithology with targeted, most perspective formations located in Lower Silurian and Upper Ordovician shales. Pore and fracture pressure gradients were also applied in tests with regard to accomplished geological surveys.

Using the collected data to recreate real wellbore conditions, each of above mentioned components was designed in Halliburton's Landmark Drilling Software [8] and then ECD was calculated. Simulations and tests for each particular wellbore were executed for a situation when last open hole section was drilled and target depth was reached. In order to verify the programs results accuracy, the outcomes were compared with PWD equipment surveys' results made during drilling operations. Analyzes indicate that there appeared some differences. The Landmark's results change in stable, continuous way. On the other hand in "PWD outcomes" increase or drop erratically without any noticeable or repeatable scheme. This situation appears due to a fact that even Landmark Software takes into account various, crucial factors it still uses mathematical equations and computer science which produce "linear" results. Wellbore environment instead, is very harsh, unpredictable and unstable ambient especially for measurement equipment sensors. Nevertheless the differences in results do not exceed 5% of their total values. For that reason it is permissible and logical to assume that not only ECD values but also conducted numerical simulations, included in this paper are correct and present a proper scientific value.

Next, after the ECD simulations, results were analyzed to check how the parameter changes in particular sections of vertical and horizontal wellbores. It was investigated how wellbore trajectory angle (inclination and azimuth) modifications impact mud pressure losses in wellbore annulus and overall ECD value. Additionally to expand scope of the work, the second group of tests was made in Drilling Fluids Laboratory at Faculty of Drilling, Oil and Gas at AGH UST in Krakow. Using Grace Sagging Tester M8500 Ultra HPHT it was examined how in wellbore conditions (high pressure and temperature) the inclination angle modifications may influence solids sedimentation process, fluid density changes and development of cuttings bed in deviated wellbore sections thus impact ECD value as well.

All tests and simulations outcomes are presented in 6 tables (Tabs 1–6, see Appendix) [1]. The results indicate that there is a strong correlation between wellbore trajectory angle changes and ECD value shifts. From analytical point of view, the outcomes are very compelling and what is more the results not only met with primary assumptions but also are confirmed by international scientific papers.

3. THEORETICAL INTRODUCTION

Below is presented simplified, pictorial version of full formula used to calculate ECD value. It plainly illustrates which factors affect ECD parameter. Furthermore it is vital to mention that this simplified version has only demonstrative form and cannot be applied in any calculations. Derivation of the full ECD formula is presented in the first paper included in references [1]. By analyzing equation (1) it is easy to notice how particular factors impact the parameter's value [1]:

$$\mathrm{ECD} = \mathrm{MW} + a \cdot \frac{\eta \cdot \mathrm{MW} \cdot Q \cdot \mathrm{MD}}{0.0981 \cdot D \cdot \mathrm{TVD}} \tag{1}$$

where:

MW – mud weight [kg/m^3],
a – proportion constant [–],
η – Bingham plastic viscosity [Pa·s],
Q – flow rate [m^3/s],
MD – measured depth or wellbore length [m],
TVD – true vertical depth [m],
D – annulus diameter [m].

Generally speaking the wellbore trajectory is a path followed by BHA and drill string from ground level to a predetermined, underground target. We can highlight two general types of wellbore trajectories:

1) vertical,
2) directional, which includes both deviated and horizontal hole trajectories.

Vertical wellbore is typically named a "straight" hole, which means that determined target is set directly below rotary kelly bushing location. Directional drilling is defined as practice of controlling direction and deviation of a wellbore to reach specified subsurface target, commonly located far from ground location of the well [3]. The directional drilling technology is so often used in the industry because it has numerous applications and enables: maximum reservoir penetration, reaching inaccessible locations, multiple wells drilling from a single site, sidetracking or well relief [5].

The wellbore trajectory has to be designed to reach planned targets and also with respect to Torque & Drag, casing wear, stuck pipe concerns and property/lease rights and rules. Additionally the trajectory has crucial impact on many other drilling aspects like borehole stability or hole cleaning process [6]. Therefore, depending on current wellbore conditions mud rheology has to be properly adjusted in order to remove cuttings from deviated or horizontal sections. As it is described above the wellbore trajectory not only determines, majority of drilling and completion parameters, but also impacts mud rheology and solids sedimentation, thus pressure losses in the annulus and equivalent circulating density.

This correlation between wellbore trajectory and ECD value is presented in Equation (1) as a wellbore measured depth and true vertical depth ratio. It is easy to notice that trajectory impact will be more crucial in directional than vertical wellbores.

Example 1

The dependence is also illustrated in an example below to present effect of the wellbore trajectory on ECD value [7]. In the paradigm it is assumed that besides MD and TVD all other factors influencing ECD are constant and exactly the same for wells number 1, 2 and 3 (Fig. 2). It is also necessary to mention that lateral sections in wellbores 2 and 3 have equal length of 2000 m.

$$\begin{gathered}\mathrm{ECD} = \mathrm{MW} + a \cdot \frac{\eta \cdot \mathrm{MW} \cdot Q \cdot \mathrm{MD}}{0.0981 \cdot D \cdot \mathrm{TVD}} \\ \left[\mathrm{MW} + a \cdot \frac{\eta \cdot \mathrm{MW} \cdot Q}{0.0981 \cdot D}\right] = \text{constant}\end{gathered} \tag{2}$$

Vertical wellbore No. 1:

$$\mathrm{MD}_1 = \mathrm{TVD}_1 = 6000 \text{ m}$$

$$\mathrm{ECD} = \mathrm{MW} + a \cdot \frac{\eta \cdot \mathrm{MW} \cdot Q \cdot \mathrm{MD}}{0.0981 \cdot D \cdot \mathrm{TVD}},$$

$$\mathrm{ECD} = \mathrm{MW} + a \cdot \frac{\eta \cdot \mathrm{MW} \cdot Q}{0.0981 \cdot D} = \text{constant}.$$

Horizontal wellbores No. 2 and No. 3

$$\mathrm{MD}_2 = 4000 \text{ m}, \qquad \mathrm{MD}_3 = 6000 \text{ m},$$

$$\mathrm{TVD}_2 = 2000 \text{ m}, \qquad \mathrm{TVD}_3 = 4000 \text{ m}.$$

$$\frac{\mathrm{MD}_1}{\mathrm{TVD}_1} = \frac{4000 \text{ m}}{2000 \text{ m}} = 2, \qquad \frac{\mathrm{MD}_2}{\mathrm{TVD}_2} = \frac{6000 \text{ m}}{4000 \text{ m}} = \frac{3}{2}.$$

This simple illustration explains the relationship between the wellbore trajectory and the ECD parameter. Both inclination and azimuth (in lateral sections) deviations from a vertical path cause that wellbore length increase greater than TVD. For that reason ECD is much greater in deviated wells than in vertical wellbores with the same MD, where MD/TVD ratio ≈ 1. Therefore in straight holes, ECD parameter is constant within one particular casing or well section.

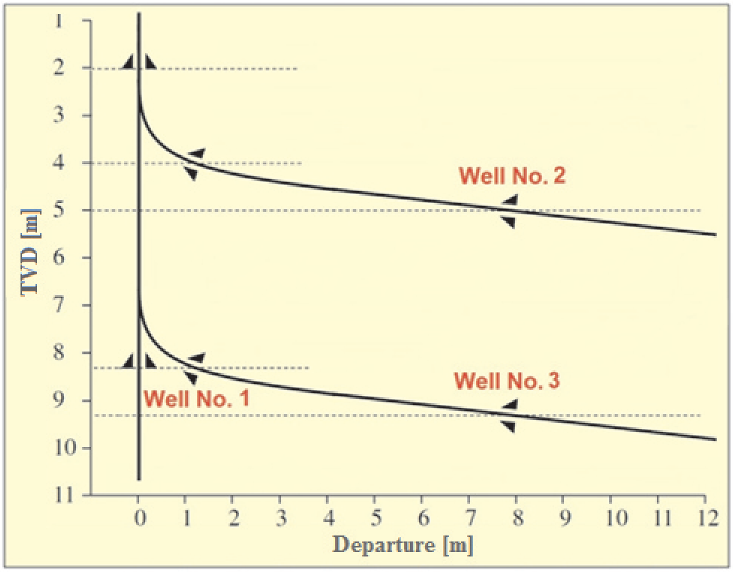

Fig. 2. Example 1 illustration

As it was mentioned above, despite that wells No. 1 and No. 3 have the same length, they have different ECD values (No. 3 > No. 1), because in deviated well the MD/TVD ratio > 1 is bigger than in vertical. What's more shallow, directional, extended reach drilling wells have much more higher ECD than wellbores with the same-length lateral sections but bigger TVD. For that reason ECD in well No. 2 is higher than in well No.3. Additionally shallow wells have little formation integrity. Moreover in ERD wells are often used drill pipes with greater OD, which directly causes reduction of annular space and increase of ECD. Therefore ECD management is even more demanding under these circumstances.

4. NUMERICAL SIMULATIONS

In order to recreate real wellbore conditions and investigate the above mentioned dependance, Halliburton's Landmark Drilling Software was used to conduct numerical simulations [8]. In both horizontal and vertical wells groups the simulations results indicate similar tendencies for all of included wellbores. The outcomes not only correspond with each other but also with previous assumptions presented in Example 1. Therefore, below are presented only two examples, one for horizontal and one for vertical wells group. The rest of the data, description which explain how to properly read the tables and understand all abbreviations are included in appendix. The results are presented in PPG unit, because it has higher nominal values than SG, thus enables to present the correlation more vividly.

The outcomes in Tables 1–4 indicate correlation between increasing inclination angle and ECD value growth. In the example, during simulations all factors influencing ECD were constant with exception of annulus diameter which changed in particular wellbore sections and due to different sizes of drilling equipment. Nevertheless from “2151 Shoe” survey point (9 5/8" section casing shoe) there was just one open hole section “OH” in which only inclination angle changed and was constantly enhancing. Therefore ECD value was increasing, especially from 63 deg to 90 deg and then boosting in horizontal section even before reaching BHA part of the drill string with reduced annular clearances. This proves previous assumptions and as it was mentioned before, this dependance refers also to three other investigated horizontal wellbores.

Contrarily, in both vertical wellbores, ECD value remained stable within each particular (casing or open hole) well section. ECD changed just between sections, therefore it is associated only with different annulus diameter. We can notice it on “the border” between casing and open hole survey points. Then ECD value remained unchanged until BHA section, where due to bigger equipment size, annular clearances are reduced, thus ECD is higher.

In order to confirm previous statemens and simulations results, below are also added two field cases. These are two wellbores (vertical and horizontal) examples prepared by K&M Technology, which worked as an operator at Offshore Gulf of Mexico [7].

Vertical (Fig. 3):
MD = TVD = 20000 ft, MW = 10 ppg, PV = 25 cP, YP = 17 lbf/100 ft^2,
drill pipe OD = 5 1/2", wellbore diameter D = 8 1/2".

The ECD value should remain the same in between approximately 11.1–11.3 ppg. Annulus pressure grows at the same rate that TVD. Any change in ECD outcome is therefore related to rock cuttings, annulus diameter or drilling mud changes.

Horizontal (Fig. 4):
MD = TVD = 20 000 ft, MW = 10 ppg, PV = 25 cP, YP = 17 lbf/100 ft^2,
drill pipe OD = 5 1/2", wellbore diameter D = 8 1/2".

This wellbore have the same drill string, drilling, hydraulic and rheology parameters as previous vertical but different, horizontal trajectory. Annulus pressure increase but TVD is constant. It is easy to notice also magnitude of ECD value difference compared to previous vertical example: in vertical hole ECD = ±11.2 ppg in horizontal ECD = ±12.7 ppg, at the same flowrate, drilling parameters and mud system.

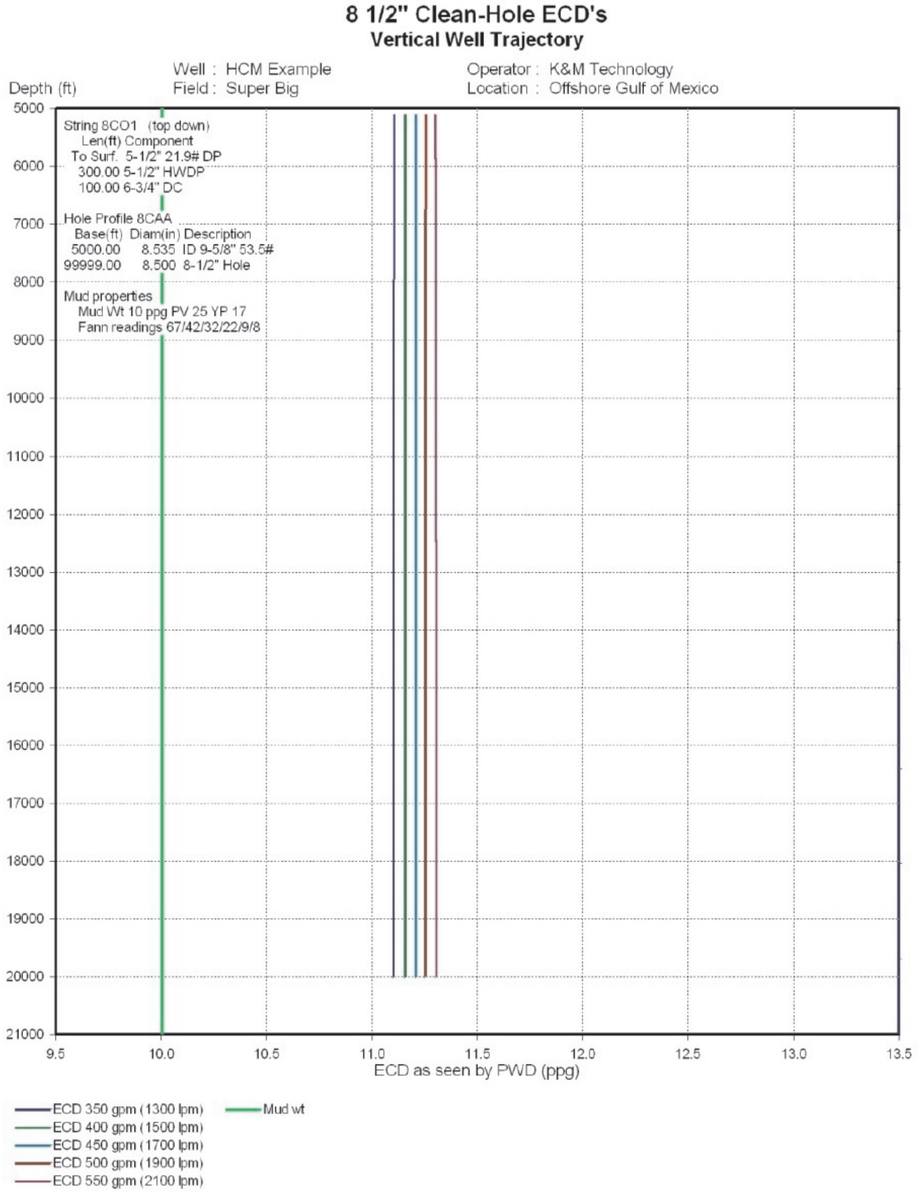

Fig. 3. ECD value in vertical wellbore

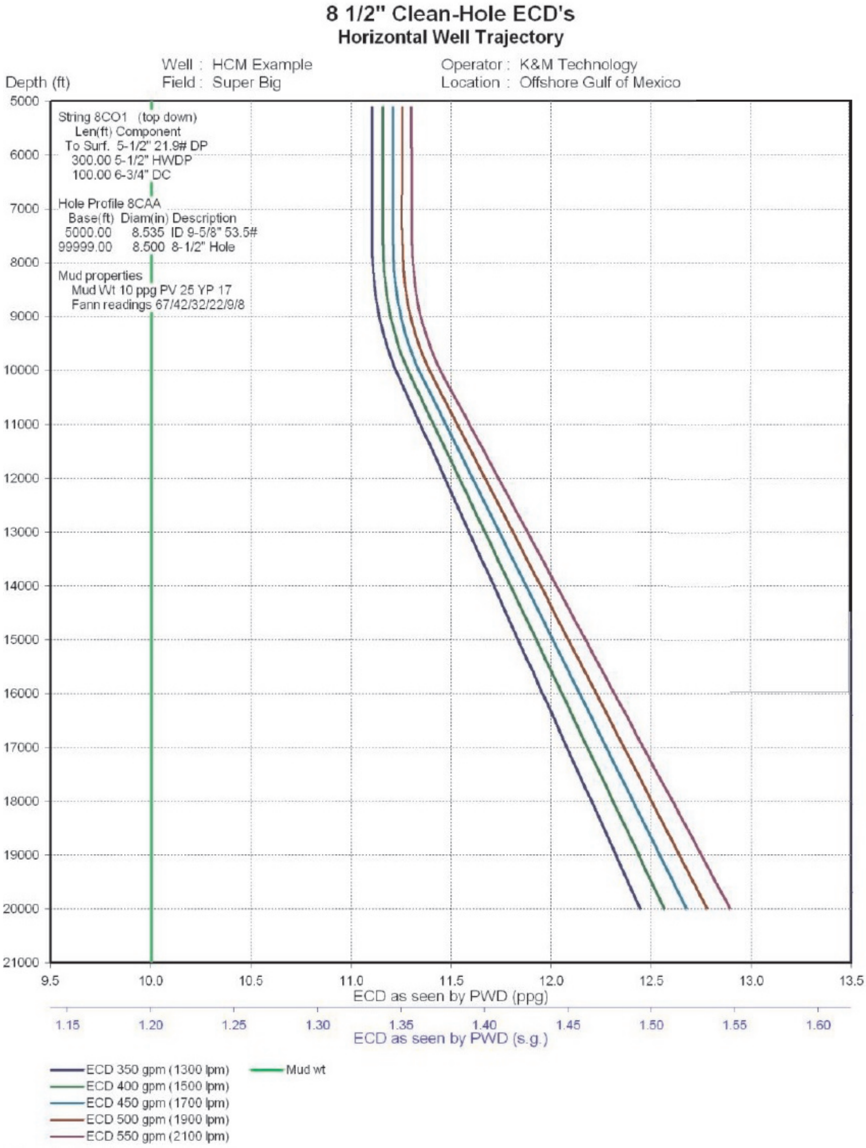

Fig. 4. ECD value in deviated wellbore

Numerical simulations conclusions

To sum up this section, is was clearly presented that wellbore trajectory has a major impact on ECD value, especially in deviated sections and lateral wells. Furthermore the assumptions are backed up with real field data. Additionally in chapter 5, there are included laboratory tests results, which confirm the statement.

5. LABORATORY TESTS

5.1. Theoretical introduction

As it was mentioned before wellbore trajectory impact on ECD value is related to solids removal and sedimentation in high angle wells. Hole cleaning process in deviated wellbores significantly varies from operations in vertical wells. Primarily in high angle and horizontal sections, rock cuttings sediment in a different way and more significantly than in vertical wells. For that reason they are much more difficult to be removed. It directly increases mud density and require additional mechanical agitation or increased flow rate and mud properties, which obviously impacts ECD. This phenomenon is caused by disparate and more complex cuttings movement in angle sections. For that reason whole cleaning process should be considered as a sum of each particular parts of the wellbore [4]:

- low angle section, approximately 0 to 45 deg,
- middle angle section, approximately 45 to 60 deg,
- high angle section, approximately 60 to 90 deg.

Low angle section (Fig. 5)

While drilling straight hole sections, hole cleaning is simply provided by flowrate and mud properties. Vertical component of gravity force then is equal or close to its value. In vertical and low angle wellbores, the cuttings move directly with the fluid and if drilling fluid velocity exceeds rock cuttings settling velocity, solid particles are lifted up the annulus and delivered to mud cleaning system. During outages, rock cuttings and solid particles are suspended by viscosity and thixotropy mud properties. Nevertheless, after some time sedimentation appears. In all illustration, blue arrow reflects movement while pumps are turned on, and red arrow shows the movement while pumps are turned off.

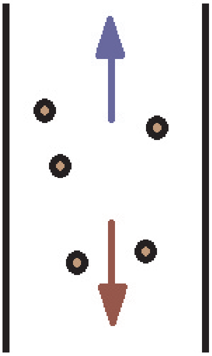

Fig. 5. Solids sedimentation in vertical wellbore

Middle angle section (Fig. 6)

In deviated wellbore sections, rock cuttings generally move on the low side of borehole and also tend to avalanche down the hole when pumps are off. The cuttings forms dunes, as distance to fall to the low side is very short and start to slide down hole, due to the gravity force component parallel to the borehole. Moreover the cuttings cannot really be suspended by viscosity of fluid as well. This can lead to many problems and complications like pipe sticking or faster bit ware. Nevertheless rotary movement of drill string combined with the flow regime are powerful enough and cuttings can be easily stirred up and transported through the annulus.

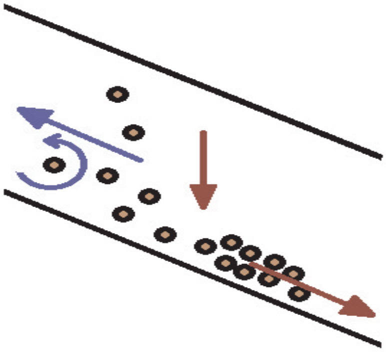

Fig. 6. Solids sedimentation in middle angle wellbore

High angle section (Fig. 7)

In high angle and horizontal sections, rock cuttings tend to fall and lay on the low side of the borehole, forming continuous cuttings bed, while drilling fluid tends to flow above drill string. While the pumps are turned off, cuttings fall immediately, regardless of the viscosity of the mud. Therefore mechanical agitation is necessary to transport cuttings because flow rate and mud viscosity is not sufficient enough to lift up solid particles.

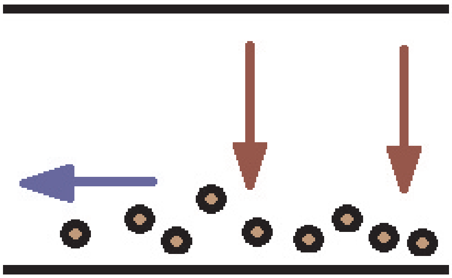

Fig. 7. Solids sedimentation in horizontal wellbore

For that reason in high angle or horizontal wellbore sections drill string rotary movement is crucial part of hole cleaning process. It is necessary to maintain high pipe rotation speed at least 120 rpm, which mechanically supports the cuttings lifting by flowing fluid, on the low side of a wellbore. This prevents form forming dunes and cutting beds big enough to complicate drilling or tripping processes.

5.2. Laboratory tests results

Additionally, in order to investigate solids sedimentation process in vertical and deviated wellbores sections there were conducted laboratory sagging tests in March 2016 in Drilling Fluids Laboratory at Faculty of Drilling, Oil and Gas at AGH University of Science and Technology in Krakow [2]. The main purpose of the research was to investigate mud density changes due to solids sedimentation process in vertical and deviated well sections during outages. Test were conducted using Sagging Tester M8500 Ultra HPHT produced by Grace Instruments (Fig. 8). The equipment is designed to change its position from 0 to 80 deg in order to simulate particular wellbore sections. Two tests were run at 0 and 80 deg angles and three tests at 30 and 60 deg. Mud density measurement sensors are located in the middle of cylinder at the lower side of a pipe containing drilling fluid.

Fig. 8. Grace Sagging Tester M8500 Ultra HPHT [9]

Unfortunately used Sagging Tester, does not allow to perform test with drilling mud containing rock cuttings. For that reason there were prepared drilling fluids with high sedimentation abilities to imitate cuttings impact and behavior. The fluids compositions are presented below:

Only for vertical measurements – triple inhibition system drilling fluid:

- Rotomag-starch additive 2%,
- PAC LV 1.5%,
- PHPA 0.15%,
- KCl 6%,
- Glycol 3%,
- H_2O 87.35%.

Every other test was conducted with mud consisting of:

- Rotomag-starch additive 2%,
- PAC LV 0.5%,
- XCD – polymer 0.05%,
- PHPA 0.1%,
- KCl 6%,
- Glycol 3%,
- H_2O 88.35%.

Each additive was mixed for 15 minutes and left for rest. Additionally, after the break and before the beginning of the tests, Carbonate Blocker (15%) was added with a couple drops of 1-octanol used in order to prevent foaming process.

Test procedures:

- Tests were performed under 100 PSI pressure and temperature of 30 Celsius.
- Every test took 9 hours to proceed.
- Samples were collected after: 1.5 and 9 hours since the beginning of each test.
- Tests were performed respectively at 0 deg, 30 deg, 60 deg, 80 deg angles.
- Samples were collected from density measurement sensors.
- After the test, specimens were checked and their density was measured.
- After each test, the equipment was decomposed and cleaned to provide high results quality of following tests.

Results of conducted research are in the Appendix.

5.3. Laboratory tests conclusions

All laboratory tests' results are presented in Tables 7–10. Conducted tests confirmed previous assumptions presented in chapters two and three.

Firstly, measurements results have proven that for vertical and nearly vertical (30 deg) sections, drilling fluid density was reduced because of mud solids sedimentation process, caused by gravity force impact.

Contrary to the first measurements, in more deviated 60 and 80 deg sections, drilling mud density rose. Unfortunately in the first run at 60 deg inclination setup, the third mud sample was not collected. The fluid was accidentally lost during sagging equipment maintenance. Nevertheless it did not affect overall results, because in the rest cases, fluid density evidently increased. This phenomenon was obviously caused by more significant and complex solids sedimentations process, in highly deviated well sections, which was explained in previous chapter.

Lastly it is crucial to remember that the drilling fluid applied in tests did not contain rock cuttings, but only special solids used for mud treatment. This additives can easily sediment and imitate cuttings behavior. For that reason it is logical to assume that, if tested fluid would be contaminated with rock cuttings, governing dependences would be more intense and density differences would be more severe as well.

6. FINAL CONCLUSIONS

Ultimately, both numerical simulations and laboratory tests indicate that wellbore trajectory greatly impacts pressure losses in the annulus thus equivalent circulating density, especially in deviated wellbores. This appearance is associated with much more severe and complex solids sedimentation and removal processes in high angle and horizontal sections. Additionally deviated wellbores require higher flow rate than vertical wells with similar length in order to lift and transport cuttings upward the annulus. Furthermore in deviated, specifically slimhole wells ECD management is more complicated because flow rate changes impact ECD value stronger than in large diameter wells. For that reason it is advised to always consider this aspect during well planning, especially in demanding and ECD management conditions, because it may prevent possible drilling failures and complications.

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APPENDIX

Table 1

Wellbore C simulations results

Wellbore C			
MD [m] /Section	Inc. [deg]	ECD [ppg]	
		PWD	Primary Conditions
1. 0 Casing	0	×	12.55
2. 2151 Shoe	0	×	12.55
3. 2262 OH	7	×	12.57
4. 2724 OH	63	×	12.60
5. 2985 OH	90	12.78	12.68
6. 3400 Horizontal	91	13.01	12.83
7. 3800 Horizontal	93	12.98	12.97
8. 4051 BHA	93	13.11	13.06
9. 4067 BHA	93	13.01	13.06
10. 4100 TD	93	13.02	13.10

Table 2

Wellbore E simulations results

Wellbore E		
MD [m] /Section	Inc. [deg]	ECD [ppg]
		Primary Conditions
1. 0 Casing	0	15.37
2. 2576 Shoe	0	15.37
3. 2621 OH	0	15.42
4. 3000 OH	0	15.42
5. 3850 BHA	0	15.47
6. 3930 BHA	0	15.47
7. 4020 TD	0	15.50

Table 3

Wellbore A simulations results

Wellbore A			
MD [m] /Section	Inc. [deg]	ECD [ppg]	
		PWD	Primary Conditions
1. 0 Casing	0	×	14.29
2. 2179 Shoe	0	×	14.29
3. 2674 OH	5	×	14.32
4. 2984 OH	61	×	14.34
5. 3180 OH	90	14.46	14.38
6. 3500 Horizontal	91	14.56	14.48
7. 3900 Horizontal	91	14.56	14.60
8. 4258 BHA	91	14.64	14.71
9. 4307 TD	91	14.70	14.76

Table 4

Wellbore D simulations results

Wellbore D			
MD [m] /Section	Inc. [deg]	ECD [ppg]	
		PWD	Primary Conditions
1. 0 Casing	0	×	12.44
2. 2082 Casing	4	×	12.44
3. 2241 Shoe	15	×	12.45
4. 2568 OH	60	×	12.47
5. 2879 OH	90	12.94	12.52
6. 3500 Horizontal	90	12.88	12.67
7. 3610 BHA	90	12.78	12.70
8. 3700 BHA	90	12.75	12.76
9. 3801 TD	90	12.62	12.83

Table 5

Wellbore B simulations results

Wellbore B			
MD [m] /Section	Inc. [deg]	ECD [ppg]	
		PWD	Primary Conditions
1. 0 Casing	0	×	13.68
2. 2517 Shoe	0	×	13.68
3. 2790 OH	5	×	13.70
4. 3290 OH	61	×	13.73
5. 3463 OH	90	13.80	13.77
6. 3900 Horizontal	91	13.85	13.89
7. 4337 BHA	91	13.96	14.01
8. 4385 TD	91	13.99	14.04

Table 6

Wellbore F simulations results

Wellbore *F*		
MD [m] /Section	Inc. [deg]	ECD [ppg]
		Primary Conditions
1. 0 Casing	0	15.45
2. 2700 Shoe	0	15.45
3. 3100 OH	0	15.47
4. 3530 OH	0	15.48
5. 3600 BHA	0	15.48
6. 3650 BHA	0	15.86
7. 3761 TD	0	15.90

In Tables 7–10 are presented computer simulation results prepared in Landmark Drilling Software. In order to read the data properly, in undermentioned description are consecutively explained meanings of all titles and abbreviations used in included tables.

Table 7

Sagging test results for 0 deg inclination angle

Angle: 0 deg	Volume of a container [$m^3 \cdot 10^{-6}$]	Weight of empty container [$kg \cdot 10^{-3}$]	Weight of fulll container [$kg \cdot 10^{-3}$]	Density of the sample [$kg \cdot 10^{-3} / m^3 \cdot 10^{-6}$]
First run				
Sample 1	4.56	164.30	169.39	1.1162
Sample 2	4.59	163.48	168.39	1.0697
Sample 3	4.68	163.83	168.61	1.0214
Second run				
Sample 1	4.68	163.79	168.86	1.0833
Sample 2	4.59	163.77	168.70	1.0741
Sample 3	4.56	164.55	169.44	1.0724

Table 8

Sagging test results for 30 deg inclination angle

Angle: 30 deg	Volume of a container $[m^3 \cdot 10^{-6}]$	Weight of empty container $[kg \cdot 10^{-3}]$	Weight of fulll container $[kg \cdot 10^{-3}]$	Density of the sample $[kg \cdot 10^{-3}/ m^3 \cdot 10^{-6}]$
First run				
Sample 1	4.56	164.54	169.41	1.0680
Sample 2	4.59	163.72	168.58	1.0588
Sample 3	4.68	163.85	168.78	1.0534
Second run				
Sample 1	4.56	164.54	169.42	1.0702
Sample 2	4.59	163.71	168.60	1.0654
Sample 3	4.68	163.83	168.81	1.0641
Third run				
Sample 1	4.56	164.54	169.47	1.0811
Sample 2	4.59	163.72	168.65	1.0741
Sample 3	4.68	163.83	168.85	1.0726

Table 9

Sagging test results for 60 deg inclination angle

Angle: 60 deg	Volume of a container $[m^3 \cdot 10^{-6}]$	Weight of empty container $[kg \cdot 10^{-3}]$	Weight of fulll container $[kg \cdot 10^{-3}]$	Density of the sample $[kg \cdot 10^{-3}/m^3 \cdot 10^{-6}]$
First run				
Sample 1	4.56	164.54	169.52	1.0921
Sample 2	4.59	163.72	168.73	1.0915
Sample 3	4.68	–	–	–
Second run				
Sample 1	4.56	164.54	169.21	1.0241
Sample 2	4.59	163.73	168.50	1.0392
Sample 3	4.68	163.83	168.80	1.0620
Third run				
Sample 1	4.56	164.54	169.51	1.0899
Sample 2	4.59	163.78	168.79	1.0915
Sample 3	4.68	163.91	169.04	1.0962

Table 10

Sagging test results for 80 deg inclination angle

Angle: 80 deg	Volume of a container $[m^3 \cdot 10^{-6}]$	Weight of empty container $[kg \cdot 10^{-3}]$	Weight of full container $[kg \cdot 10^{-3}]$	Density of the sample $[kg \cdot 10^{-3} / m^3 \cdot 10^{-6}]$
First run				
Sample 1	4.56	164.54	169.40	1.0658
Sample 2	4.59	163.75	168.66	1.0697
Sample 3	4.68	163.85	168.89	1.0769
Second run				
Sample 1	4.56	164.58	169.47	1.0724
Sample 2	4.59	163.76	168.70	1.0763
Sample 3	4.68	163.89	168.98	1.0876

The first column (counting from the left, Tabs 1–6) include particular survey points, which were vital from ECD management point of view. Numbers indicate wellbore measured depth (MD) in meters while words and abbreviations present selected part of well. Hence “0 Casing” means that measurement was made at 0 m MD in 9 5/8" casing string. “Shoe” always refers to casing shoe of 9 5/8" intermediate section. “OH” stands for open hole 8 1/2" section. “3900 Horizontal” means that survey was made in horizontal part of open hole section at 3900 m of MD. “BHA” regards to wellbore section with bottom hole assembly part of drill string. “TD” indicates that the last measurement point is located in drill bit position at target depth.

The second column “Inc [deg]” stands for wellbore trajectory inclination angle value at particular survey stages.

In “PWD” column are presented real data surveys from pressure while drilling equipment. X regard to the points where PWD measurements were not made, because this tool was used only in horizontal sections.

“Primary Condition” columns include results from Landmark Drilling Software which presents ECD values in primary well conditions, without changes or optimizations in any parameter whatsoever. As it was mentioned at the beginning, results from this column were compared with PWD data in order to check the software’s accuracy.

Sagging tests results – diagrams (Figs 9–12)

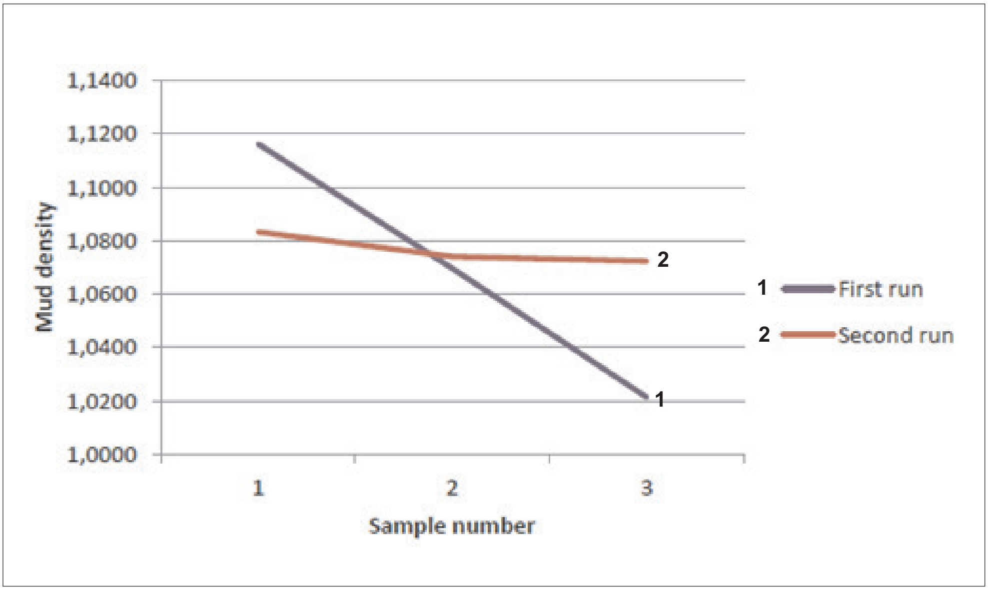

Fig. 9. Mud density changes for 0 deg inclination angle

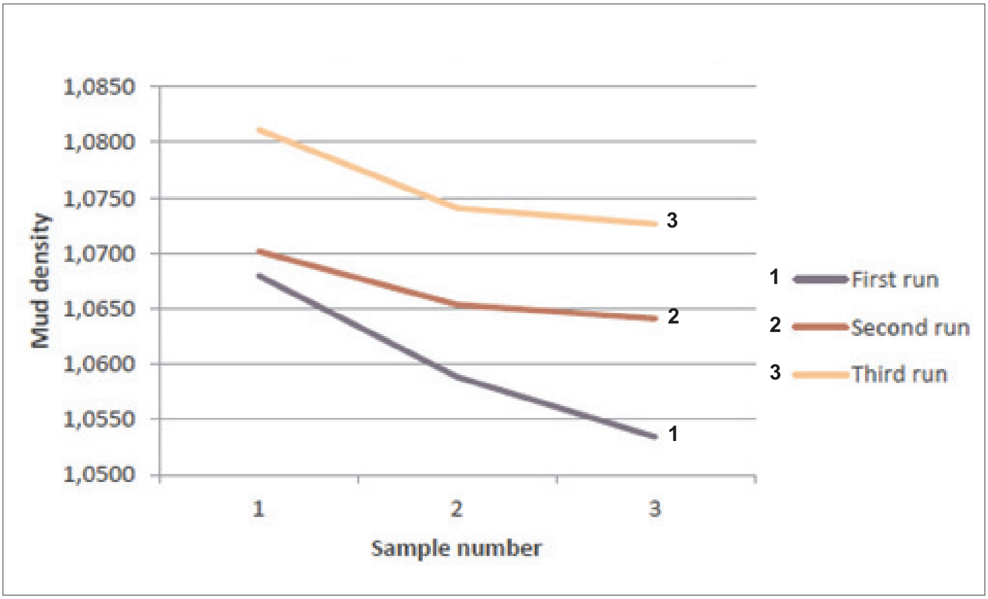

Fig. 10. Mud density changes for 30 deg inclination angle

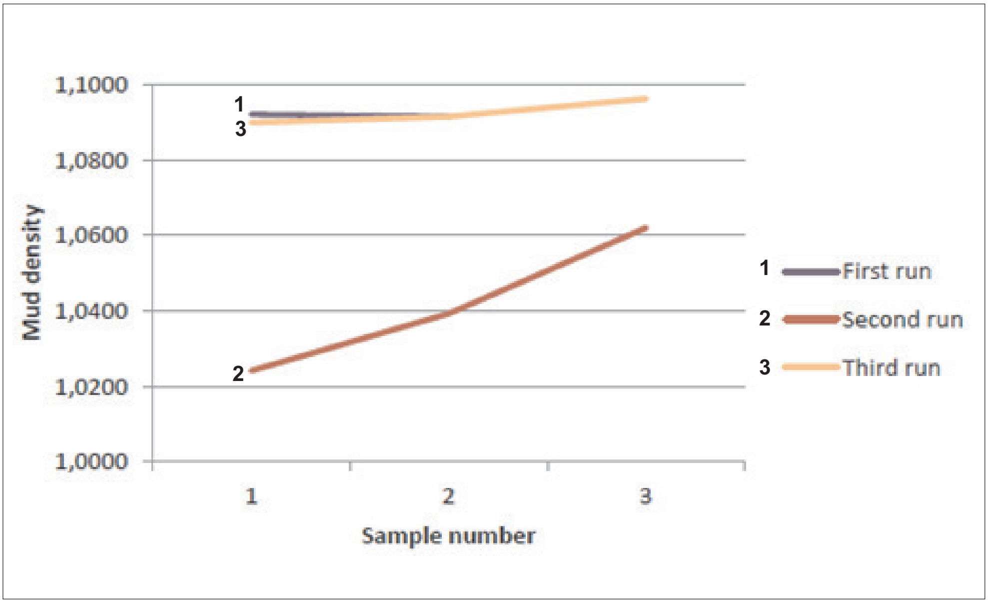

Fig. 11. Mud density changes for 60 deg inclination angle

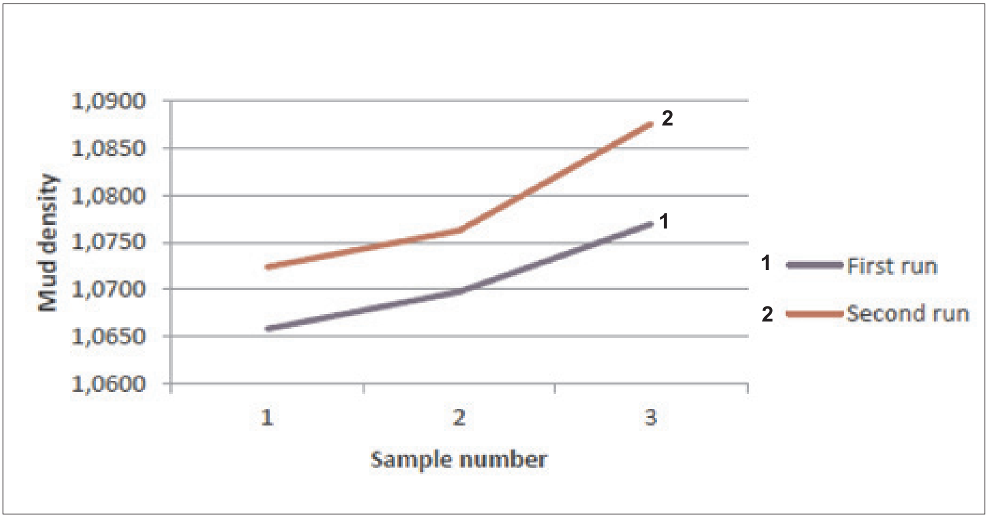

Fig. 12. Mud density changes for 80 deg inclination angle