energies

Article

Hybrid Washer Fluid for Primary Cementing

Marcin Kremieniewski

Oil and Gas Institute—National Research Institute, 25A Lubicz Str., 31-503 Krakow, Poland;
kremieniewski@inig.pl

Abstract: This article presents the results on the basis of which a new hybrid drilling washer fluid was designed. The use of fluid from such a drilling washer increases the mud-cake removal efficiency. Its operation is based on both chemical and mechanical removal of the mud cake. This article presents a group of agents and admixtures of various solid fractions, the appropriate selection of which enabled the design of a hybrid drilling washer fluid. The liquid has much better washing parameters than the drilling washers used so far. The tests were carried out in a drilling fluid flow simulator. A significant improvement in the scrubbing mud-cake removal efficiency resulted from the action of surfactants and fine-grained abrasive additives. Their proper concentration was also very important. The hybrid drilling washer fluid was designed on the basis of tests measuring the adhesion of the hardened cement slurry to the rock from which the previously produced mud was removed. In this way, the effectiveness of the washing liquids was determined. Upon analyzing the obtained results and correlating them with the reference samples, one can see a significant improvement in the efficiency of the removal of the drilling sediment by the hybrid drilling washer fluid. The hybrid drilling washer fluid is an innovative solution because it combines chemical and mechanical action in the removal of drilling fluid. Additionally, such a washing liquid has not been used so far.

Keywords: washing liquid; hybrid drilling washer fluid; annular space washing; surfactants; fine-grained additives; drilling fluid additives; borehole washing

check for updates

Citation: Kremieniewski, M. Hybrid Washer Fluid for Primary Cementing. *Energies* **2021**, *14*, 1295. https://doi.org/10.3390/en14051295

Academic Editor: Arild Saasen

Received: 15 January 2021
Accepted: 23 February 2021
Published: 26 February 2021

1. Introduction

In order to obtain adequate bonding at the rock formation–cement sheath–casing pipe contact, the annular space must be properly washed before the cementing procedure. Thanks to this, it is possible to eliminate gas migration or exhalation after cementing [1,2]. Proper washing of the annular space and sealing of the pipe column affect the long-term operation of the well. This reduces the effect of the corrosive environment on the pipe column in aggressive conditions. The issue of washing the annular space covers many scientific aspects. These are the rheology of drilling fluids, fluid mechanics, the action of chemicals (surfactants), and the action of chemical additives during cement slurry hydration [3–7]. The development of techniques and technology has not yet made significant progress in improving well bonding. Gas migration from wells is still recorded. Therefore, this article contains the results of research on improving the washing of the annular space [8–14]. The sealing condition is considered in terms of the used washing and buffer liquids and the cement slurry. The influence of these liquids on the filtration sediment from the drilling fluid and on rock formation is also investigated [15–17]. One main cause of ineffective sealing cannot be distinguished. There are many different factors contributing to the appearance of leaks and gas migration pathways. These are geological, technical, mechanical, or organizational factors [18–21]. Processing factors include, but are not limited to, preparation of the casing and cementing hole. It is at this stage that the type, composition, and mechanism of operation of the wash used are of decisive importance [22,23].

After placing the cement slurry in the annular space, at the interface between the cement and the mud, processes occur that favor gas migration at the contact of the cement jacket with the rock or the pipe. Therefore, the most important thing is to wash the annular space of the borehole and remove the mud and the remaining mud cake [24–26]. Otherwise, poorly displaced drilling mud and mud cake result in the appearance of channels for the migrating gas [1,10,27]. This is mainly due to poor washing of the hole prior to cementation. Most often, the quality and the quantity of the mud cake left on the opening wall deteriorate the sealing efficiency of the pipe column. Therefore, the most important step is thorough washing of the annular space before the cementation procedure [1,2,5,7,10,28–30]. In addition, the issue that affects the quality of sealing the annular space is the adhesion of the hardened cement slurry to the rock through the remains of the remaining mud cake. The bonding of the joint between the rock and hardened cement slurry is affected by the thickness and consistency of the mud cake [2,4,7–9,14,15,31]. The thickness of the mud cake depends on the degree of washing, as well as the time and intensity of washing. The coarse, soft mud cake is removed with a washing liquid with suitable properties and flow velocity. In turn, a thin hard deposit under these washing conditions will be indelible [4,7,8,14,32]. Therefore, it is important to develop and use a hybrid liquid. In addition to surfactants, the liquid should also contain small fractions of abrasive materials. It, thus, has a dual action, thanks to which a thin layer of hard, consolidated mud cake is removed by mechanical stripping of the mud cake [2,8,33,34]. When designing the hybrid fluid, measures are selected to limit the fractionation of the abrasive material. It is important to select materials that will increase the viscosity of the hybrid wash liquid and not fix the washed mud cake. Previously, washers with a chemical effect on the mud cake were used. This article discusses the effects of a hybrid drilling washer fluid.

2. Materials and Methods

2.1. Materials

In order to check the effectiveness of the hybrid drilling washer fluid, it should be tested after designing it. For this purpose, a mud cake was formed on a sandstone core and removed by pressing the washing wash. Then, the washed core was sealed with cement slurry, and the adhesion strength was checked. The mud-cake removal efficiency was determined by comparing the adhesion of the base sample without mud cake to the sample after washing with a hybrid wash. To do this, a hybrid wash was prepared, and the second drilling fluid constituted cement slurry.

To prepare a hybrid wash, a surfactant was used, which was a mixture of C12–14 ethoxylated alcohols) called ROKAnol L10/80. It was purchased from PCC Exol S.A. The surfactant used was a mixture of C12–15 ethoxylated alcohols and sodium salts. This mixture was purchased from PCC Exol S.A. Polyethyleneimine with the trade name Basoblock was also used. This product was obtained from BASF. Nut shells with a specific density of 1.0–1.2 g/cm^3 and a Mohs hardness of 2.5–3.5 were used as the abrasive, in addition to a plastic shot with a specific density of 1.5 g/cm^3 and a Mohs hardness of 3.5–4.0 and a glass microsphere with a bulk weight of 0.12 g/cm^3 (all from Rewa pph). A defoamer was also used, i.e., a mixture of unsaturated fatty acid esters and refined hydrocarbons. It was a product with a bulk density of 880–920 kg/m^3, with the trade name PSP061, obtained from Polski Serwis Płynów Wiertniczych. The proportion of agents used to prepare the leaven is summarized in Table 1.

Table 1. Composition of the hybrid drilling washer fluid (Patent PL 235159).

Ingredients	Concentration (%)
Water	100
Surfactant (C12–14 ethoxylated alcohols)	0.2
Surfactant (mixture of C12–15 ethoxylated alcohols and sodium salts)	0.2
Polyethyleneimine	0.05
Nut shells (fractions with dimensions of 100–250 µm)	0.1
Plastic shot (fractions with dimensions of 20–40 mesh)	0.2
Microspheric glass fractions with dimensions of 100–200 µm	0.2
Defoamer (product of saturated fatty alcohol ethoxylation and propoxylation)	0.01

When designing the cement slurry, CEM I 42.5R Portland cement was used. It is a Portland cement PN-EN 197-1—CEM I 42.5R meets the requirements of the PN-EN 197-1 standard "Cement—Part 1: Composition, requirements and compliance criteria for common cements". The cement had 2.66% SO_3 and 0.065% Cl^-. Materials were used to adjust the parameters of the grout. Plasticizer PSP 046 (from Polski Serwis Płynów Wiertniczych. Sp. z o.o. Poland) was used as a dispersant based on lignosulfonates with a bulk density of 440–550 kg/m^3 and a pH value ranging from 6.6 to 8.5. To extinguish the foam, a defoaming agent was used, i.e., a mixture of esters of unsaturated fatty acids and refined hydrocarbons. It was obtained from the company Polski Serwis Płynów Wiertniczych. Sp. z o.o. Poland. The cement slurry also had an antifiltrating agent and a setting accelerator; it was purchased from the company Polski Serwis Płynów Wiertniczych. Sp. z o.o. Poland. The cement slurry was sealed with latex, which is a dispersion of styrene–butadiene copolymer, also purchased from the company Polski Serwis Płynów Wiertniczych. Sp. z o.o. Poland. The pores in the cement slurry were filled with 10% microcement, which was purchased from Halliburton Micro Matrix. The microcement had grains smaller than or equal to 10 µm, and its specific surface area was approximately 1400 m^2/kg. The proportion of agents used to prepare the leaven is summarized in Table 2.

Table 2. Recipe and parameters of the cement slurry used in the adhesion test on the hardened cement–rock contact [34].

Ingredients	% by Mass of Cement
Water–cement ratio	0.45
Plasticizer	0.2
Latex	10.0
Stabilizer	1.0
Defoaming agent	0.5
Antifiltrating agent	0.2
Setting accelerator	4.0
Microcement	10.0
Cement CEM I 42,5R	100.0

2.2. Preparation of the Washing Liquid

To prepare the hybrid washer, the following components were used: 0.2% ethoxylated alcohol (nonionic surfactant), 0.05% antifractionation polymer, 0.1% fine-grained lightweight abrasive fraction (Figure 1), 0.2% medium-weight coarse-grained abrasive fraction (Figure 2), 0.2% fine-grained abrasive fraction to improve the hydraulic parameters of the liquid (Figure 3), and 0.01% antifoaming agent [34].

For the design of the hybrid washer, the water volume was measured using a measuring cylinder. The water was put into a mixer at a mixing speed of 500 rpm. The individual components were added to the water in the percentages according to Table 1. The liquid was stirred for 15 min to homogenize it. Solid fractions were introduced in order to obtain an additional mechanical effect of removing the mud cake.

Figure 1. Fine-grained lightweight abrasive fraction.

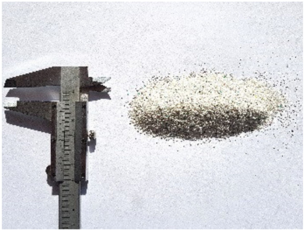

Figure 2. Medium-weight coarse-grained abrasive fraction.

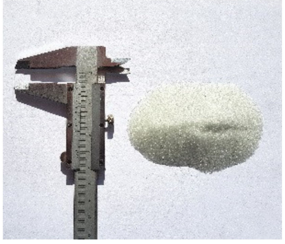

Figure 3. Fine-grained abrasive fraction to improve the hydraulic parameters of the liquid.

2.3. Preparation of the Cement Slurry

The required amount of water was measured with a measuring cylinder. The water was placed in a mixer with a rotation speed of 1600 rpm. Chemicals necessary for the slurry were added to the water and mixed for 10 min. Later, loose materials (microcement, microspheres, microsilica, and cement) were poured into the water/agent solution and mixed for another 20 min. Mixing at such a rotational speed is similar to the conditions used for the preparation of slurry in a hole.

2.4. Experimental Procedures

Properties of the cement slurry were tested in accordance with the standard PN—EN ISO 10426-2 (Oil and gas industry. Cements and materials for cementing holes. Lot 2: Testing of drilling cements). A test was done for slurry density, filtration, and thickening time. The adhesion test was carried out according to the standard PN—EN 196-1: 2006 (Cement testing methods. Strength marking).

The above methodology was developed for the purposes of research, the results of which allowed determining the effectiveness of the new hybrid washer. The operation of the hybrid washer was based on washing the mud cake produced on the surface of the rock sample. For the purpose of the research, a device was constructed that pushes drilling fluid in a closed circuit (drilling fluid flow simulator, Figure 4). The tested fluids were pumped at a constant value of the delivery rate. The pressing parameters were selected during preliminary tests. A flow rate of 11.2 L/min was assumed for the tests, which corresponded to pumping the liquid in a turbulent flow with a Reynolds number of approximately 3150. The contact time of the washing liquid with the sample surface was 4 min. This value corresponds to natural conditions. A mud cake was created on a sandstone core with an external diameter of 25 mm and a length of 60 mm (Figure 5). The mud cake was formed on the core by pressing mud in a flow simulator. Dry cores were placed on a tripod (Figure 6), which was located inside a plastic tube (Figure 7). A drilling fluid (mud and washing fluid) circulated inside the pipe. Such an arrangement highlighted the annular space of the borehole [34].

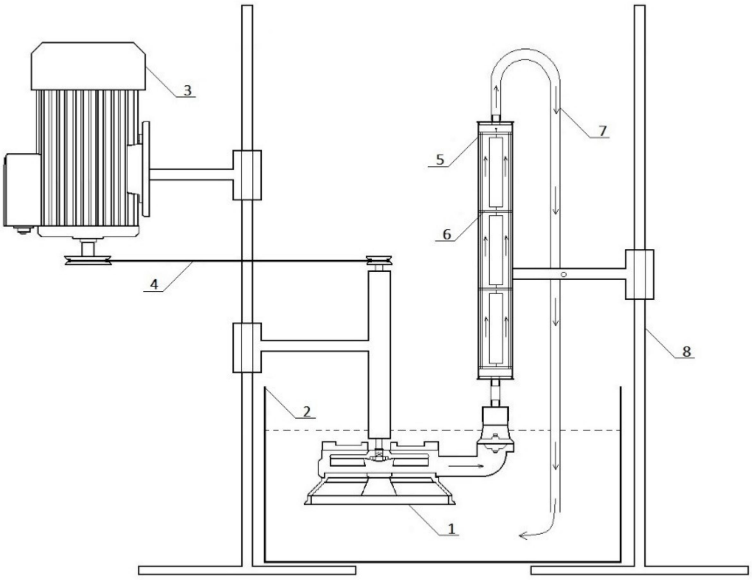

Figure 4. Diagram of the drilling fluid flow simulator. (1) Pump with a centrifugal impeller; (2) tank with drilling fluid; (3) electric motor; (4) drive belt; (5) polyvinyl chloride (PVC) pipe; (6) core holder; (7) drilling fluid supply pipe; (8) tripod.

Figure 5. Sandstone sample core.

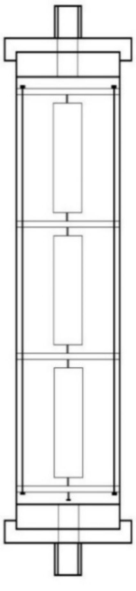

Figure 6. Scheme of cores in the pipe.

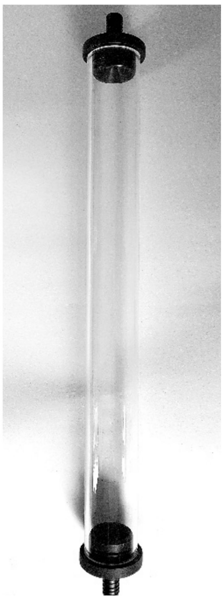

Figure 7. Plastic pipe in which the cores were placed and the wash was pressed.

The developed methodology allowed determining the efficiency of washing mud removal by the pumped washing liquid. The adhesion to the contact between the hardened cement slurry and the rock formation was tested before and after washing. The core samples with the formed mud cake, after washing with the washing liquid, were placed in a tripod (Figure 8) and filled with cement slurry (Figure 9). After a binding time of 48 h, the adhesion was tested between the cement stone and the sandstone core. For this purpose, the samples were placed in a testing machine (Figure 10) and the breaking force of adhesion at the contact of the surfaces was measured.

Figure 8. Sandstone core ready to be sealed with cement slurry.

Figure 9. Sandstone core ready for adhesion testing on contact with cement slurry.

Figure 10. Device for measuring adhesion on the contact of tested surfaces.

After each measurement, the adhesion expressed in MPa was calculated according to Equation (1).

$$\sigma_{\mathrm{P}} = \frac{\mathrm{P}}{\mathrm{s}} \times 10^{-3} [\mathrm{MPa}], \tag{1}$$

where σ_{P} is the contact adhesion between the cement stone and sandstone core (MPa), P is the force needed to sever the adhesion (kN), and s is contact area of the sandstone core with the cement stone (m^2).

The pressure force (P) was read from the indication on the testing machine, and the contact surface of the sandstone core sample with the cement stone was equal to the outer surface of the core and the height of the slurry in the mold. The dimensions needed for the calculations are shown in Figure 11.

$$s = \pi \cdot d \cdot h, \tag{2}$$

where the core diameter (d) = 25 mm = 0.025 m, and the height of the cemented part of the core (h) = 44 mm = 0.044 m.

$$s = \pi \cdot 0.025 \cdot 0.044 = 0.003465\ [\mathrm{m2}] \tag{3}$$

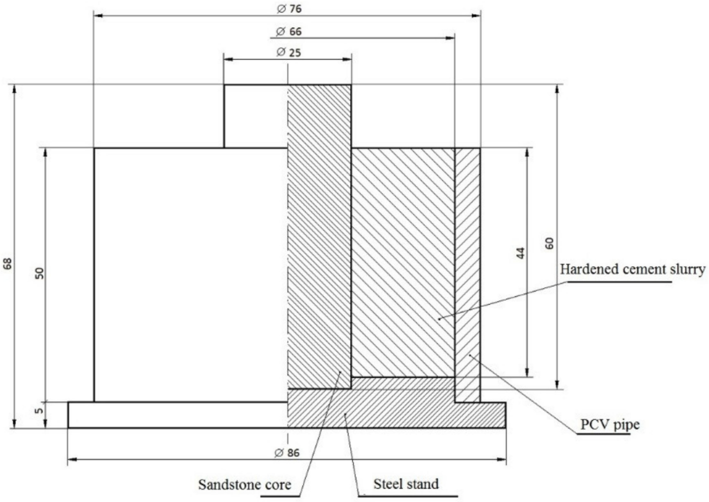

Figure 11. Half-section of the mold with the sample core placed.

The adhesion to the contact between the hardened cement slurry and rock was determined as follows:

$$\sigma_{\mathrm{P}} = \frac{\mathrm{P}}{0.003465} \times 10^{-3}\ [\mathrm{MPa}] \tag{4}$$

For calculation of the maximum base adhesion, additional adhesion tests were performed for a "clean" core without mud cake, which was only wetted with a hybrid washer. However, to calculate the minimum adhesion, a test was performed for the core with the mud cake. Successive test results were compared to these values (maximum and minimum base adhesion). All cores were filled with set cement of the same composition and parameters presented in Table 2. The base values are shown in Table 3.

Table 3. Base adhesion to the contact between hardened cement slurry and rock.

	The Strength of Breaking Adhesion (kN)	Adhesion to Contact between HARDENED Cement Slurry and Rock (MPa)
Maximum base adhesion	8.2	2.37
Minimum base adhesion	2.1	0.61

3. Results and Discussion

The adhesion to the contact between the cement sheath and the rock core, with the mud cake, ranged from 1.01 to 1.24 MPa. The hybrid washer allowed removing the mud cake, which gave an adhesion of 2.26 MPa. Comparing the results to the minimum base adhesion of 0.61 MPa, the increase in adhesion value was from 66% (using water as a washing liquid) to 103% (using the previously used washing liquid MDC (MDC—Washing agent with the name coded by the manufacturer) agent). On the other hand, the new hybrid washer resulted in a 271% increase in adhesion compared to the base adhesion. Comparing the adhesion values with the maximum base adhesion, which was equal to 2.37 MPa (Table 4), the obtained results ranged from 57% lower than when washing with water to less than 5% when using the hybrid washer. The obtained values, together with a comparison to the maximum and minimum base adhesion, are presented in Table 4 [34]. A comparison of the results of the mud-cake efficiency in the liquid used and the base value is shown in Figure 12 [34].

During the tests, the mud cake was formed on the surface of the rock (reference sample), which was then removed with various washing liquids (water was used as the standard liquid). The tests were carried out in a drilling fluid flow simulator, which mapped the pumping of liquids from the well conditions to the laboratory conditions. The effect of selected washing liquids on the effectiveness of washing the annular space was determined by measuring the adhesion to the contact between the hardened cement slurry and the rock core, cleared of the created mud cake.

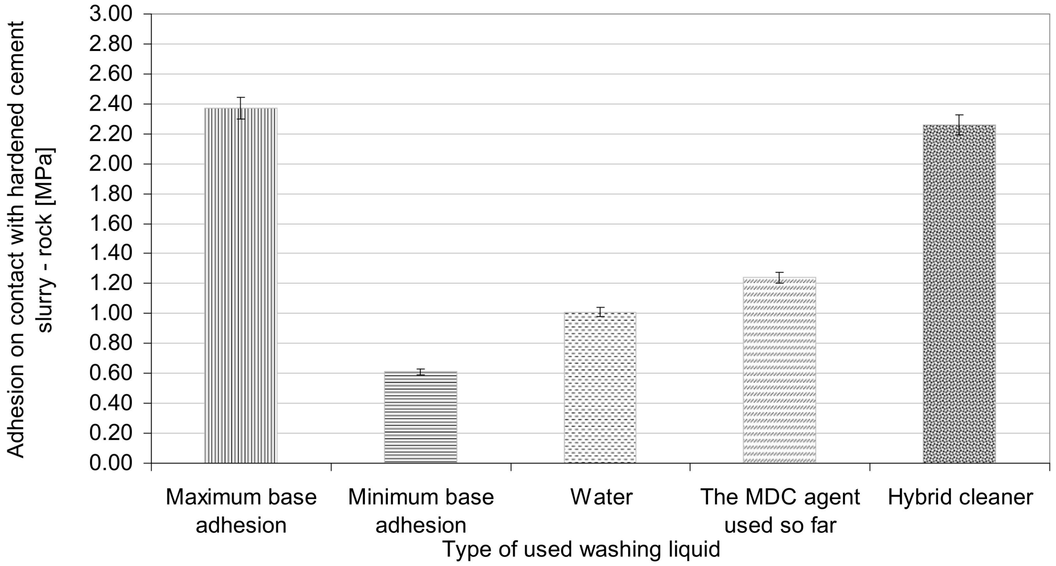

Figure 12. Adhesion to contact between hardened cement slurry and rock for various washing liquids at a delivery rate of 11.2 L/min; contact time of the washing liquid, 4 min.

Table 4. Adhesion values for the hardened cement slurry–rock contact for selected washing liquids. Contact time of the liquid, 4 min; flow rate, 11.2 L/min.

Type of Flushing Liquid	Adhesion Breaking Strength (kN)	Adhesion to Hardened Cement Slurry–Rock Contact (MPa)	Percentage Reduction in Adhesion Compared to the Maximum Base Adhesion	Percentage Increase in Adhesion Compared to the Minimum Base Adhesion
Maximum base adhesion	8.2	2.37	—-	—-
Minimum base adhesion	2.1	0.61	—-	—-
Water	3.5	1.01	↓ 57%	↑ 66%
The MDC agent used so far	4.3	1.24	↓ 48%	↑ 103%
Hybrid drilling washer fluid	7.8	2.26	↓ 5%	↑ 271%

The research showed a significant increase in adhesion to the contact between the hardened cement slurry and rock formation and, thus, an improvement in the removal of mud cake after using the hybrid washer. The designed hybrid washer has a dual-purpose washing action (chemical and mechanical). Furthermore, 0.01% defoamer was added to limit the formation of foam in the wash. The use of a hybrid washer resulted (in laboratory conditions) in an almost threefold increase in adhesion compared to the minimum base adhesion. This value is almost comparable to the value of maximum base adhesion of 2.37 MPa. The hybrid washer caused a reduction in the adhesion value in relation to the maximum base value by only 5% (Table 3). The hybrid washer is considered to best remove precipitate generated from the polymer–potassium scrubber.

The addition of abrasive fractions to the washing liquid had a very positive effect on the effectiveness of the washing removal of mud cake. This was visible during the studies on the removal of mud cake formed from the polymer–potassium scrubber. It should be rememberd that the high efficiency of a given liquid cannot be generalized, and the differentiation of the washing mud cake must be taken into account. The different nature of the mud cake depends on the type of rock drilled through, the type and parameters of the drilling fluid, and the well conditions (temperature and pressure). Therefore, it is necessary to individually select the washing liquid for a given borehole and the existing geological and technical conditions.

4. Conclusions

1. On the basis of the obtained test results, it can be stated that the best efficiency in removing the mud cake produced from the polymer–potassium scrubber was achieved using the washing liquid containing a mixture of suitably selected agents.
2. The addition of fine-grained and coarse-grained abrasive fractions to the washing liquid resulted in an improvement in the mud-cake removal efficiency through additional mechanical stripping of the washing mud cake formed.
3. The developed hybrid washer showed very good washing properties due to both its chemical and its mechanical influence on the washing mud cake formed on the rock surface.
4. The use of a hybrid washer resulted in an almost threefold increase in the value of adhesion to the contact between the hardened cement slurry and the rock formation. This value was almost comparable to the maximum base adhesion.
5. The use of a hybrid washer caused a reduction of less than 5% in the adhesion value in relation to the maximum base value (adhesion to the contact between the hardened cement slurry and rock formation).
6. The hybrid washer is considered to be the best liquid for removing mud cake from the polymer–potassium scrubber.

Funding: This work was financially supported by the Ministry of Science and Higher Education Warsaw (Internal order Oil and Gas Institute—National Research Institute Project No. 58/KW/17 and 0015/KW/21).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Acknowledgments: The author thanks the anonymous reviewers for their constructive comments and the editor for handling the paper.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Kremieniewski, M.; Rzepka, M. *Przyczyny i Skutki Przepływu Gazu w Zacementowanej Przestrzeni Pierścieniowej Otworu Wiertniczego Oraz Metody Zapobiegania Temu Zjawisku*; Nafta-Gaz: Hünenber, Switzerland, 2016; p. 9. [CrossRef]
2. Błaż, S. *Nowe Rodzaje Cieczy Przemywających Osady z Płuczki Inwersyjnej Przed Zabiegiem Cementowania Otworów Wiertniczych*; Nafta-Gaz: Hünenber, Switzerland, 2017; Volume 5, pp. 302–311. [CrossRef]
3. Kremieniewski, M.; Kędzierski, M. *Badanie Frakcjonowania Lekkich Materiałów Obniżających Gęstość Jako Wstępnego Parametru Podczas Projektowania Receptury Zaczynu Lekkiego*; Nafta-Gaz: Hünenber, Switzerland, 2019; Volume 12, pp. 35–42. [CrossRef]
4. Ryan, D.F.; Browne, S.V.; Burnham, M.P. Mud clean-up in horizontal wells: A major joint industry study. In Proceedings of the Paper Presented at the SPE Annual Technical Conference and Exhibition, Dallas, TX, USA, 22–25 October 1995. [CrossRef]
5. Kremieniewski, M. *Ocena Skuteczności Oczyszczania Kolumny Rur Okładzinowych Przed Cementowaniem na Podstawie Badań Przy Użyciu Wiskozymetru Obrotowego*; Nafta-Gaz: Hünenber, Switzerland, 2018; Volume 9, pp. 59–66. [CrossRef]
6. Adari, R.B.; Miska, S.; Kuru, E.; Bern, P.A.; Saasen, A. Selecting drilling fluid properties and flow rates for effective hole cleaning in high-angle and horizontal wells. In Proceedings of the Paper Presented at the SPE Annual Technical Conference and Exhibition, Dallas, TX, USA, 1–4 October 2000. [CrossRef]
7. Jasiński, B. *Ocena Wpływu Cieczy Przemywającej na Jakość Zacementowania Rur w Otworze Wiertniczym po Użyciu Płuczki Glikolowo-Potasowej*; Nafta-Gaz: Hünenber, Switzerland, 2016; Volume 6, pp. 413–421. [CrossRef]
8. Kremieniewski, M. *Korelacja Skuteczności Usuwania Osadu za Pomocą Cieczy na Osnowie Jonowych (Anionowych) i Niejonowych SPCz*; Nafta-Gaz: Hünenber, Switzerland, 2019; Volume 3, pp. 38–48. [CrossRef]
9. Zamora, M.; Jefferson, D.T.; Powell, J.W. Hole-cleaning study of polymer-based drilling fluids. In Proceedings of the Paper Presented at the SPE Annual Technical Conference and Exhibition, Houston, TX, USA, 3–6 October 1993. [CrossRef]
10. Kremieniewski, M.; Kędzierski, M.; Rzepka, M. *Symulator Przepływu Cieczy Wiertniczych—Zasada Pomiaru i Możliwości Badawcze*; Nafta-Gaz: Hünenber, Switzerland, 2018; Volume 7, pp. 46–53. [CrossRef]
11. Bizhani, M.; Rodriguez Corredor, F.E.; Kuru, E. Quantitative evaluation of critical conditions required for effective hole cleaning in coiled-tubing drilling of horizontal wells. *SPE Drill Compl.* **2016**, *31*, 188–199. [CrossRef]
12. Kremieniewski, M. Recipe of lightweight slurry with high early strength of the resultant cement sheath. *Energies* **2020**, *13*, 1583. [CrossRef]
13. Kremieniewski, M. Ultra-lightweight cement slurry to seal wellbore of poor wellbore stability. *Energies* **2020**, *13*, 3124. [CrossRef]
14. Sanchez, R.A.; Azar, J.J.; Bassal, A.A.; Martins, A.L. The effect of drillpipe rotation on hole cleaning during directional well drilling. In Proceedings of the Paper Presented at the SPE/IADC Drilling Conference, Amsterdam, The Netherlands, 4–6 March 1997. [CrossRef]
15. Zima, G. *Wpływ Właściwości Płuczek Wiertniczych na Jakość Cementowania w Gazonośnych Poziomach Miocenu*; Nafta-Gaz: Hünenber, Switzerland, 2014; Volume 12, pp. 899–907.
16. Kremieniewski, M. *Badania nad Opracowaniem Hybrydowej Cieczy Buforowej*; Nafta-Gaz: Hünenber, Switzerland, 2020; pp. 517–526. [CrossRef]
17. Boyou, N.V.; Ismail, I.; Sulaiman, W.R.W.; Haddad, A.S.; Husein, N.; Hui, H.T.; Nadaraja, K. Experimental investigation of hole cleaning in directional drilling by using nano-enhanced water-based drilling fluids. *J. Pet. Sci. Eng.* **2019**, *176*, 220–231. [CrossRef]
18. Kremieniewski, M. *Korelacja Skuteczności Działania Środków Dyspergujących o Różnym Mechanizmie Upłynniania*; Nafta-Gaz: Hünenber, Switzerland, 2020; pp. 816–826. [CrossRef]
19. Hirpa, M.M.; Arnipally, S.K.; Kuru, E. Effect of the particle size on the near-wall turbulence characteristics of the polymer fluid flow and the critical velocity required for particle removal from the sand bed deposited in horizontal wells. *Energies* **2020**, *13*, 3172. [CrossRef]
20. Sifferman, T.R.; Becker, T.E. Hole cleaning in full-scale inclined wellbores. *SPE Drill Eng.* **1992**, *7*, 115–120. [CrossRef]
21. Zhang, F.; Miska, S.; Yu, M.; Ozbayoglu, E.; Takach, N.; Osgouei, R.E. Is well clean enough? A fast approach to estimate hole cleaning for directional drilling. In Proceedings of the Paper Presented at the SPE/ICoTA Coiled Tubing & Well Intervention Conference & Exhibition, The Woodlands, TX, USA, 24–25 March 2015. [CrossRef]
22. Saasen, A.; Løklingholm, G. The effect of drilling fluid rheological properties on hole cleaning. In Proceedings of the Paper Presented at the IADC/SPE Drilling Conference, Dallas, TX, USA, 11 February 2002. [CrossRef]
23. Sayindla, S.; Lund, B.; Ytrehus, J.D.; Saasen, A. Hole-cleaning performance comparison of oil-based and water-based drilling fluids. *J. Pet. Sci. Eng.* **2017**, *159*, 49–57. [CrossRef]
24. Wiśniowski, R.; Skrzypaszek, K.; Małachowski, T. Selection of a suitable rheological model for drilling fluid using applied numerical methods. *Energies* **2020**, *13*, 3192. [CrossRef]
25. Li, J.; Walker, S. Sensitivity analysis of hole cleaning parameters in directional wells. *SPE J.* **2001**, *6*, 356–363. [CrossRef]

26. Okrajni, S.; Azar, J.J. The effects of mud rheology on annular hole cleaning in directional wells. *SPE Drill Eng.* **1986**, *1*, 297–308. [CrossRef]
27. Bilgesu, H.; Nekkhil, I.M.; Ameri, S. Understanding the effect of drilling parameters on hole cleaning in horizontal and deviated wellbores using computational fluid dynamics. In Proceedings of the Paper Presented at the Eastern Regional Meeting, Lexington, KY, USA, 17–19 October 2007. [CrossRef]
28. Ahmed, A.; Mahmoud, A.A.; Elkatatny, S.; Chen, W. The effect of weighting materials on oil-well cement properties while drilling deep wells. *Sustainability* **2019**, *11*, 6776. [CrossRef]
29. Valluri, S.G.; Miska, S.; Yu, M.; Ahmed, R.M.; Takach, N. Experimental study of effective hole cleaning using sweeps in horizontal wellbores. In Proceedings of the Paper Presented at the SPE Annual Technical Conference and Exhibition, San Antonio, TX, USA, 24–27 September 2006. [CrossRef]
30. Yu, M.; Takach, N.; Nakamura, E.; David, R.; Shariff, M.M. An experimental study of hole cleaning under simulated downhole conditions. In Proceedings of the Paper Presented at the SPE Annual Technical Conference and Exhibition, Anaheim, CA, USA, 11–14 November 2007. [CrossRef]
31. Rubaii, A.; Murif, M.; Sehsah Ossama, R.; Omini, E. Approach to improve well drilling performance. In Proceedings of the Paper Presented at the SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition, Dammam, Saudi Arabia, 23–26 April 2018. [CrossRef]
32. Saasen, A. Hole cleaning during deviated drilling—The effects of pump rate and rheology. In Proceedings of the Paper Presented at the European Petroleum Conference, The Hague, The Netherlands, 20–22 October 1998. [CrossRef]
33. Gbadamosi Afeez, O.; Junin, R.; Oseh Jeffrey, O.; Agi, A.; Yekeen, N.; Abdalla, Y.; Ogiriki Shadrach, O.; Adeyinka, S.Y. Improving hole cleaning efficiency using nanosilica in water-based drilling mud. In Proceedings of the Paper Presented at the SPE Nigeria Annual International Conference and Exhibition, Lagos, Nigeria, 6–8 August 2018. [CrossRef]
34. Kremieniewski, M., Rzepka M. Hybrydowa Ciecz Przemywająca Do Oczyszczania Przestrzeni Pierścieniowej Otworu Wiertniczego; Nafta-Gaz: Hünenber, Switzerland, 2018; Volume 5, pp. 372–379. [CrossRef]