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Comparison of Efficient Ways of Mud Cake Removal from Casing Surface with Traditional and New Agents

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Abstract: The tightness of the casing-rock formation interface is one of the most important elements of drilling and cementing jobs. In the absence of the required tightness, there is a risk of gas migration directly to the ground, groundwater or atmosphere. In order to eliminate this type of uncontrollable and unfavorable gas flows, the casing column is sealed with cement slurry in the annular space or beyond casing. Cement slurry displaces mud present in the annular space, although the mud cake cannot be completely removed, which is required for obtaining proper binding of cement slurry with the casing surface and the surface of the drilled formation. Therefore, it is important to prepare the well and remove the mud cake from the annular space with spacer fluid. An occasional lack of wellbore tightness requires continuous improvement of the cementing technology. Accordingly, analyses are conducted on mud cake removal with modified or new spacer fluids. Properly designed fluid should efficiently clean the surface of the casing and of the rock mass. One of the basic measurements is the analysis of the efficiency of mud cake removal from the surface of a rotational viscometer. The efficiency of traditional and newly designed fluids for mud cake removal from the casing surface with new and traditional agents has been compared further in this paper. The methodology of mud cake removal with the use of a rotational viscometer was also presented. Tests were performed for various concentrations of agents already used for spacer fluids and for a group of new agents. The efficiency of annular space cleaning was determined on the basis of a comparison with the results obtained for the reference sample, i.e., water which was used for mud cake removal from the rotor surface. The analysis of the results of experiments created bases for the comparison of the efficiency of the analyzed spacer fluids and finding the most suitable ones for mud cake removal from casing columns.

Keywords: cleaning of annular space; casing column; mud cake; cementing of a wellbore; surface active agents

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1. Introduction

One of the major problems recently encountered in the oil industry has been the lack of tightness in wellbores; therefore, special emphasis is put on wellbore cementing and pre-cementing jobs, i.e., cleaning of the annular space from mud cake residue. Scientific and research institutions, such as the Oil and Gas Institute—National Research Institute and the Faculty of Drilling, Oil and Gas at AGH-UST, have already cooperated to improve cementing conditions, as well as modifying or creating new drilling fluids. Recently, attention has been paid to methods which can increase mud cake removal from the annular space. Spacer fluids were analyzed, and their composition was modified [1–3].

Before cementing, a sequence of fluids is usually injected to the annular space in order to displace drilling mud and mud cake residues. The parameters of mud used for drilling are adjusted to the wellbore conditions, but they frequently have an unfavorable effect on mud cake removal [4–6]. Therefore, it is important to properly modify mud parameters before cementing jobs, i.e., to change rheological parameters during mud treatment after casing the well [7–9]. After lowering the mud's yield point, the pre-cementing jobs continue and advancing fluids (spacer and cushion fluids) are introduced [10]. The advancing fluids are required [11,12] to leave the casing column and the surface of rock formation water-wet to improve the binding ability of the injected cement slurry. These fluids should also be pumped turbulently to improve the efficiency of mud and mud cake removal [13]. Importantly, a possibility of cracks in the rock formation should be eliminated if the injection yield and hydrostatic pressure were to increase excessively. The contact time of the advancing fluids in the annular space or beyond the pipes should be long enough to provide an optimal removal of drilling mud and mud cake from the casing and the rock formation. The advancing fluid should be easy to remove from the annular space with the injected cement slurry [3,6,12,14].

The efficiency of advancing fluids depends, inter alia, on the contact time of fluid with the surfaces in the annular space. Such fluids include spacers (unloaded fluids) and loaded cushion fluids (buffers) (see Figure 1). Spacers cause a strong drilling mud dispersion and have a rheological characteristic described with the Newtonian model [14]. Spacer fluids are especially efficient when they go in a turbulent flow because of its low plastic viscosity values [15]. Spacer fluids are used for cleaning the annular space from drilling mud residue. With spacer fluids, the adhesiveness of cement slurry to the casing column and the drilled geological profile can be considerably improved [11,16–18]. Mud residue can be thoroughly removed with the use of chemical spacers, which are a mixture of solvents and surface-active agents; therefore, their technological parameters should be properly designed [11,12,18].

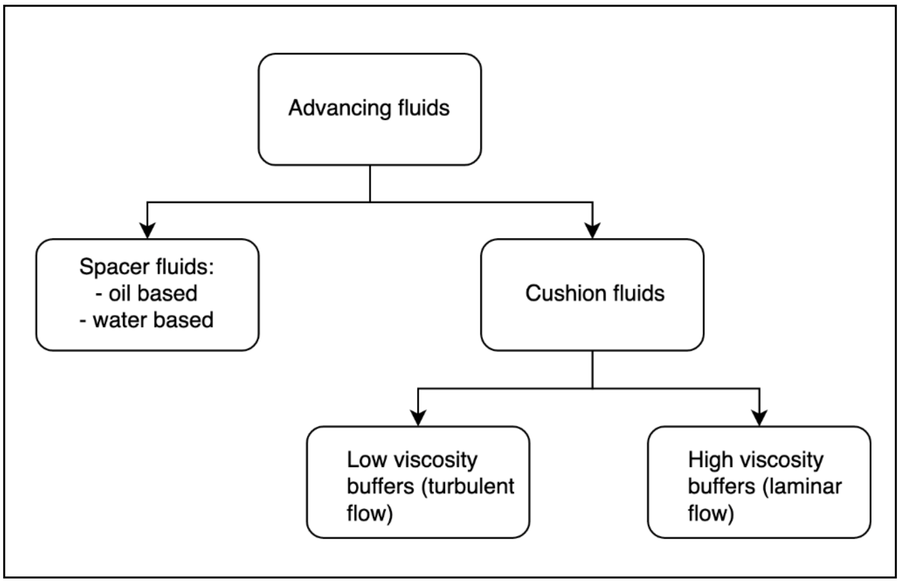

Figure 1. Classification of advancing fluids.

If spacer fluid is injected in a turbulent flow, the efficiency of mud cake removal is high, which is certainly an advantage of low viscosity spacers. However, in this case, there is a risk of formation fluid flux occurrence when circulation stops. This is due to the low viscosity of spacer fluids. Accordingly, when working out the advancing fluids schedule, one should make sure that the hydrostatic pressure in the annular space does not drop below the reservoir pressure value. The hydrostatic pressure of spacer fluid can be maintained on a required level after adding some load to the spacer fluid, which gives it properties of the cushion fluid. It should be noted that densifying agents added to the spacer fluid require applying agents which increase its viscosity, and this may result in lower adhesiveness to the hardened cement/casing/rock interface. In this case, it would be better to apply the spacer fluid first and then the properly loaded cushion fluid. The efficiency of mud cake removal from the flushed surfaces in the annular space (casing and rock formation) depends on a number of parameters. Apart from the above-mentioned contact time of fluid with flushed surfaces, the following factors are of importance [3,4,6]:

- Injection yield and the associated flow rate of spacer fluid in annular space;
- Chemical composition of agents used for making spacer fluids;
- Concentration of surface-active agents, surfactants or other additives applied to the spacer;
- Type of surface from which a mud cake is removed;
- Type of applied mud and its technological parameters. Recent studies show that the use of nanoparticles in drilling fluids has a positive effect on the reduction of a mud cake [19,20];
- Borehole conditions (temperature and pressure).

Attention should also be paid to a considerably different behavior of a mud cake on the surface of the casing and on the rock formation, especially the coefficient of mud cake filtration to the rock formation and the lack of filtration if casing surfaces are involved. The coarseness of the casing surface is very important. Therefore, one should take into account the complexity of mud cake removal from various surfaces.

The current research aims to improve the efficiency of sealing wellbores by increasing the mud cake removal efficiency. In the current research, both traditional and new agents for improving mud cake removal from the annular space have been used. Laboratory experiments were followed by the analysis of the obtained results. Finally, new spacer fluids were worked out and compared with the traditional ones for their efficiency in mud cake removal.

2. Materials and Methods

Research works aimed at comparing the efficiency of mud cake removal from the casing surface with new and traditional agents were performed in the Oil and Gas Institute—National Research Institute in co-operation with the Faculty of Drilling, Oil and Gas at AGH-UST based on the following standards:

- PN-85/G-02320 *Cements and cement slurries used for cementing wellbores*;
- PN-EN 10426-2 *Oil and gas industry. Cements and materials for cementing wellbores. Part 2: Analysis of drilling cements*;
- API SPEC 10 *Specification for materials and testing for well cements*.

The efficiency of the selected spacer fluids was compared based on the measurement of mud cake removal from the surface of a rotational viscometer rotor. This was one of the basic tests for determining the mud cake removal efficiency. This type of test can be carried out for spacer fluids before cementing jobs and at the stage of selecting the quality and quantity of agents for spacer fluids or during replacement of spacer fluids with packer fluid. The test consisted of putting the rotor of the rotational viscometer in mud, representing the surface of the casing in drilling mud, and generating sediment on its surface, being the result of rotor rotations at a given speed. The linear speed of a spacer fluid flow was calculated for rotational speed with dependence of linear speed on angular speed:

$$\omega = \frac{v}{R} \tag{1}$$

where ω is the angular speed [rad/s], or leaving out radians [1/s = s^{-1}]; R is the radius of a circle containing the arc [m]; v is the linear speed, i.e., 'regular' speed of a point [m/s]:

$$v = \omega \times R \tag{2}$$

Substituting the definition of an angle to the formula for linear speed:

$$\omega = \frac{\Delta\alpha}{\Delta t} = \frac{\frac{\Delta L}{R}}{\Delta t} = \frac{\Delta L}{\Delta t} * \frac{1}{R} \quad (3)$$

Taking into account that linear speed equals to:

$$\frac{\Delta L}{\Delta t} = v \quad (4)$$

The equation for angular speed is obtained:

$$\omega = \frac{v}{R} \quad (5)$$

As the casing surface is coarser than the surface of the viscometer's rotor, a grid was introduced (see Figure 2)—the mesh and thickness of the string are indicated in Figure 2. This type of modification allowed for capturing more mud sediments during the rotational movement. After a mud cake had been produced on the modified rotor surface (see Figure 3), it was flushed with spacer fluid (see Figure 4). In the literature [2,3], the rotational speed during the tests was 100 rpm. However, on the basis of calculations of drilling fluid flow speed and the performed preliminary tests, the rotational speed was set to 60 rpm and the liquid contact time was 5 min.

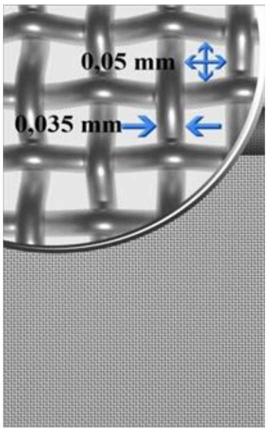

Figure 2. Mesh placed on the rotational viscometer's rotor.

Figure 3. Rotor with a mud cake.

During the tests on mud cake removal from the casing with a rotational viscometer, the rotor was weighted before the cake managed to form on it (m_0). Then, the cake was formed and the rotor was re-weighted with the cake (m_1). The rotational movement of the rotor in spacer fluid removed the cake from the rotor surface. Afterward, the rotor with mud cake residue (m_2) was re-weighted. On this basis, the efficiency of mud cake removal (%) was determined with the formula:

$$\% = 100 \times \frac{m_1 - m_2}{m_1 - m_0} \quad (6)$$

where % is the mud cake removal in percentages; m_0 is the rotor weight before the test (without mud cake); m_1 is the rotor weight with the mud cake; m_2 is the rotor weight with mud cake residue (after flushing).

Figure 4. Removal of a mud cake from the rotor surface.

In this research, a clay-free polymer-potassium wellbore mud containing contaminants from the 7″ casing interval was used. The sediment produced with this type of mud was used for determining the efficiency of a given spacer fluid. For measuring the efficiency of mud cake removal from the casing, the mud cake formed on the rotor surface was removed with preselected spacer fluids. The obtained value was compared with the reference efficiency value for water. The applied spacer fluids contained 0.5%, 1% and 5% of the following traditional agents:

- MDC—anionic surface-active agent used for cleaning the annular space;
- RL8—ethoxylated alcohol C9-C11 non-ionic surface-active compound;
- CD—fatty alcohol alkyl polyglucoside C8-C10.

Then, the obtained efficiency values were compared with the fluid efficiency based on the following new agents:

- SL225—ethoxylated alcohol C12-C14 (anionic surfactant from alkyl ether sulfate group);
- SL327—ethoxylated alcohol C12-C15 (anionic surfactant from alkyl ether sulfate group);
- RB2—ethoxylated alcohol C16-C18 (non-ionic surface-active compound used as a component of cleaning and washing products);
- RB7—ethoxylated alcohol C12-C15 (used as an intermediate product for cleansing, cleaning and washing preparations);
- RL80—ethoxylated alcohol C12-C14 (surface active agent used for wetting and as a non-ionic component of emulsifiers);
- RL22—ethoxylated alcohol C12-C14 (non-ionic surface-active compound used as emulsifier).

The new agents were applied in the same concentrations: 0.5%, 1% and 5%.

3. Results

The results of the tests of the efficiency of mud cake removal using traditional agents have been presented in Table 1.

Table 1. Efficiency of mud cake removal from the rotor's surface with traditional agents.

Agent	Concentration of Spacer Fluids [%]	Weight of Rotor before Test m_0 [g]		Weight of Rotor after Mud m_1 [g]		Weight of Rotor after Spacer Fluid m_2 [g]		Flushing		% of Flushing (Cake Removal) Average Value	Efficiency Change of Cake Removal Relative to Ref. Value (Water) [%]
water	—	72.18	72.21	74.57	74.85	73.27	73.36	54.39	56.44	55.42	0.0
MDC	0.5%	72.18	72.14	74.32	74.49	72.72	72.77	74.77	73.19	73.98	33.50
	1.0%	72.25	72.32	74.42	74.27	72.8	72.78	74.65	76.41	75.53	36.30
	5.0%	72.2	72.22	74.31	74.22	72.84	72.85	69.67	68.50	69.08	24.66
RL8	0.5%	72.29	72.28	73.93	74.22	72.68	72.94	76.22	65.98	71.1	28.30
	1.0%	72.11	72.13	74.09	74.13	72.57	72.7	76.77	71.50	74.13	33.78
	5.0%	72.11	72.13	74.09	74.13	72.57	72.64	76.77	74.50	75.63	36.48
CD	0.5%	72.18	72.24	74.3	74.35	72.71	72.89	75.00	69.19	72.1	30.10
	1.0%	72.13	72.25	74.25	74.29	72.68	72.75	74.06	75.49	74.77	34.93
	5.0%	72.35	72.43	74.4	74	72.88	72.79	74.15	77.07	75.61	36.44

At the beginning, the reference test with water as spacer fluid was performed and the reference value of 55.4% was obtained. Then, spacer fluids with traditional agents were used.

MDC (0.5%, 1.0% and 5.0%) was tested at first. The 0.5% MDC concentration resulted in 73.98% efficiency of mud cake removal from the rotor surface. A doubled MDC concentration (1.0%) caused a slight increase of the efficiency of mud cake removal (75.53%). The 5% concentration of MDC lowered the efficiency of mud cake removal to 69.08%. Another traditional agent used for mud cake removal was RL8. The following mud cake removal efficiency values were obtained for the 0.5%, 1% and 5% RL8 concentrations: 71.1%, 74.13% and 75.63%, respectively. The third agent used with a spacer fluid was CD. The obtained efficiency of mud cake removal ranged from 72.1% for the 0.5% CD concentration to 75.61% for the 5% CD concentration. The obtained results listed in Table 1 were visualized in the Figure 5.

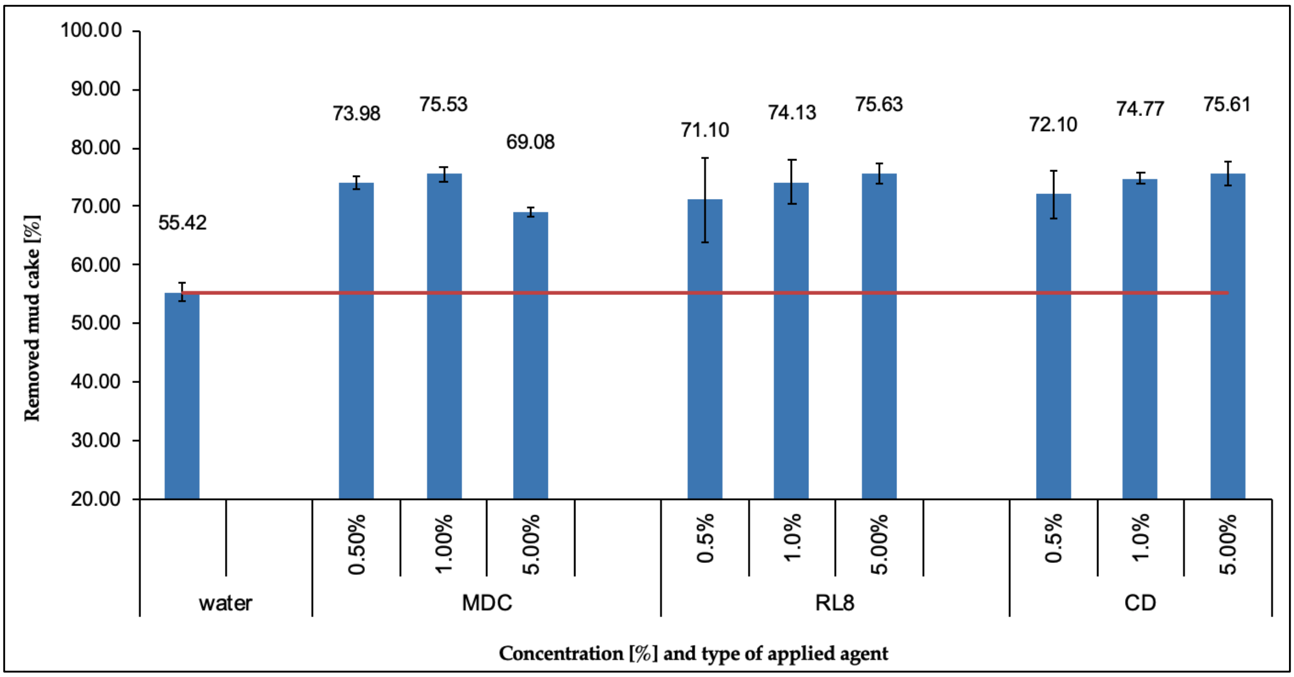

Figure 5. Efficiency of mud cake removal from the rotor's surface with traditional agents. The red line shows the reference value for water.

It should be emphasized that the efficiency of mud cake removal depends on the type and the parameters of the applied mud. Bearing this in mind, the obtained results were compared with a reference (water as a spacer fluid) value. The efficiency change of cake removal relative to the reference, water as a spacer fluid, was calculated using the formula below:

$$\text{Efficiency change of cake removal relative to ref. value } [\%] = \frac{\%\text{ of flushing (cake removal)} \times 100}{\text{ref. value}} - 100 \tag{7}$$

The comparative analysis revealed that MDC solutions generated an increase in the efficiency of mud cake removal from 24.66% to 36.30%, compared with the reference value (see Figure 6). The lowest efficiency change was observed for the maximal MDC concentration of 5%. The increase of efficiency of mud cake removal ranged from 28.30% to 36.48% for RL8 and from 30.1% to 36.44% for CD. The efficiency trend almost linearly increased with a percentage increase of RL8 and CD agents. In the case of MDC, the efficiency deteriorated for the 5% concentration, but it was still 24.66% better in comparison to the reference water value. The obtained test results have been listed in Table 1 and Figure 6. A level of 0% refers to the reference (water as a spacer fluid) value.

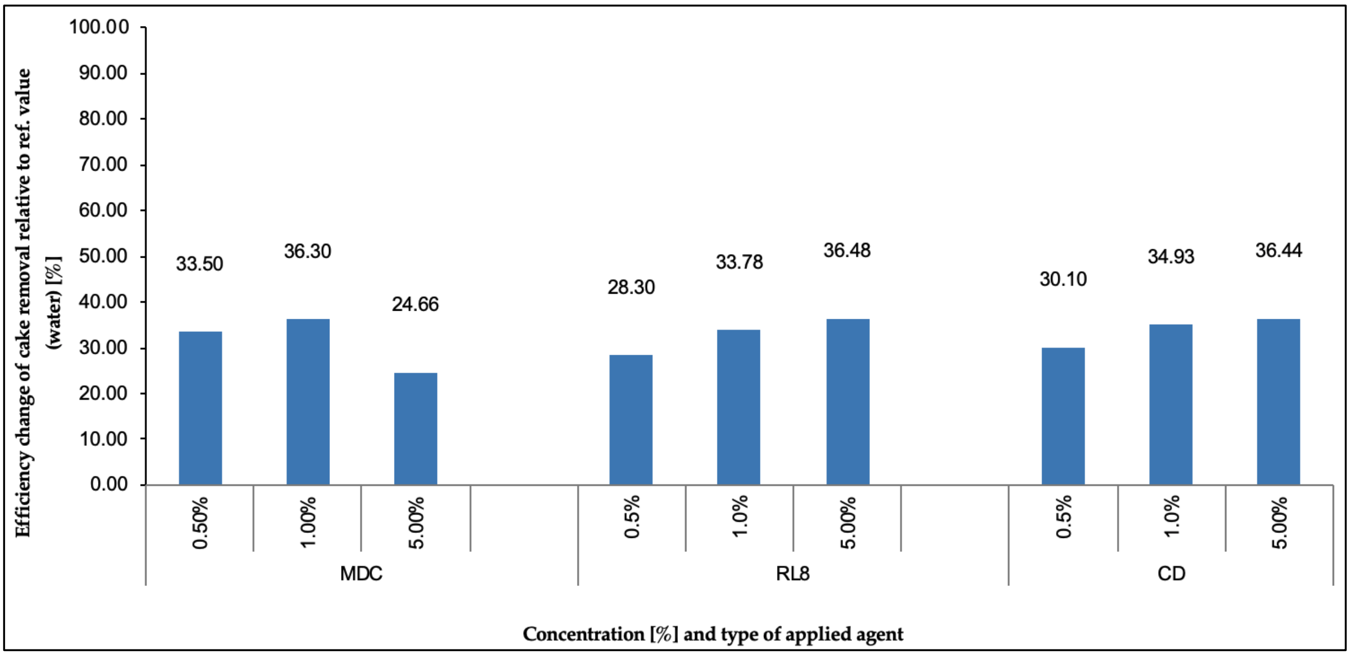

Figure 6. Percentage change in the efficiency of mud cake removal with traditional fluids compared with the reference value of water (55.42%).

At the successive stage, new agents were used for testing the efficiency of mud cake removal. The tests were performed similarly to the traditional substances and for the same concentrations of spacer fluids: 0.5%, 1.0% and 5.0%. The efficiency change of cake removal was calculated using formula 7. The results are presented in Table 2.

The flushing efficiency with fluids based on SL225 ranged between 61.37% and 69.12% (see Table 2 and Figure 7). In comparison with the water reference value, SL225 increased the efficiency of mud cake removal from 10.75% to 24.73% depending on its concentration (see Table 2 and Figure 8).

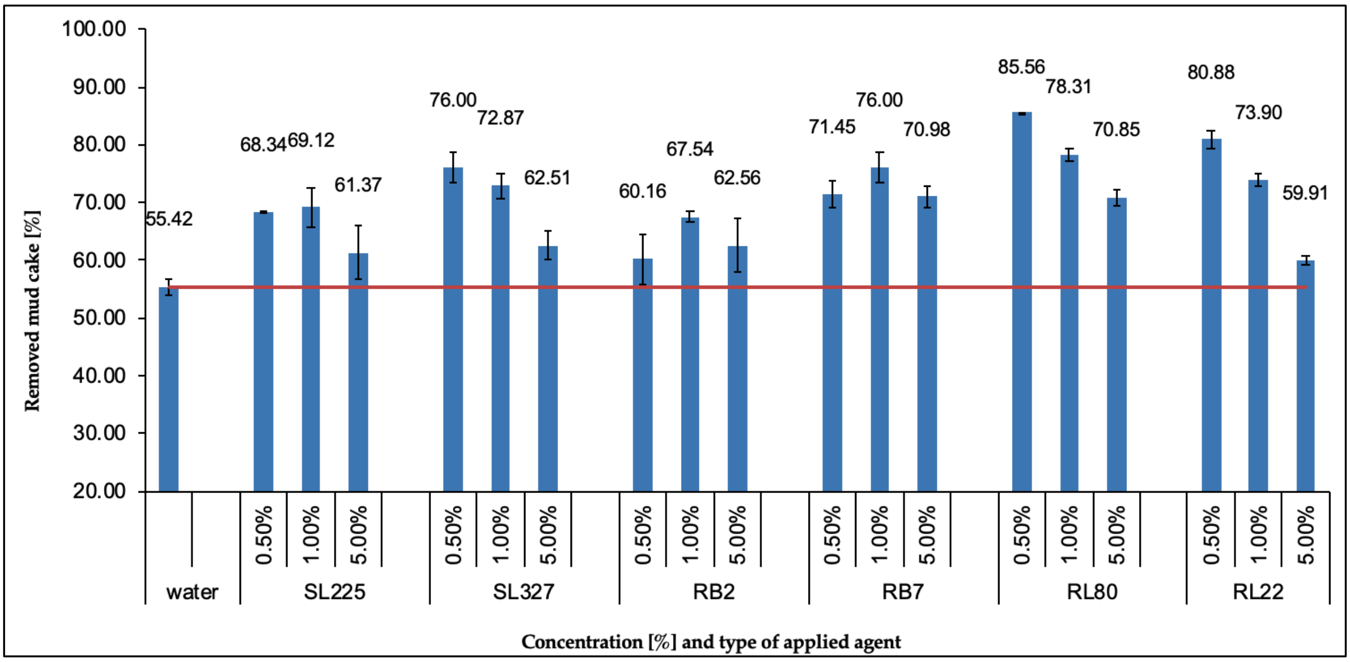

Figure 7. Efficiency of mud cake removal from the rotor's surface with new fluids. The red line shows the reference value for water.

Table 2. Efficiency of mud cake removal from the rotor's surface with new agents.

Agent	Concentration of Spacer Fluids [%]	Weight of Rotor before Test m_o [g]		Weight of Rotor after Mud m_1 [g]		Weight of Rotor after Spacer Fluid m_2 [g]		Flushing		% of Flushing (Cake Removal) Average Value	Efficiency Change of Cake Removal Relative to Ref. Value (Water) [%]
water	—	72.18	72.21	74.57	74.85	73.27	73.36	54.39	56.44	55.42	0.0
SL225	0.50%	72.11	72.13	74.09	74.13	72.74	72.76	68.18	68.50	68.34	23.32
	1.00%	72.09	72.19	74.35	74.43	72.84	72.83	66.81	71.43	69.12	24.73
	5.00%	72.12	72.21	74.53	74.36	73.13	72.97	58.09	64.65	61.37	10.75
SL327	0.50%	72.15	72.16	74.12	74.06	72.66	72.58	74.11	77.89	76.00	37.15
	1.00%	72.15	72.16	74.18	74.22	72.67	72.75	74.38	71.36	72.87	31.50
	5.00%	72.06	72.14	74.48	74.52	73.01	72.99	60.74	64.29	62.51	12.81
RB2	0.50%	72.14	72.15	74.49	74.52	73.15	73.02	57.02	63.29	60.16	8.55
	1.00%	72.14	72.11	74.43	74.19	72.9	72.77	66.81	68.27	67.54	21.88
	5.00%	72.06	72.18	74.42	74.08	73.02	72.83	59.32	65.79	62.56	12.88
RB7	0.50%	72.15	72.13	74.63	74.81	72.9	72.85	69.76	73.13	71.45	28.93
	1.00%	72.15	72.16	74.12	74.06	72.66	72.58	74.11	77.89	76.00	37.15
	5.00%	72.15	72.18	74.26	74.31	72.79	72.77	69.67	72.30	70.98	28.09
RL80	0.50%	72.15	72.17	74.09	74.04	72.43	72.44	85.57	85.56	85.56	54.40
	1.00%	72.17	72.19	74.4	73.86	72.67	72.54	77.58	79.04	78.31	41.31
	5.00%	72.1	72.16	73.87	74.09	72.6	72.74	71.75	69.95	70.85	27.85
RL22	0.50%	72.22	72.19	74.6	74.57	72.65	72.67	81.93	79.83	80.88	45.95
	1.00%	72.19	72.17	74.02	73.98	72.68	72.63	73.22	74.59	73.90	33.36
	5.00%	72.13	72.17	74.42	74.04	73.06	72.91	59.39	60.43	59.91	8.11

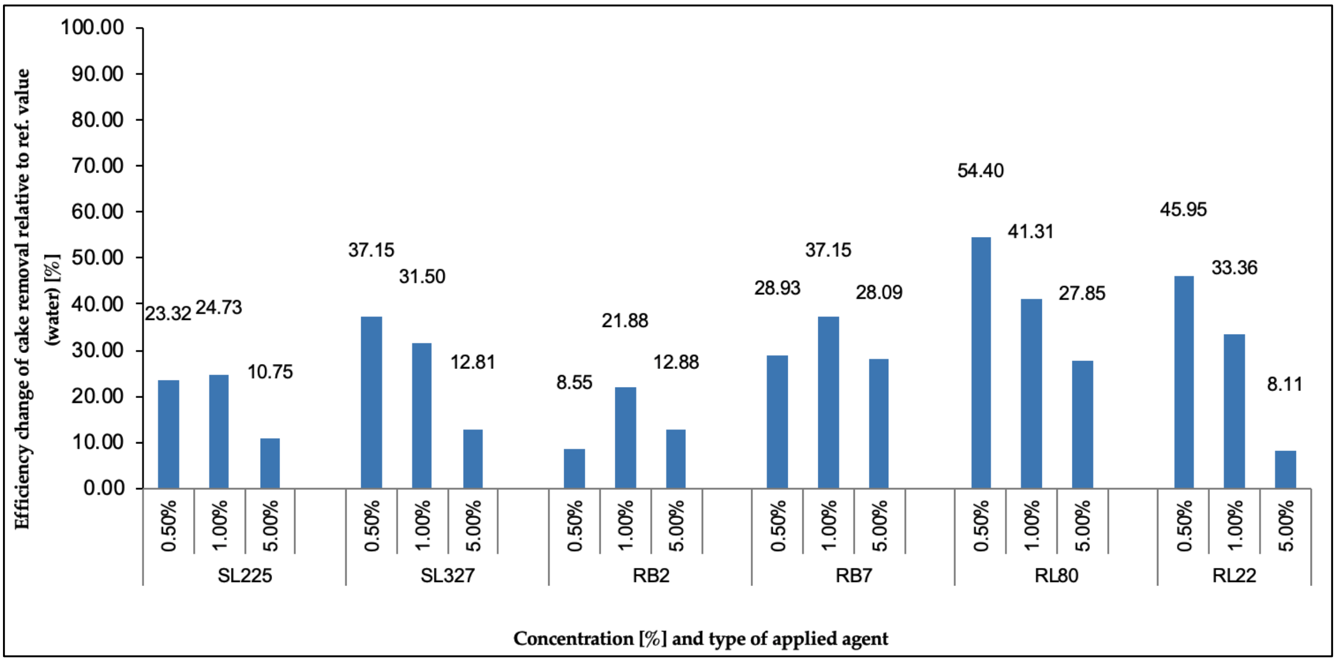

Figure 8. Percentage change in the efficiency of mud cake removal with new fluids as compared to the reference value of water (55.42%).

The second agent, on the basis of which a spacer fluid was prepared, was SL327. For the concentration of 0.5%, the efficiency of mud cake removal was 76%, i.e., a 37.15% increase of removal efficiency compared with the reference value. The concentration of 1% also increased the efficiency of flushing by 31.5% in comparison with water; however, as can be seen, the results are worse than for the concentration of 0.5%. Further increase of SL327 up to a concentration of 5% caused the smallest efficiency increase, by only 12.81% (see Table 2 and Figures 7 and 8).

RB2 was another agent used as a spacer fluid. With the 0.5% RB2 solution, 60.16% of the cake was removed and with 1% solution, 67.54% was removed (see Figure 7), being, respectively, an 8.55% and 21.88% increase compared with the reference water value (see Figure 8). A further increase of the RB2 concentration caused 62.56% of mud cake removal, which was 12.88% more efficient than water.

A test performed with the RB7 agent showed rotor cleaning efficiency equal to 71.45% for 0.5% concentration and 76% for 1% RB7 concentration. Similarly to the previous agents, in this case, a high concentration of RB7 also did not cause a further increase in cleaning. The results have been presented in Table 2 and Figures 7 and 8.

The successive tests were performed for various concentrations of RL80. At the lowest concentration (0.5%), the agent cleaning efficiency was very high, i.e., 85.56%, being a 54.4% increase in cake removal compared to the reference value (see Table 2 and Figure 8). A further increase of the RL80 concentration in the spacer fluid lowered its cleaning efficiency, giving the worst result for the 5% concentration.

The last analyzed agent was RL22. Its maximal efficiency of 80.88% was obtained for the 0.5% concentration. Higher concentrations of this agent deteriorated the efficiency of mud cake removal; a 5% concentration of the RL22 agent gave the worst results among all agents—only an 8.11% cleaning increase in reference to water. The obtained results are listed in Table 2 and Figures 7 and 8.

The analysis of the results reveals changes in the behavior of spacer fluids depending on the concentration of the agent used. For traditional fluids, the efficiency of mud cake removal is comparable within the analyzed range of concentrations, as presented in Figure 9. Only the 5% MDC solution sticks out from the polynomial tendency. The analysis of the plot in Figure 10 shows that new agents behave differently from the traditional ones. Higher efficiencies were observed at lower concentrations of the analyzed agents. The polynomial trend line in Figure 10 decreases with an increase of agents' concentration. The observed behavior of the analyzed fluids can be attributed to the critical micelle concentration, i.e., a given medium is efficient if its free parts are in equilibrium with the aggregated forms and the increase of concentration evokes aggregates formation, thus weakening the efficiency of the cleaning fluid [21].

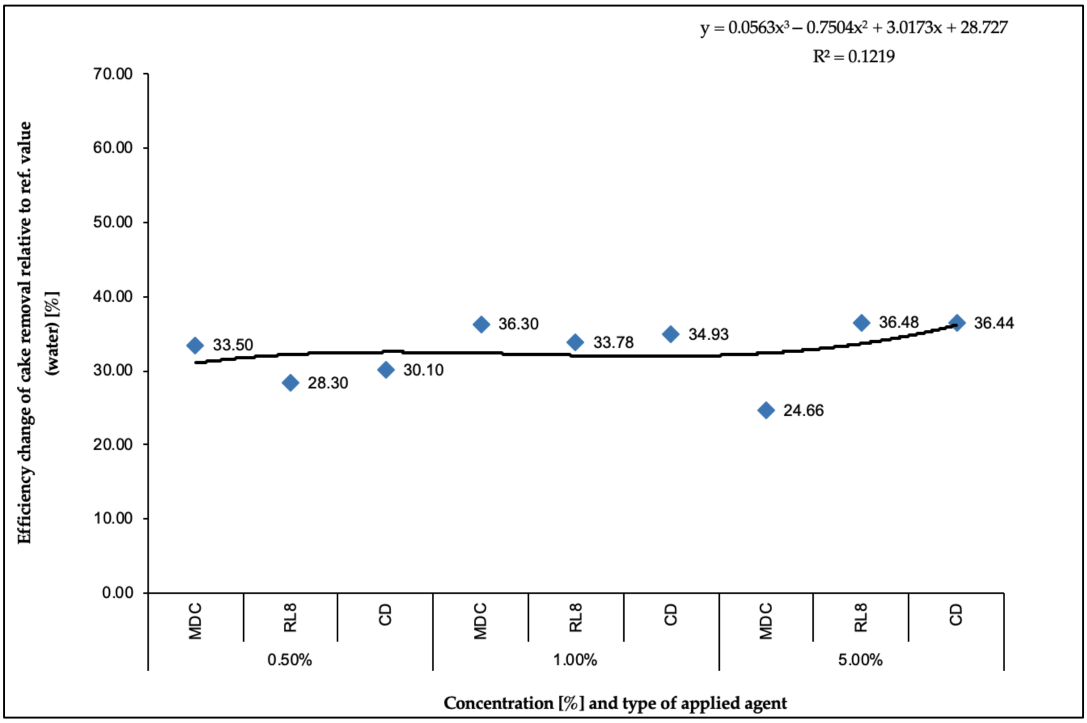

Figure 9. Efficiency change of cake removal with traditional agents, depending on the applied concentration. Water was used as a reference value.

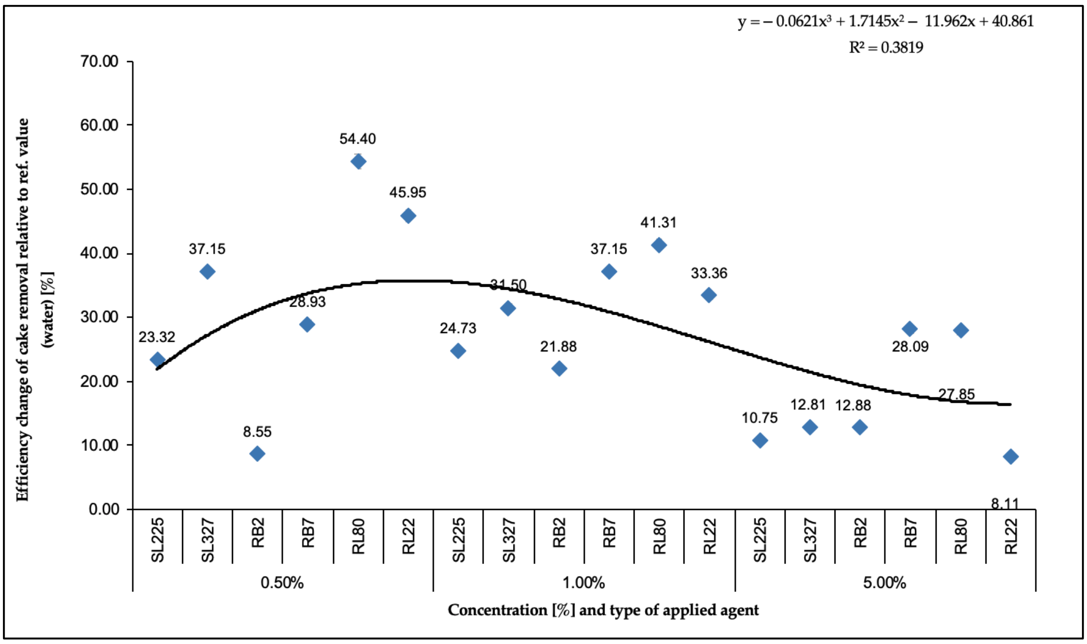

Figure 10. Efficiency change of cake removal with new agents, depending on the applied concentration. Water was used as a reference value.

4. Discussion

The analysis of the results shows that the efficiency of the traditional agents was comparable. The efficiency of mud cake removal from the rotor surface stayed within a relatively narrow interval from 69.08% to 75.63%. With a growing concentration of the traditional agents, the efficiency of mud cake removal slightly increased, excluding the 5% MCD concentration, which lowered the efficiency of a spacer fluid; however, the result was still 24.66% better in comparison with water. If not for this exception, the efficiency of all traditional agents would be comparable, as shown in Figure 9. It should be noted that the efficiency of all fluids based on traditional agents was not lower than the reference value of water, 55.42%.

The comparison of the efficiency of mud cake removal with new agents showed a bigger differentiation between them. The efficiency of mud cake removal from the rotor surface with fluids based on new agents ranged from 59.91% to 85.56%, which was an increase from 8.11% to 54.40% in relation to the reference value (water as a spacer fluid). The highest efficiency was observed for agents applied in 0.5% and 1.0% concentrations. A significant efficiency deterioration was observed for 5% solutions as visualized in Figure 10.

The analyzed agents turned out to be economically advantageous. Even for the lowest (0.5%) concentrations, very high mud cake removal values were obtained. Attention should be paid to the critical micelle concentration—after exceeding of which the efficiency of a given agent declines considerably. Therefore, preliminary tests on the efficiency of a given agent in terms of its concentration should be performed.

5. Conclusions

(1) The traditional agents had a comparable efficiency of operation.
(2) The efficiency of mud cake removal from the rotor surface (casing) for the traditional agents ranged from 69.08% to 75.63%.
(3) For the traditional agents, the percentage efficiency change of mud cake removal as compared with the water reference value ranged from 24.66% to 36.48%. With one exception (5% MDC), it increased with the increase of concentration.
(4) The efficient applicability range of traditional agents was 0.5% to 5%.
(5) New agents used for preparing spacer fluids were diversified in their efficiency, depending on the applied concentrations.
(6) The efficiency of mud cake removal with fluids based on new agents ranged from 59.91% to 85.56%.
(7) The percentage efficiency change of mud cake removal as compared with the reference value ranged from 8.11% to 54.40%.
(8) The most efficient applicability range for new agents was observed for the 0.5% and 1% solutions. The worst efficiency was observed for the 5% solutions, except RB2, for which the worst result was observed for the 0.5% solution.
(9) An increase over 1% of the concentration of new agents resulted in exceeding the critical micelle concentration, and thus, considerable deterioration of the efficiency of the spacer fluids.

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