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Invert Drilling Fluids with High Internal Phase Content

Sławomir Błaż , Grzegorz Zima, Bartłomiej Jasiński and Marcin Kremieniewski *

Oil and Gas Institute–National Research Institute, 31-503 Krakow, Poland; blaz@inig.pl (S.B.); zima@inig.pl (G.Z.); jasinski@inig.pl (B.J.)
* Correspondence: kremieniewski@inig.pl

Abstract: One of the most important tasks when drilling a borehole is to select the appropriate type of drilling fluid and adjust its properties to the borehole's conditions. This ensures the safe and effective exploitation of the borehole. Many types of drilling fluids are used to drill holes for crude oil and natural gas. Most often, mainly due to cost and environmental constraints, water-based muds are used. On the other hand, invert drilling fluids are used for drilling holes in difficult geological conditions. The ratio of the oil phase to the water phase in invert drilling fluids the most common ratio being from 70/30 to 90/10. One of the disadvantages of invert drilling fluids is their cost (due to the oil content) and environmental problems related to waste and the management of oily cuttings. This article presents tests of invert drilling fluids with Oil-Water Ratio (OWR) 50/50 to 20/80 which can be used for drilling HPHT wells. The invert drilling fluids properties were examined and their resistance to temperature and pressure was assessed. Their effect on the permeability of reservoir rocks was also determined. The developed invert drilling fluids are characterized by high electrical stability ES above 300 V, and stable rheological parameters and low filtration. Due to the reduced content of the oil, the developed drilling fluid system is more economical and has limited toxicity.

Keywords: oil-based mud; invert drilling fluid; water phase; oil phase; emulsion stability; emulsifier

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1. Introduction

Invert drilling fluids are one type of fluid that can be used to drill boreholes in almost any geological condition. The invert drilling fluid consists of two phases: the oil phase and the water phase. The oil phase consists most often of mineral or synthetic oils. The oil phase is the continuous phase of the emulsion, and very often it is also referred to as the dispersion medium. Sometimes the emulsion phases are called the inner and outer phases. In this case, the concept of the outer phase is synonymous with the continuous phase, while the inner phase is the dispersed phase. The water phase, on the other hand, is most often brine solution, which is the internal phase of the emulsion. In addition to the oil and water phases, weighting agents that regulate the drilling fluid are added to the fluid [1–5]. The first invert drilling fluids were made on the basis of crude oil, which was successively replaced with diesel oil, and then with mineral oil. Each of the replaced oils has a lower amount of polycyclic aromatic hydrocarbons, which makes it less toxic to the environment. The next step towards reducing the toxic impact of invert drilling fluids on the environment was the use of enhanced mineral oil (EMO) or linear paraffin (LP) in their composition. These oils are characterized by limited toxicity due to the low amount of aromatic hydrocarbons. Environmental legislation imposes specific restrictions on the use of invert drilling fluids for offshore drilling. A particular problem is related to oil-contaminated drilled material that must be disposed of on the offshore platform or transported to the shore. It should be disposed of in an environmentally safe manner [6–10]. The increase in these requirements gave rise to multidirectional research aimed at developing chemical compounds with properties similar to diesel fuel, harmless to the natural environment. Based on these experiments, it is concluded that these compounds can be oils of plant and animal origin. However, the lack of thermal stability at higher temperatures and the rapid biodegradation of these compounds makes it impossible to use them in practice. Studies show that it is possible to obtain synthetic compounds from vegetable oils characterized by greater thermal and oxidative stability. The conducted research contributes to the development of chemical compounds such as esters, polyalphaolefins, ethers and acetyls, linear alkylbenzene (LAB), linear alpha-olefine (LAO) and internal (isomeric) olefin. Among the presented chemical compounds, the esters and chemical compounds from the olefin group have the greatest application in drilling fluid technology [11–16].

Invert drilling fluids are recommended to be used when drilling clay-shale and salt rock formations. Due to their low density, they can also be used for drilling boreholes in areas with low formation pressure. The excellent lubricating properties of the invert drilling fluids allow the drilling of directional and horizontal holes. They make it possible to reduce frictional resistance and torque. Invert drilling fluids also contribute to increasing the drilling speed, extending the lifetime of the drill bit and reducing the adhesion force of the drill string to the filter cake on the borehole wall. These are just some of the advantages of invert drilling fluids that are taken into account when choosing the type of drilling fluid in difficult geological and technical conditions [17–19].

The ratio of the oil phase to the water phase in inversion drilling fluids ranges from 65/35 to 90/10, with the most common ratio being from 70/30 to 80/20. Several factors determine such ranges. These are, among others: the solid phase content in the drilling fluid, including the weighting agents used to ensure the appropriate density of the drilling fluid adapted to the geological and technical conditions. An increased content of the oil phase in the invert drilling fluid is also needed in order to render the weighting agents and cuttings sufficiently oil wettable. At such ratios of the oil phase to the water drilling fluid, they are characterized by high temperature resistance and appropriate rheological and structural parameters that allow drilling in HTHP conditions [20–23].

One of the disadvantages of invert drilling fluids is their cost (due to the oil content) and environmental problems related to waste and the management of oily cuttings. Sometimes high costs are reduced by using a drilling fluid after proper cleaning to drill a few or several boreholes. Invert drilling fluids are also difficult to service in comparison to water dispersion drilling fluids. Drilling fluid losses during drilling in areas with caverns and rocks of high porosity are also costly. When drilling with an invert drilling fluid, special precautions must be taken to avoid direct contact with the invert drilling fluid. It is important to avoid inhaling its vapors and pay special attention to the fire hazard resulting from the possible ignition of its vapors. The use of invert drilling fluids requires special cleaning of the borehole prior to cementing and the near-hole area prior to operation. It is necessary to use special washing liquids based on solvents and surfactants. They enable the dissolution and removal of oil deposits and the reversal of the wettability of the borehole wall before the cementing procedure and of the near-hole area before exploitation [24–26].

2. Related Works

Al-Ajmi et al. [27] presented the laboratory tests invert emulsion fluids to protect the reservoir core from drilling fluid. Invert drilling fluids contained no damaging materials, such as barite, asphaltic material, or organophilic clay. Invert drilling fluids are more resistant to weighting material sag than conventional invert fluids systems of similar rheology.

Askø et al. [28] present laboratory tests for invert drilling fluids designed for drilling long horizontal wells in extremely depleted chalk reservoirs within the limitations of a narrow mud weight window, high overbalance, high solids contamination when drilling a water injection well on the Valhall Flank North in the southern Norwegian Continental Shelf.

Wagle et al. [29] describe the formulation of medium density organoclay-free invert emulsion drilling fluids. These fluids were formulated with acid-soluble manganese tetroxide as a weighting agent and specially designed bridging agent package. The tests carried showed that invert emulsion drilling fluids formulated with nanoparticles and rheology modifiers were stable at 120 °C and 150 °C.

In the article by Elkatatny [30], he presented the effect of using a new copolymer (based on styrene and acrylic monomers) on the rheological properties and stability of invert emulsion drilling mud. The deflection test was performed under static conditions (vertical and 45 inclination) and dynamic conditions to evaluate the ability of the copolymer to strengthen the suspension properties of drilling mud.

Ramasamy and Amanullah [31] conducted a comparative study has out by formulating invert emulsion OBM using commercially available emulsifier and the emulsifier derived from used (cooking)/vegetable oil.

Sheer et al. [32] describe the formulation of laboratory tests to analyze the optimal approach to drill invert drilling fluids of ratio o/w 60:40. The designed system reduces the use of diesel consumption by 26% in total oil-based mud formulation, lowers the percentage of Low Gravity Solids (LGS) compared to the 80:20 OWR mud, and decreases the impact on the environment. The articles presented show the standard compositions of invert drilling fluids with an o/w ratio of 60/40 to 80/20. There are no examples of invert emulsion fluids with an o/w ratio below 50/50 in the analyzed articles.

One of the examples of such scrubbers with an o/w ratio below 50/50 is invert emulsion fluid [33], which is designed to carry a gravel packing a wellbore in a subterranean formation. The present emulsion contains oil as the external phase, clear brine as the internal phase and an effective emulsifier with an HLB value of 3 to 8. In addition, the emulsion contains a wetting agent with an HLB value of about 4. An emulsifier was used to prepare the emulsion which was selected from the group consisting of amides and imidazolines. The invert emulsion fluids contained an oil-to-brine ratio of 45/55.

The second example is an invert emulsion fluid [34] in which the oil phase ratio is less than 50:50. The role of emulsifier in this type of emulsion was played by alkoxylated ether acid. The presented emulsion compositions were characterized by the electric stability of the emulsion depending on the ratio of the oil phase to the water phase in the range from 25 to max. of 287 Volt.

The article presents one of the methods of reducing the cost of an invert drilling fluid and reducing its toxic impact on the environment by developing invert drilling fluids with a reduced oil phase content and an increased water phase content. Formulated Drilling fluids with an o/w ratio less than or equal to 50/50 differ from conventional invert drilling fluids in their composition and properties. Due to the higher concentration of the dispersed internal phase, these drilling fluids are characterized by reduced stability and high values of rheological and structural parameters. The appropriate values of the drilling fluid's parameters and high stability can be maintained by use of new emulsifiers adapted to a given emulsion system with a specific oil phase to water phase ratio.

3. Materials and Methods

3.1. Materials

Mineral oil made by Brenntag is used to prepare an invert drilling fluid with a high concentration of the water phase. It has a boiling point above 200 °C and a low aromatic content below 0.2%.

The primary emulsifier used is ENI, which is the reaction product of unsaturated fatty acids with diethylenetriamine and fatty alcohol polyoxyalkylene glycol ether. The second type of emulsifier is an agent called ENII. It is a mixture of sorbitan monooleate and ethoxylated coconut oil fatty acid amides. The aqueous phase is a 35% solution of calcium chloride. Organophilic clay purchased from Polski Serwis Płynów Wiertniczych Sp. z o.o. Polska is used to modify the rheological and structural parameters of the emulsion.

The composition of applied drilling muds is shown in Table 1.

Table 1. Composition of applied drilling muds.

Composition	Invert Drilling Mud on Ratio o/w						
	o/w 50/50	o/w 50/50	o/w 40/60	o/w 35/65	o/w 30/70	o/w 25/75	o/w 20/80
Mineral oil, cm^3	472	472	377	331	283	235	189
emulsifier ENI, cm^3	37.5	37.5	37.5	37.5	37.5	37.5	37.5
emulsifier ENII, cm^3	18.5	18.5	18.5	18.5	18.5	18.5	18.5
35% solution $CaCl_2$, cm^3	472	472	566	613	660	707	754

3.2. Preparation of the Invert Drilling Fluid

In order to compare the properties of drilling fluids with different concentrations of the oil phase to the water phase, invert drilling fluids with the following coefficients are prepared: o/w = 50/50, o/w = 40/60, o/w = 35/65, o/w = 30/70, o/w = 25/75, o/w = 20/80. The emulsions are prepared as follows: organophilic clay is added to a specific amount of oil and mixed for 5 min at a speed of 16,000 rpm. Then, selected emulsifiers are introduced into the prepared emulsion and mixed for 5 min. Next, the water phase, which is made up of 35% $CaCl_2$, is added to the mixture and stirring is continued for 30 min. Then the type of the resulting emulsion is checked, and its properties are determined.

3.3. Experimental Procedures

The following procedure is performed to evaluate the feasibility of developing an invert drilling fluid with reduced oil phase content and increased water phase content.

Invert drilling fluids with different oil phase to water phase ratios were prepared.

(1) Density, filtration, electric emulsion stability, rheological and structural properties and filtration at ambient temperature were determined.
(2) The influence of the water phase content in the invert drilling fluids on the emulsion stability was investigated by determining the TSI index.
(3) The rheological properties of selected invert drilling fluids were measured in a wide temperature range from 20 to 120 °C.
(4) The filtration properties of the developed invert drilling fluids were measured at 120 °C and a differential pressure of 500 psi.
(5) The influence of the developed invert drilling fluids on the permeability of reservoir rocks was determined.

3.3.1. Testing Procedures

The technological properties of drilling fluids, such as density, rheological parameters, filtration and electric emulsion stability were determined in accordance with the PN-EN ISO 10414-2 standard. Petroleum and natural gas industries–Field testing of drilling fluids—Part 2: Oil-based fluids (ISO 10414-2:2011).

3.3.2. Density Measurement

The density of the drilling fluids was determined by means of a Baroid type fluid balance at a temperature of 20 °C and at atmospheric pressure. The fluid balance is designed in such a way that the vessel for drilling fluid situated on one end of the arm is balanced by a fixed counterweight placed on the other end of the arm. The balance arm is equipped with a weight moved along the scale and a level, enabling precise weighing [35].

3.3.3. Measurements of Rheological Parameters

The rheological parameters of drilling fluids are measured at 20 °C using an Ofite 900 viscometer. The viscometer is used to directly determine the relationship between the shear rate of a liquid and the existing shear stress, enabling the calculation of plastic viscosity, apparent viscosity, the yield point, and the measurement of the gel strength [35,36]. The

Ofite 77 high-temperature and high-pressure viscometer was used to measure rheological parameters at higher temperatures. The drilling fluids are tested in both the heating and cooling cycles in the temperature range from 20 to 120 °C with shear rates from 5.1 to 1020 s^{-1}.

3.3.4. Filtration Measurement

The filtration of drilling fluids at ambient temperature is determined using a low-pressure filter press at a pressure of 0.7 MPa for a period of 30 min. On the other hand, at a temperature of 120 °C, filtration is measured with a static HTHP filter press at a differential pressure of 3.4 MPa [36].

3.3.5. Stability Tests of Invert Drilling Fluids

The stability of the resulting emulsion is determined by the Emulsion Stability Meter, which measures the ES value by applying a voltage between plate electrodes immersed in the liquid. The resulting current remains low until the threshold voltage (61 ± 5A) is reached. Then the voltage of the current is increased to the point where a so-called puncture occurs. The voltage value is given in volts. If the breakdown occurs at a low voltage level, then this indicates an o/w emulsion. In the event of an electric breakdown only at high voltage, it indicated a w/o emulsion. The higher the ES value, the more stable the emulsion is [36].

Stability studies of invert drilling fluids with different oil phase to water phase ratios were also tested using the Turbiscan Tower device. It allows to measure the stability of suspensions, emulsions and foams. The analyzer works by analyzing multiple scattered light (transmitted and reflected back). Thanks to the moving head and two detectors working synchronously, the device collects data on the intensity of the transmitted and reflected light at a specific frequency. Then all signal changes in the sample are summed up to give a unique TSI number reflecting the destabilization of a given sample. The greater the number of TSIs, the more unstable the sample.

3.3.6. Test of the Influence of the Developed Invert Drilling Fluids on the Permeability of Reservoir Rocks

In the first stage of the test, the initial gas permeability of the sandstone cores (nitrogen) is determined. The measurement is made by passing nitrogen at a pressure of 2.2 MPa (inlet) through the core to a pressure of 2MPa (outlet) at a temperature of 120 °C. Using Darcy's law and the measurement data, the initial baseline permeability of the cores is calculated.

The next stage of the test is saturation of the core with selected invert drilling fluids. The pressure of the drilling fluid at the inlet to the core (P_1) is 5MPa and the pressure at the outlet from the core (P_2) is 2MPa. The core saturation process at a differential pressure of ΔP = 3MPa is carried out for 30 min.

Nitrogen is then passed through the core from the formation side, in the opposite direction to the direction of saturation with the drilling fluid, resulting in a pressure depression value of 2 MPa. The next step is to measure the permeability, which allows us to determine the degree of damage to the deposit by a given drilling fluid.

3.3.7. Determination of Loss of Permeability of a Sample

The coefficient of loss of permeability, WU (1), is defined as the percentage decrease in the permeability of the initial sample after the solid phase and filtrate particles penetrate into its pore space, and is expressed by the formula:

$$\mathrm{WU} = \left(1 - \frac{k_d}{k_0}\right) \cdot 100\% \quad (1)$$

where: k_d—permeability of damaged porous rock (after exposure to drilling fluid), taking into account the Klingenberg correction, [mD]; k_0—initial permeability (undamaged porous rock), taking into account the Klingenberg correction, [mD].

4. Results and Discussion

4.1. Properties of the Invert Drilling Fluid Depending on the Ratio of the Oil Phase to the Water Phase

Table 2 shows the properties of invert drilling fluids with an oil phase to water phase ratio of 50/50 to 20/80, prepared with the use of specially selected emulsifiers ENI and ENII. The electric stability ES of the prepared drilling fluids ranged from 610 Volt with an o/w 50/50 to 630 Volt ratio in drilling fluids with an internal phase content of 80% (Table 2). The differences between the drilling fluids can be seen mainly in the rheological and structural parameters, TSI value, and density. The lowest drilling fluid density of 1.1 g/cm^3 was obtained with an o/w phase mixing ratio of 50/50. This drilling fluid is also characterized by the lowest stability defined by the TSI index of 6.9 and the lowest values of rheological parameters (PV = 15 mPa·s, YP = 2.4 Pa). The TSI instability of 3.6 is defined in a drilling fluid with an oil to water ratio of 40/60. Increasing the proportion of the water phase to 40% increases the plastic viscosity to 27mPas and the yield point to 4.8Pa. Higher TSI values and low values of the yield point of drilling fluids with an o/w ratio of 50/50 and 40/60 indicate the necessity to increase the rheological and structural parameters in these drilling fluids by introducing organophilic clay into their composition or modifying the oil fraction composition. Therefore, 2% organophilic clay is added to the drilling fluid composition with an oil phase to water phase ratio of 50/50 (Table 2, item 2). Due to the use of hydrophobic bentonite in the invert drilling fluid with an oil phase to water phase ratio of 50/50, the yield point of the drilling fluid is now 4.3 Pa, and the sample stability index decreased from 6.9 to 0.5. (Table 2). On the other hand, in a drilling fluid with an oil phase to water phase ratio of 40/60, the use of 1% organophilic clay increases the yield point to 5.7 Pa and reduces the TSI index to 0.7 (Table 2, Figure 1).

Table 2. Parameters of applied drilling muds.

Invert Drilling Mud on Ratio, o/w	Density, g/cm^3	Plastic Viscosity, mPa·s	Apparent Viscosity, mPa·s	Yield Point, Pa	Gel Strength, I/II, Pa	TSI	Electrical Stability, Volts
	±0.05	±1	±1	±0.75	±0.25	±0.1	±1
	20 °C						
o/w—50/50	1.1	15	17.5	2.4	0.48/0.96	6.9	610
o/w—50/50 +2% Viscosifier	1.1	21	25.5	4.3	0.96/1.4	0.5	580
o/w—40/60	1.14	27	32	4.8	1.9/2.4	3.6	640
o/w—40/60 +1% Viscosifier	1.14	27	33	5.7	1.9/2.4	0.7	610
o/w—35/65	1.16	42	53	10.5	3.3/4.3	1.5	670
o/w—30/70	1.19	50	64.5	13.9	3.8/4.3	1.7	680
o/w—25/75	1.21	61	89.5	27.2	6.2/7.6	2.0	690
o/w—20/80	1.23	85	116.5	30.1	9.1/10.5	0.9	630

The reduction of the oil phase to water phase ratio in invert drilling fluids causes an increase in rheological and structural parameters and slight changes in the electrical stability of the drilling fluids, ranging from 610 Volts to 690 Volts (Table 2). A properly selected composition of emulsifiers allows for obtaining invert drilling fluids with a water phase content of up to 75%. Above this value, the drilling fluid is characterized by high rheological and structural parameters, a plastic viscosity of 85 mPa·s and a yield point of 30.1 Pa (Table 2).

The increase in the water phase content in the invert drilling fluid makes it possible to increase the density of the drilling fluid to 1.23 g/cm^3 without the need to add any weighting materials. In this type of drilling fluid, the rheological and structural properties can be partially controlled by slightly changing the ratio of the oil phase to the water phase. Reducing the o/w ratio increases the rheological parameters while increasing the ratio reduces them.

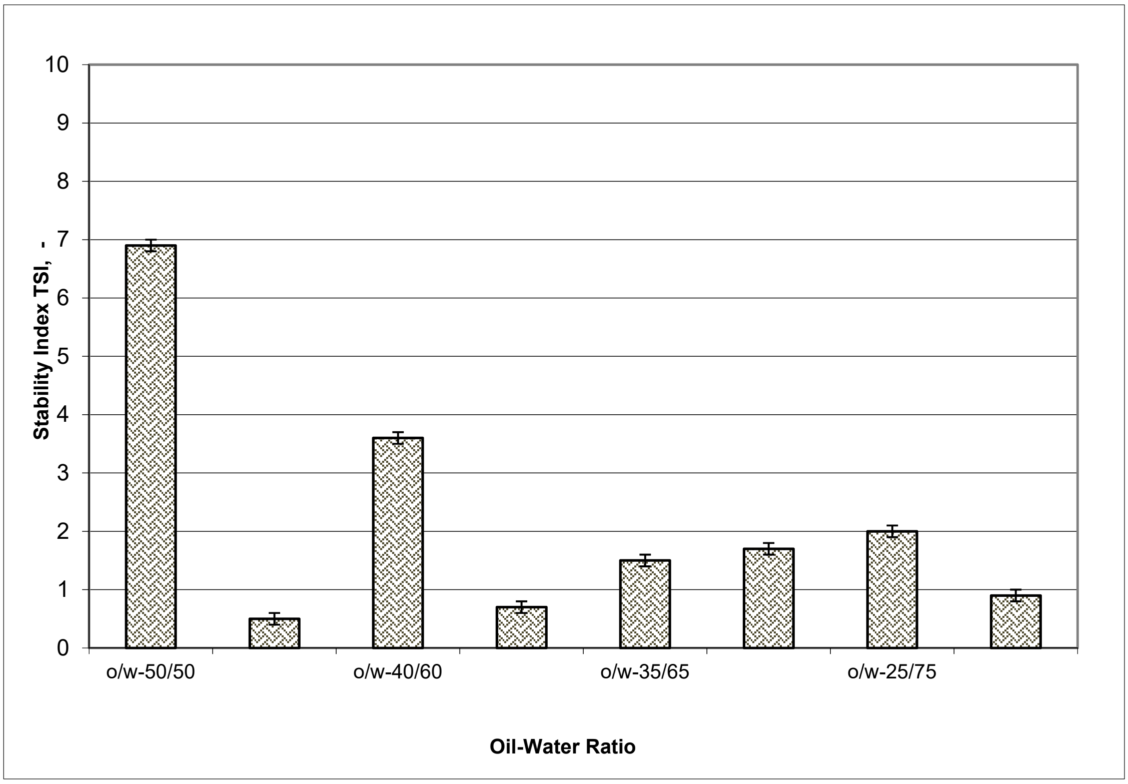

Figure 1. Destabilization kinetics of selected invert drilling fluids with a different ratio of oil to water phase.

4.2. Determining the Influence of Elevated Temperature on Rheological and Structural Properties and Filtration of the Developed Invert Drilling Fluids

Two invert drilling fluids with an oil phase to water phase ratio of 40/60 and 30/70 were selected for the research. For comparative analysis, the drilling fluids were weighted with barite to the same density of 1200 kg/m^3. The drilling fluids were tested in both the heating and cooling cycle in the temperature range from 20 to 120 °C. The measurement results are presented in Figures 2–5 in the form of a graph of changes in the plastic viscosity and the yield point versus temperature.

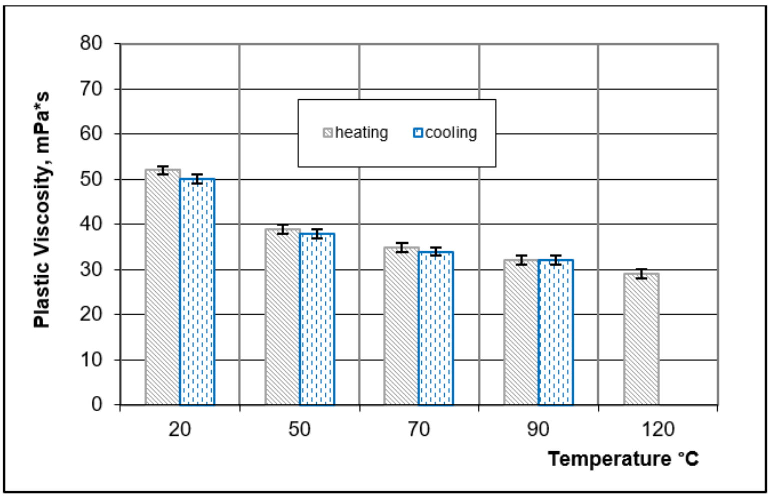

Figure 2. Changes in the plastic viscosity of invert drilling fluids with an oil to water ratio of 40/60 depending on temperature changes.

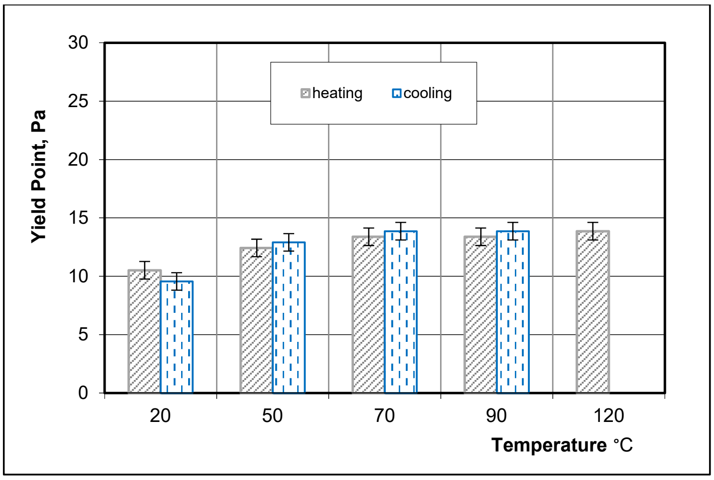

Figure 3. Changes in the yield point of invert drilling fluids with an oil phase to water phase ratio of 40/60 depending on temperature changes.

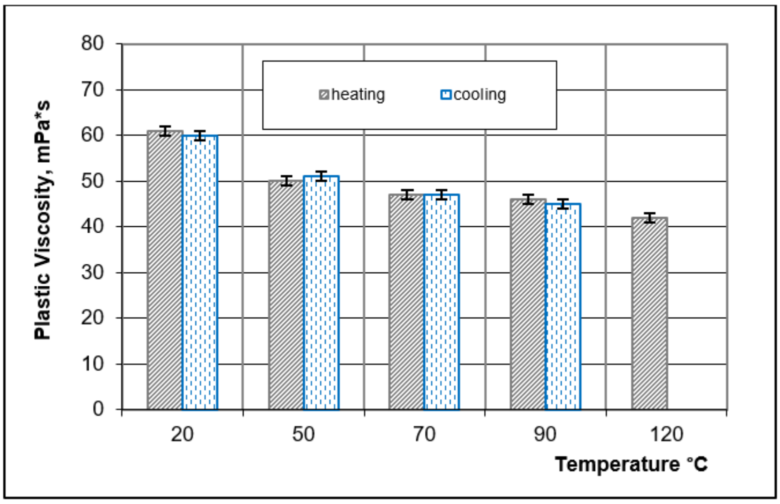

Figure 4. Changes in the plastic viscosity of invert drilling fluids with an oil to water ratio of 30/70 depending on temperature changes.

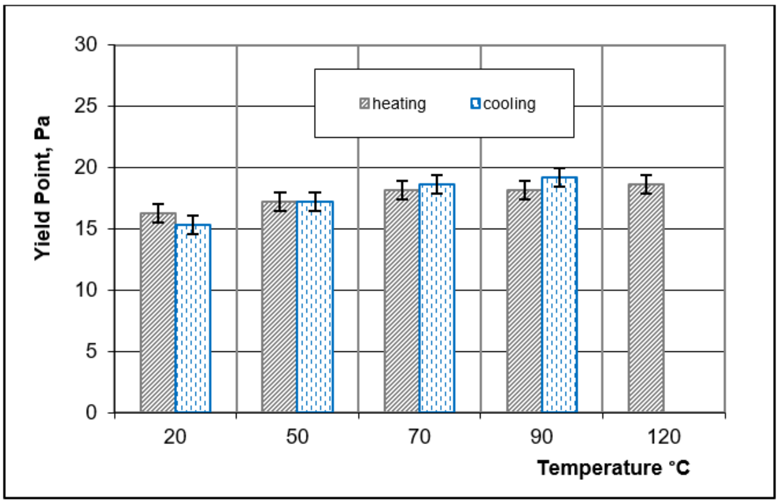

Figure 5. Changes in the yield point of invert drilling fluids with an oil phase to water phase ratio of 30/70 depending on temperature changes.

The invert drilling fluid with an oil phase to water phase ratio of 40/60 at 20 °C and atmospheric pressure is characterized by a plastic viscosity of 52 mPa·s and a yield point of 10.5 Pa (Figures 2 and 3). As a result of the temperature of up to 120 °C, the plastic viscosity of the drilling fluid is gradually reduced. At 50 °C it drops to 39 mPa·s, at 90 °C to 32 mPa·s, and at 120 °C it reaches the value of 29 mPa·s (Figure 2). Changes in the yield point due to the effect of temperature are similar only to the temperature of 50 °C. As a result of heating the drilling fluid to 50 °C, the yield point decreases to the value of 12.4 Pa, then when the temperature rises to 70 °C, the yield point slightly increases to the value of 13.4 Pa (Figure 3). Another increase in temperature to 90 and 120 °C does not change the yield point of the drilling fluid. In the drilling fluid cooling cycle to the temperature of 20 °C, the drilling fluid restores its rheological parameters to the initial values of the drilling fluid before annealing. Plastic viscosity is 2 mPa·s higher and the yield point is 1 Pa higher.

The invert drilling fluid with an oil phase to water phase ratio of 30/70 at 20 °C is characterized by a plastic viscosity of 61 mPa·s and a yield point of 16.3 Pa (Figures 4 and 5). As a result of the gradual increase in temperature, the plastic viscosity of the drilling fluid falls. At 50 °C, the plastic viscosity of the drilling fluid drops to 50 mPa·s, at 90 °C to 46 mPa·s, and at 120 °C to 42 mPa·s (Figure 4). In the cycle of cooling the drilling fluid to ambient conditions, the plastic viscosity is restored to the value of 60 mPa·s (Figure 4). When analyzing the diagram of changes in the yield point of the drilling fluid depending on the temperature, it is stated that the decrease in the yield point value takes place to the temperature of 50 °C. At 50 °C, the yield point has the lowest value of 17.2 Pa. A further increase in temperature to 120 °C increases the yield point to 18.6 Pa (Figure 5). In the cycle of cooling the drilling fluid to the ambient temperature, the yield point is reduced to 15.3 Pa (Figure 5). After cooling the drilling fluid to the ambient temperature, it was observed that the drilling fluid withstood the temperature of 120 °C and did not decompose into the water and oil phases, and the electric stability value of the ES invert drilling fluid was 660 Volts.

In the next stage of the research, the influence of temperature and pressure on the filtration of invert drilling fluids was observed. The filtration of the drilling fluids was tested on an HPHT filter press at a temperature of 120 °C with a differential pressure of 3.4 MPa. The influence of elevated temperature and pressure on the filtration value was investigated for invert drilling fluids with an oil to water phase ratio of 50/50, 40/60, 30/70 and 20/80. The test results are shown in Figure 6.

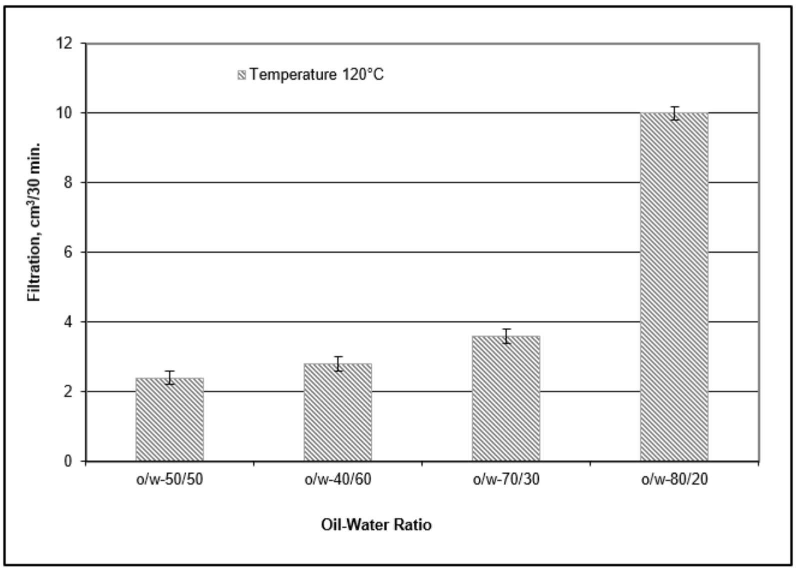

Figure 6. Filtration loss of invert drilling fluids depending on the ratio of the oil phase to the water phase at the temperature of 120 °C and a differential pressure of 3.4 MPa.

The filtration of an invert drilling fluid with a 50/50 ratio of the oil phase to the water phase at a temperature of 120 °C is 2.4 cm^3/30 min. Lowering the share of the oil phase in the invert drilling fluid to 40% increases filtration of the drilling fluid to 2.8 cm^3/30 min (Figure 6). As the concentration of the water phase in the invert drilling fluid increases, the filtration increases. In an invert drilling fluid with a 30/70 ratio of the oil phase to the water phase, filtration increased to 3.6 cm^3/30 min. The highest filtration, which is 10 cm^3/30 min, was recorded for the invert drilling fluid with an o/w ratio of 20/80 (Figure 6).

The performed tests confirm that the drilling fluid shows high temperature resistance while maintaining the electrical stability of ES of over 570 Volts under variable pressure and temperature.

4.3. Investigation of the Influence of Selected Invert Drilling Fluids on the Change of the Permeability Coefficient of Reservoir Rocks

The study of the reservoir rock permeability coefficient was carried out on sandstone cores with permeability from 28.57 to 34.55 mD. The results of the study of permeability changes of reservoir rock samples are presented in Figures 7 and 8. To determine the impact of changes in the permeability of reservoir rocks, the developed invert drilling fluids with an oil phase to water phase ratio of 50/50, 40/60, 30/70 and an invert drilling fluid with an oil phase to water phase ratio of 80/20 were selected for comparison.

On the basis of the analysis of the obtained results and the presented drawings (Figures 7 and 8), it is concluded that the tested drilling fluids, depending on the water phase content, have a different effect on the amount of damage to the permeability of the rocks in the near-hole area. The highest value of the sandstone reflux permeability coefficient is obtained by operating the drilling fluid with an oil phase to water phase ratio of 40/60. Measurements of changes in the hydraulic conductivity for gas show that the tested drilling fluid at a differential pressure of 2 MPa causes slight damage to the reservoir rock permeability. The final value of the permeability coefficient after the effect of the drilling fluid decreases from 34.55 to 31.78 mD (Figure 7). The calculated loss of sandstone hydraulic conductivity for gas is 8.02% (Figure 8).

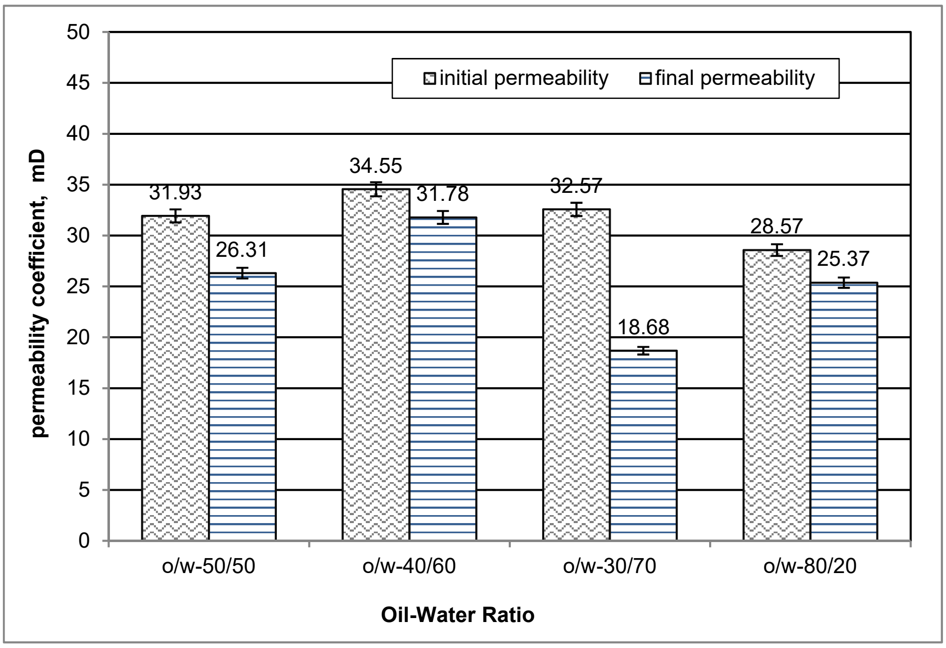

Figure 7. Influence of the type of invert drilling fluid on the change of sandstone gas permeability.

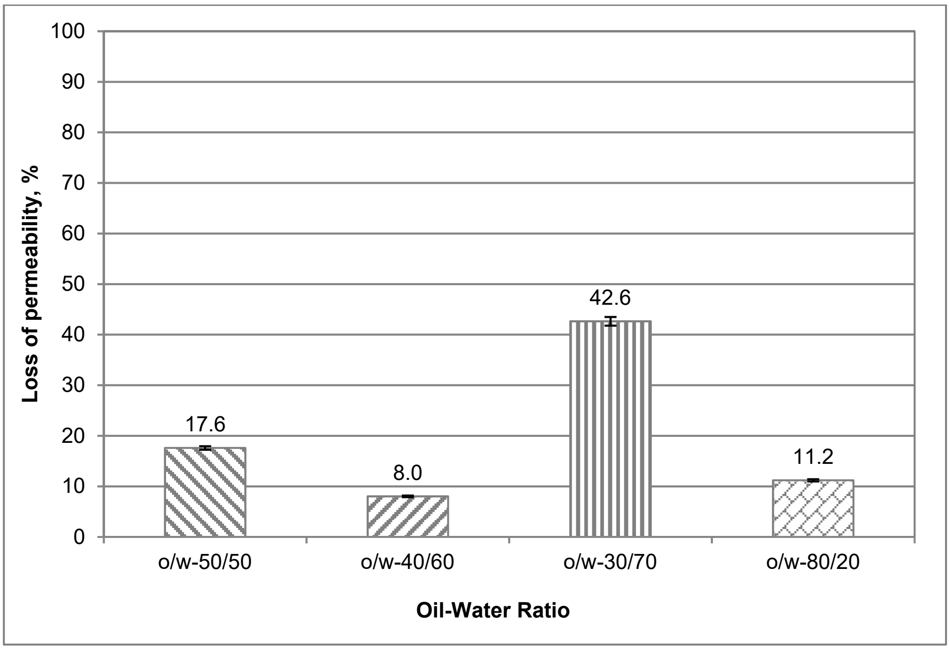

Figure 8. Loss of permeability of tested samples after the effect of invert drilling fluids for gas.

In comparison, the sandstone permeability coefficient was measured after treatment with an invert drilling fluid with an o/w ratio of 80/20. As a result of the contact of the drilling fluid with the reservoir rock, a decrease in the hydraulic conductivity of the reservoir rock sample is visible from 28.57 to 25.37 mD (Figure 7), which results in a loss of the sample's permeability by 11.20% (Figure 8).

Another permeation test was carried out for an invert drilling fluid with an oil phase to water phase ratio of 50/50. Balancing the amount of the oil phase in relation to the water phase reduces the sandstone permeability coefficient from 31.93 to 26.31 (Figure 7). The drilling fluid damages the sample permeability by 17.60% (Figure 8).

The greatest decrease in reservoir rock permeability among the invert drilling fluids selected for the tests was observed after using a drilling fluid with an oil phase to water phase ratio of 30/70. Permeation studies show that the drilling fluid causes a loss of permeability of the sandstone sample by 42.65% (Figure 8). The permeability coefficient after the effect of the drilling fluid decreased from the value of 32.57 to 18.68 mD (Figure 7).

5. Conclusions

(1) The conducted laboratory tests confirm that there is a real possibility of developing invert drilling fluid compositions with a low oil phase to water phase ratio below 50/50.

(2) Invert drilling fluids with a high internal phase concentration are obtained by using emulsifiers synthesized under laboratory conditions. These emulsifiers are the reaction product of unsaturated fatty acids with diethylenetriamine and fatty alcohol polyoxyalkylene glycol ether and an emulsifier which is a mixture of sorbitan monooleate and ethoxylated coconut fatty acid amides.

(3) The analysis of the quality, stability and resistance of the prepared emulsion systems under ambient conditions allows the selection of invert drilling fluid compositions characterized by high electrical stability ES ranging from 580 to 690 Volts and low TSI indexes from 0.5 to 6.9.

(4) The density of the developed invert drilling fluids can be partially controlled by the content of the internal phase, which may be salt solutions. This limits the solids content (weighting agents) in the drilling fluid. The density of the developed drilling fluids is determined by the content of the water phase, which is 35% r-r $CaCl_2$. The developed invert drilling fluids, depending on the ratio of the oil phase to the water phase, can be used without the use of any weighting agents to the density of:

- 1140 kg/m^3 invert drilling fluids with an o/w 40/60 phase ratio;
- 1190 kg/m^3 invert drilling fluids with an o/w 30/70 phase ratio;
- 1230 kg/m^3 invert drilling fluids with an o/w 20/80 phase ratio.

(5) The tests of the drilling fluids under HTHP conditions show that the developed invert drilling fluids with an oil phase to water phase ratio from 50/50 to 30/70 are characterized by high resistance to temperature and pressure. Invert drilling fluids maintain stable rheological parameters to a temperature of 120 °C and are characterized by low filtration—lower than 4 cm^3/30 min.

(6) Based on the obtained results, it is stated that the developed drilling fluids, depending on the ratio of the oil phase to the water phase, have a different effect on the permeability of reservoir rocks. The highest value of the sandstone reflux permeability coefficient is obtained after the treatment with a drilling fluid with an oil phase to water phase ratio of 40/60. The drilling fluid causes a loss of the sandstone's hydraulic conductivity for gas at the level of 8%. On the other hand, the impact of a drilling fluid with an oil to water ratio of 30/70 on the sandstone core reduces the formation damage index by approximately 43%. Based on the conducted studies of the permeability coefficient, it is concluded that the developed drilling fluids with an increased 50/50 and 40/60 water phase content affect the formation damage in a similar way as in the case of the conventional 80/20 invert drilling fluid, which reduced gas permeability by about 11%.

(7) The cost of preparing the developed invert drilling fluid with the ratio o/w—30/70 will be lower by approx. 60% in relation to the conventional invert drilling fluid with the ratio o/w 70/30. Due to the reduced content of the oil, its toxicity and its impact on the environment will be reduced.

(8) Further tests of the developed invert drilling fluids will be carried out to determine their thermal resistance to temperatures above 160 ° C and pressures above 34 MPa.

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Nomenclature

o/w	the ratio of the oil phase to the water phase in invert drilling fluids
HTHP	high temperature high pressure
MPa	Megapascal—pressure unit
mD	millidarcy—unit of permeability
Pa	pascal—unit of the yield point and structural strength
mPa·s	millipascal second—unit of plastic and apparent viscosity
ES	electric stability of the emulsion
TSI	Emulsion Stability Index
OBM	Oil based mud
HLB	Hydrophilic-Liophilic Balance

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