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Application dispersed particle gels as in-situ fluid diversion agent

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Abstract

From year to year, the number of fields in late stages of development is increasing, which is inevitably accompanied by a decrease in oil production rates and an increase in the volume of produced water. One of the most effective technologies for dealing with this problem is the application of flow diverting technologies. The paper presents the synthesis of the dispersed-gel particles (DPG) for modifying the injectivity profile of the well, the displacement front and diverting the filtration flows in the reservoir. A series of experiments were carried out to determine the particle size distribution, resistance factor of the proposed composition, both on sandpack models and on core samples was studied. The use of the DPG composition allows the injection of the solution into the formation without a significant increase in the injection pressure, which was confirmed by the low values of the resistance factor. The composition possesses selectivity of isolation effect, which is proved by more significant decrease of relative water permeability than relative oil permeability. The selectivity of the action provides a significant reduction in the water cut of the production well. Thus, DPG can serve as an effective tool to divert the filtration flows in the reservoir, blocking the highly permeable areas and channels in heterogeneous reservoirs.

Keywords: *change in filtration flows in the reservoir, dispersed particle gels, oil recovery factor, selective isolation.*

Introduction

High water cut of the produced fluid is one of the most serious problems for petroleum engineers [1–3]. From year to year, the number of fields in late stages of development is increasing, which is inevitably accompanied by a decrease in oil production rates and an increase in the volume of produced water [4, 5]. The economic and technological consequences of this process are widely known and do not require a separate explanation. However, it should be noted that a number of reasons for the increase in water cut include the methods used to increase oil recovery [6–8]. Thus, during long-term waterflooding, which is the most common method of maintaining reservoir pressure, highly permeable channels appear over time [9–13]. This is explained by long-term removal of rock by streams of injected water, incorrectly chosen regimes of displacing agent injection, etc. In fact, there can be many reasons and often it is not possible to point out the main one [14–18]. There is an urgent need to control the water cut of the production well [19–22]. For this purpose various methods, which are classified into three main groups, are applied [23–26]:

mechanical methods – are based on the use of various downhole equipment to prevent or isolate zones of water breakthrough;

chemical methods – are based on the use of reagents that form water-impermeable screens in the formation, the most common use for this purpose are various polymer systems;

combined methods – are consisting in the combined application of the two previous methods.

As noted earlier, the use of polymer gels in recent decades has become most widespread due to both economic profitability and the availability of the components used [27, 28]. Gel-forming compositions, having a low initial viscosity, easily penetrate into highly permeable reservoir zones [29, 30]. The gelation process takes place directly in the formation and the gel formed in the highly permeable parts of the formation serves as a reliable screen that redirects filtration flows to less permeable layers [31]. The main disadvantages of gel-forming compositions application are difficulty of controlling gelation time, poor stability in reservoir conditions and the application is often limited by particle size, the range of formation permeabilities acceptable for implementation [32].

This paper presents the composition of Dispersed Particle Gels for diverting filtration flows in the formation. Unlike the traditional gel compositions, the gelation process of the DPG does not occur in the formation but happens on surface. Therefore, no chemical reaction happens in formation, but only swelling of the DPG particles, which eliminate the difficulty of controlling gelation time. Consequently, the stability of the composition in reservoir conditions significantly increases, and the controlled particle size and selectivity of the isolation zone significantly expand the possibilities of using DPG composition in a wide range of reservoir permeabilities.

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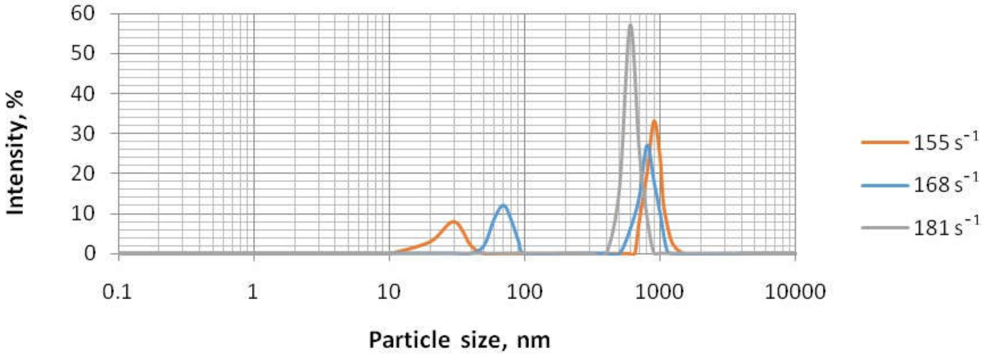


Figure 1 – Particle size distribution of DPG

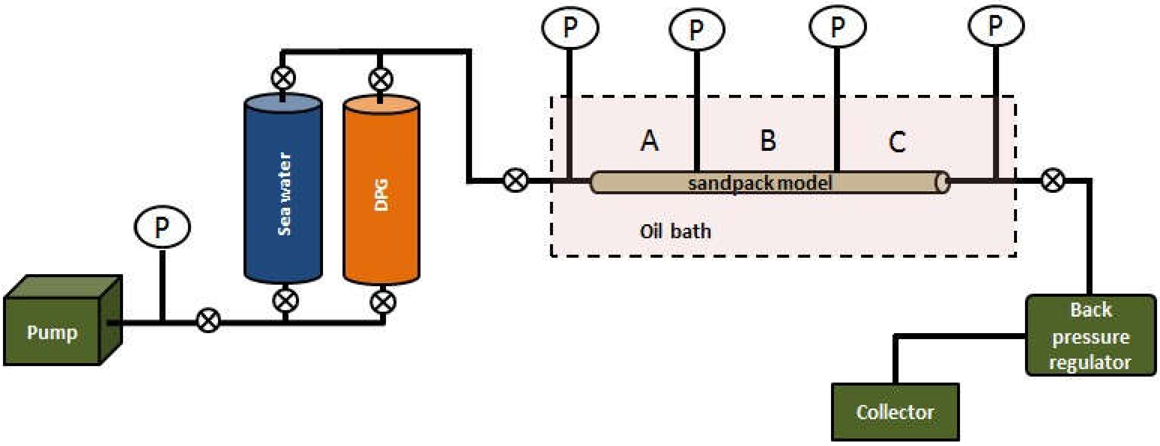


Figure 2 – Experimental setup of sandpack model for determining the resistance and residual resistance factor

Experimental

Polymer: sulfonated polyacrylamide (SPAM) (copolymer of 2-acrylamide2-methyl-propane sulfonic-acid sodium salt and acrylamide) purchased from Sigma Aldrich, >99.99 %).

Crosslinker: N,N-methylenebisacrylamide (purchased from Sigma Aldrich, >99.99 %).

Synthesis of dispersed particle gels (DPG)

The DPG were prepared by a colloid mill for the grinding and homogenization (CM-2000) with high speed shearing method. The preparation procedures are divided into two stages: first, gelation reaction stage and the second, Dispersed Particle Gel milling stage. The first stage is the preparation of the gelant solution. Initially, a gel composition consisting of 4000 mg/L polymer and 500 mg/L crosslinking agent was prepared, which is consequently stirred to obtain homogenous mixture at room temperature and the crosslinking reaction is initiated in the oven at 60 ^{o}C. Then, the bulk gel crosslinking reaction process begins a forming the bulk gel with a three-dimensional network structure. The crosslinking reaction period can be completed within 6 hours, or in a shorter time at a higher temperature. In the second stage synthesized bulk gel and brine water (1:1) were put into the colloid mill and milled with different shearing speeds (1000–14000 rpm) for 15 min at room temperature. The obtained yellowish solution was the final product.

Particle size distribution

Particle size distributions were measured by dynamic light scattering method using Malvern's Zetasizer Nano S (DLS) particle size analyzer. The results of the measurements are shown in Figure 1.

Determination of resistivity and residual resistivity factors

Resistivity factor during injection of the proposed composition was determined using a sandpack model (Figure 2). The length of the model was 60 cm, internal diameter 2.85 cm, permeability 0.50 μm^2, pore volume 134 ml, porosity 35 %. The model was conventionally divided into three sections (A, B, C), limited by differential pressure manometers.

The concentration of the injected DPG solution was 500 mg/l, with an average particle size of 410 nm. After saturating the model with synthetic seawater, the DPG solution was injected. After establishing a stable flow rate at the outlet of the model, an additional 3 pore volumes of DPG were injected, thus total 10 pore volumes of DPG were injected during the procedure. Then, in order to determine the residual resistance factor, synthetic seawater was injected until stabilization of the differential pressure values. After stabilization of the differential pressure, the injection of synthetic seawater continued in order to determine the duration of the effect obtained. During all of the above operations, the pump flow rate remained unchanged and amounted to 1 ml/min. Resistance and residual resistance factors were determined according to the formulas:

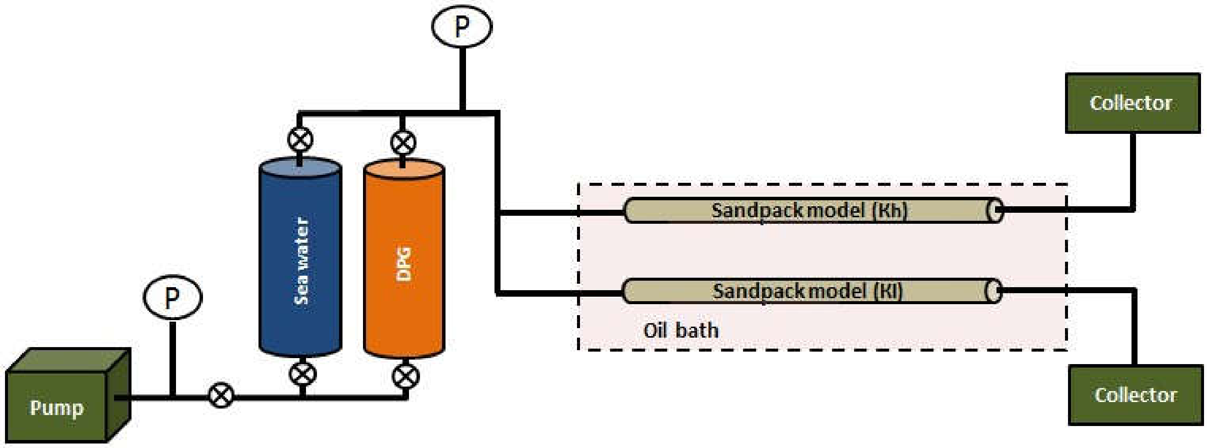


Figure 3 – Experimental setup for parallel sandpack model

$$RF = \frac{\Delta P_{DPG}}{\Delta P_p};$$

$$RRF = \frac{\Delta P_k}{\Delta P_p},$$

where *RF* is resistance factor; *RRF* is residual resistance factor; ΔP_{in} is initial differential pressure; ΔP_{DPG} is differential pressure after injection of *DPG* solution, ΔP_{last} is differential pressure after displacement of *DPG* solution.

Selectivity of isolation of DPG

The selectivity of isolation was determined on the core sample with plotting of relative permeability curves according to the method described in the standard. The core sample was 5.5 cm in length, 2.5 cm in diameter, had 480 mD permeability, 7.1 mL pore volume and 26.2 % porosity. As a synthetic oil, kerosene was used with the following characteristics: viscosity 2.2 mPa·s, density 0.80 g/cm^3 at 30 °C. The concentration of the injected DPG solution was 500 mg/l, with an average particle size of 410 nm, pump flow rate was 0.4 ml/min.

Determination of the oil recovery factor

The oil recovery factor was determined using parallel filled sandpack models with different permeabilities in order to simulate the layered heterogeneity of the reservoir (Fig. 3). The length of both models was 30 cm, and the diameter was 2.5 cm. The concentration of the injected DPG solution was 500 mg/l, with D50 – 410 nm, the pump flow rate was 1.0 ml/min. The experiment was carried out according to the following procedure:

1. Synthetic seawater was injected into both models until a flowrate at the outlet was stabilized.
2. To simulate the residual water saturation, synthetic oil (kerosene) was injected into the model until 95 % of the of effluent was synthetic oil.
3. Further, to simulate the residual oil saturation, synthetic seawater was injected into the model until water cut reached 95 %.
4. The solution of DPG was injected.
5. Synthetic seawater was injected to simulate subsequent waterflooding.

During the experiment, the relative injectivity was calculated, that is, the ratio of fluid volumes filtered through each model to the total volume of injected fluid.

Results and discussion

Resistance and residual resistance factor

Dynamics of the change in the resistance factor for each of the sections of the model are presented in Fig. 4. The resistance factors for all three sections of the model had low values even after injection of 10 pore volumes of the DPG solution, which indicates good filtration characteristics of the proposed composition. However, the subsequent injection of seawater (7 pore volumes) led to an increase in this value. Further, differential pressure stabilized and a slight decrease in the values of the resistance factor was observed, which is most likely associated with the partial washing out of the DPG solution from the sandpack. The initial effect of an increase in hydraulic resistance during injection of seawater is explained by the retention of the polymer in a porous medium, which significantly reduces the removal of DPG particles during subsequent waterflooding. This assumption is also supported by a gradual drop in the values of the resistance factor in sections B and C. The mechanism of polymer retention by a porous medium can be explained by the DLVO theory. According to this theory, the aggregate stability of a dispersed medium is determined by the resulting energy of interacting particles, which is the sum of the energy of the forces of attraction and repulsion. The change in the value of the resulting interaction energy of particles depending on the distance between the particles is shown in Fig. 5. Thus, at a small distance between the particles, E_T takes a positive value, that is, the repulsive forces prevail over the forces of attraction. This process takes place during injection of the DPG solution, since a high concentration of the solution leads to a significant decrease in the distance between the particles. In the porous model, the following process takes place: the initially injected portion of the DPG solution is adsorbed on the surface of the porous medium, while the subsequent portion is filtered further through the pore channels. The mechanism of this phenomenon is explained by the predominance of repulsive

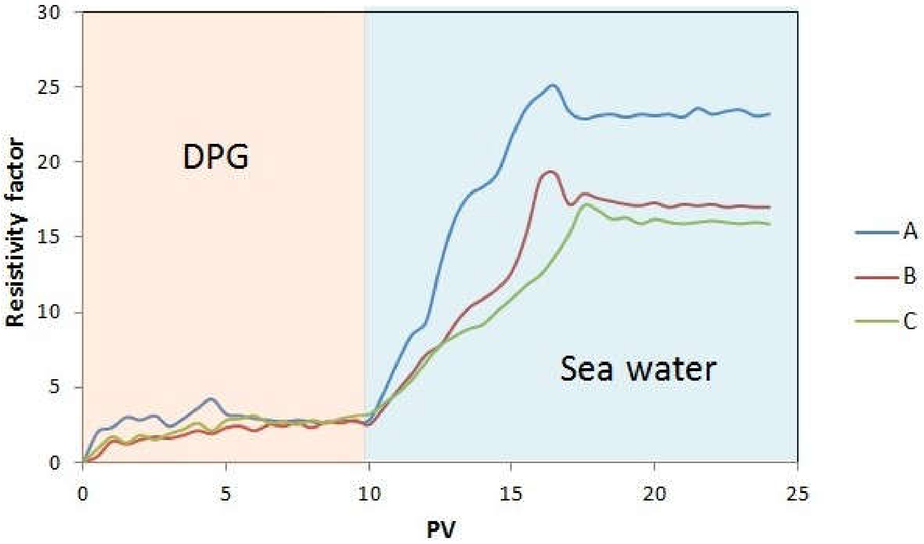
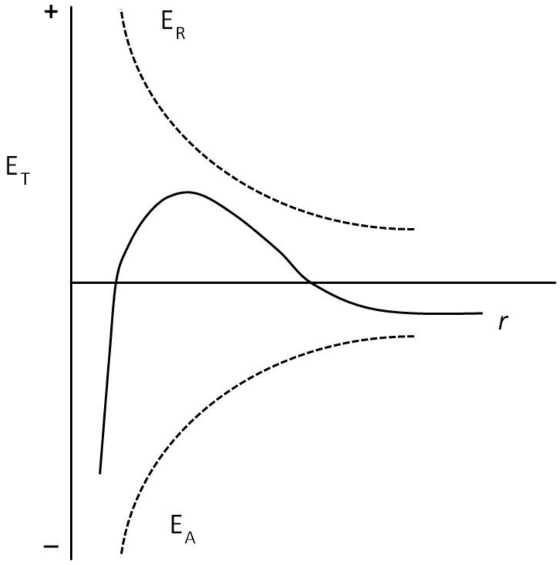


Figure 4 – Dynamics of resistance factor changes on different sections of the sandpack model



E_R – repulsive energy, E_A – attractive energy,
E_T – total potential energy

Figure 5 – The dependency of the interaction energy on the distance

forces in the DPG solution, which does not allow the DPG particles to attach in the initially formed adsorption layer. With the subsequent injection of seawater, the reverse process takes place, the distance between the DPG particles increases, which leads to the predominance of attractive forces. At this stage, the resulting energy of particle interaction becomes negative. The process of random aggregation of DPG particles proceeds with the formation of the largest number of aggregates in the zone of high concentration of the solution, that is, the number of aggregates decreases in the direction of the filtration flow (i.e., from section A to section C). The results obtained are consistent with the hypothesized mechanism of polymer retention by the porous medium, the resistance factor is maximum in section A and decreases in subsequent sections as the model is approached.

Selective isolation

The results of the above studies on the selectivity of isolation effect of the applied composition are presented in Table 1. Irreducible water saturation increased from 0.35 to 0.54 and the residual oil saturation decreased, which testifies to selectivity of influence of DPG solution. To all appearances, solution of DPG, penetrating first of all into water-saturated pore channels, contains in them more concentration and the subsequent injection of sea water initiating aggregation of particles leads to permeability decrease of these channels, clogging considerable volumes of water. It is the trapped volumes of water that increase irreducible water saturation, and the subsequent volumes of injected seawater rush into the oil-saturated portions of the model, resulting in increased oil recovery. Small particle size and good dispersion in the solution are the main reasons for this effect.

Table 1 – Changes in relative permeability values before and after injection of DPG solution

Treatment	Irreducible water saturation	Endpoint relative permeability of oil	Residual oil saturation	Endpoint relative permeability of water
Before injecting DPG	0.35	1.00	0.45	0.24
After injecting DPG	0.54	0.58	0.31	0.032

Oil recovery factor

The purpose of this series of experiments was to study the effect of reservoir heterogeneity on the effectiveness of the proposed composition. Two sandpack models with different permeability ratios were used in the experiments and the volume of fluids filtered through each model was measured. The results of the

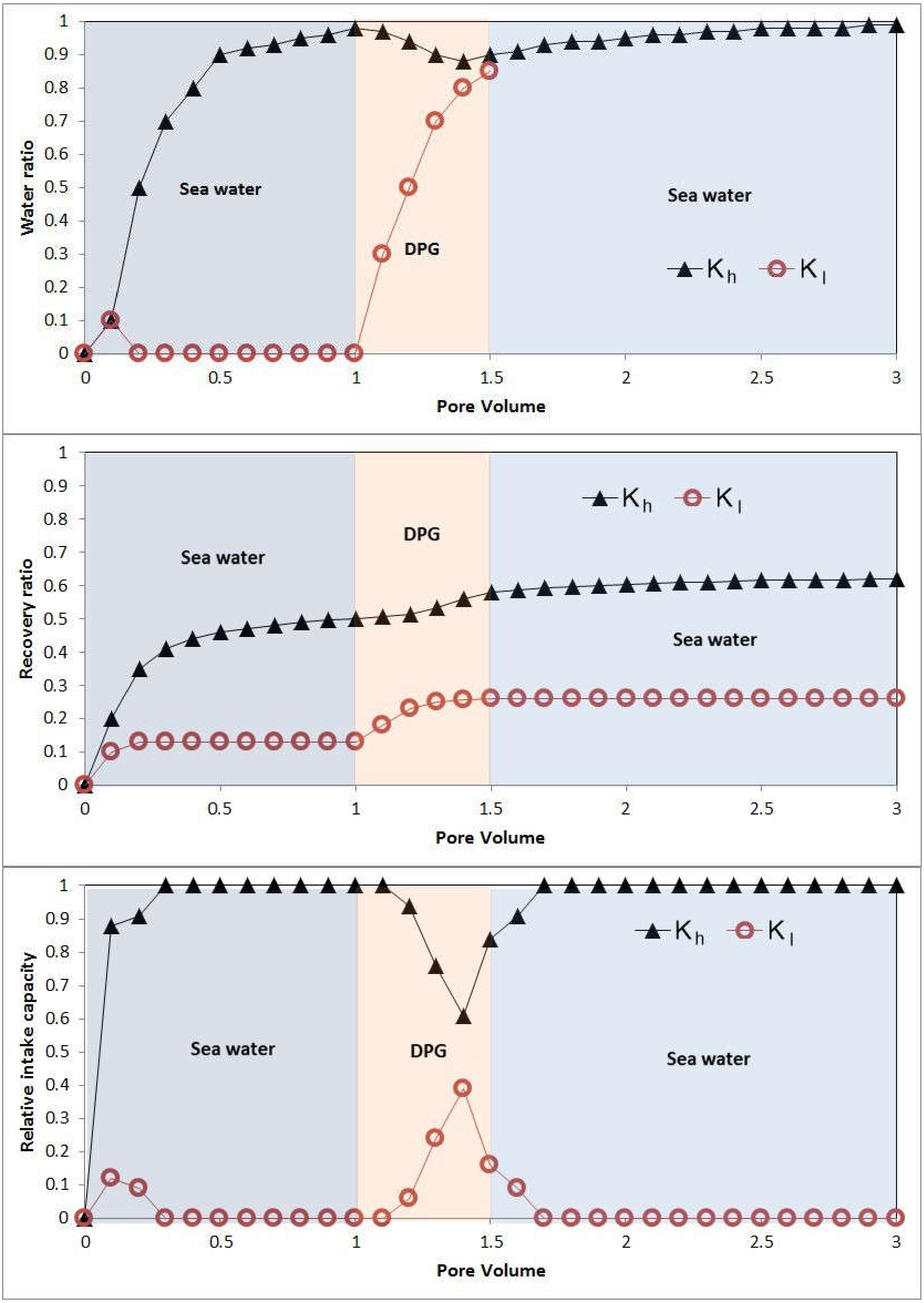


Figure 6 – Dynamics of changes in the oil displacement ratio (experiment 1)

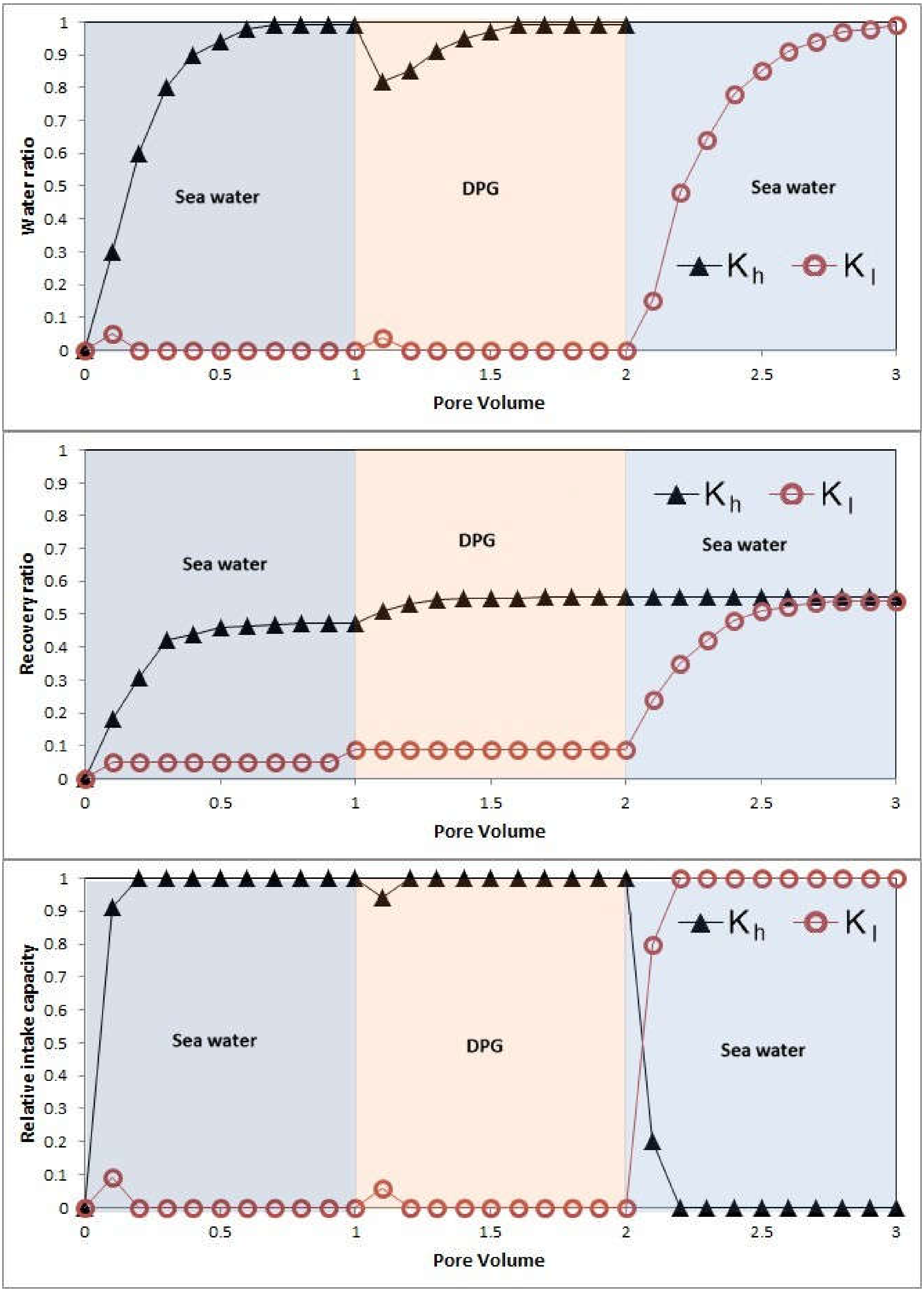


Figure 7 – Dynamics of changes in the oil displacement coefficient (experiment 2)

experiments are shown in Table 2. Obviously, as the permeability ratio of the models increases, so does the oil recovery factor. And the dependence has practically proportional character, so with doubling the permeability ratio the oil recovery coefficient also doubles from 35.5 % to 63 % (Figs. 6, 7). The reason behind observed phenomena is associated with diversion of filtration flows in sandpack model after gel screen formation. In fact, subsequent filtration flows are directed to low-permeable sandpack models (K_N) increasing oil recovery, which is provided by high irreducible oil saturation of these models.

Table 2 – Main parameters of sandpack models

Experiment	Description	Permeability, Darcy	Permeability contrast K_h /K_l	Porosity, %
1	K_h	2.64	2	35.0
	K_l	1.29		38.0
2	K_h	4.64	4	32.5
	K_l	1.15		38.5

Conclusions

Application of the proposed composition allows the injection of the working fluid into the formation without a significant increase in the injection pressure, which was confirmed by the low values of the resistance factor.

The proposed composition has the ability of selective isolation, since a significant decrease in the phase permeability to water was observed while only a slight drop in the phase permeability to oil happened.

DPG solution is an effective flow diverting agent, leading to a decrease in the permeability of highly permeable areas and channels.

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Застосування гелів з диспергованими частинками як агента для відведення рідини на місці

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З року в рік збільшується кількість родовищ на пізніх стадіях розробки, що неминуче супроводжується зниженням дебітів нафти та підвищенням об'ємів видобутої води. Однією з найефективніших технологій для вирішення цієї проблеми є застосування технологій відведення потоку. У роботі описано синтез частинок дисперсного гелю (DPG) для зміни профілю нагнітання свердловини, фронту зміщення та відведення фільтраційних потоків у пласті. Проведено серію експериментів для визначення гранулометричного складу, досліджено коефіцієнт опору запропонованої композиції як на моделях піщаного пакета, так і на зразках керна. Використання складу DPG дозволяє закачувати розчин у пласт без значного підвищення тиску нагнітання, що підтверджується низькими значеннями коефіцієнта опору. Композиція має селективність ізоляційного ефекту, що підтверджується більш значним зниженням відносної водопроникності, ніж відносної нафтопроникності. Вибірковість дії забезпечує значне зниження обводнення експлуатаційної свердловини. Таким чином, DPG може служити ефективним інструментом для відведення фільтраційних потоків у пласт, блокуючи високопроникні ділянки та канали в гетерогенних пластах.

Ключові слова: *гелі дисперсних частинок, зміна фільтраційних потоків у пласті, коефіцієнт видобутку нафти, селективна ізоляція.*