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INVESTIGATION AND OPTIMIZATION OF EMULSION TREATMENT FOR SELECTIVE GAS AND WATER ISOLATION IN FRACTURED RESERVOIRS

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Filtration and rheology characteristics of the inverse emulsion based on a low viscosity, low tar oil, the effect of the direction of injection of the emulsion, oil saturation and permeability of porous media on the filtration results are studied in this research paper. Hydrophobic inverse emulsion can be used to align the front of oil displacement by water in fractured reservoirs (injection into injection wells) and for the selective gas and water isolation in the producing wells. It is recommended to use the emulsion compositions with low content of oil phase in the latter case. A mathematical model of emulsion treatment on the reservoir is developed and optimum parameters of the technological characteristics of the process are established.

Keywords: *emulsion, fractured reservoir, viscosity, permeability of the porous medium, surface-active agent, stabilizer, two-phase filtration, water saturation*

Effectiveness of deposit's flooding, especially with highly viscous oil, and of gas technologies in fractured reservoirs can be greatly increased due to their interconnecting with the emulsion exposure. Integration of technology allows you to adjust and, if necessary, isolate the gas and water seepage in producing wells, thereby increasing the coverage of the process of oil displacement.

Filtration processes of viscous emulsions in porous bodies and fractures of oil layers have been sufficiently studied. Of greatest interest is the work of [1], which investigated the filtering of the inverse emulsion through a model of the fractures (slit-like Healey-Shaw cell) and a micro model of the porous medium. In [1] it is showed that the inverse emulsion ability to reduce the permeability of porous media is close to the cross-linked polymer systems. Visualization of the filtration of emulsions through the Healey-Shaw cell and micro model of the porous medium showed that the movement in porous media and fractures is accompanied by a change in structure and properties of emulsions and their partial destruction of (parts oil and water phases are separated, large aggregates of water are formed, part of emulsion in porous media is squeezed etc.).

The results of the study of filtration and rheological characteristics of the emulsion based on inverse low-viscosity, low-tar oil of Devonian strata, the effect of the direction of emulsion injection, oil saturation and permeability of porous media on the filtering results are presented in the article.

Emulsions based on the emulsifier Neftenol NZ, dead oil (viscosity – 29 mPa·sec, density – 880 kg/m^3) and saline water (viscosity – 1.46 mPa·sec, density – 1083 kg/m^3) of the Devonian strata Sergeevskoye field have been investigated. Rheological properties of emulsions were studied using rotational viscometer Reotest-2.

Artificial porous medium (simulating fractured reservoirs) where the hydrophobic emulsion was not wetting phase were selected for filtration experiments. In filtration experiments the mineralized water of the Sergeevskoye field and iso-viscous model of oil from Sergeevskoye field with viscosity 5.41 mPa·sec and density of 847 kg/m^3 were used.

For the experiments, we used porous media that simulate the "small" (permeability of about 4 μm^2) and "large" (permeability of about 30 μm^2) fractures.

Freshly prepared emulsion was pumped into the reservoir model and then immediately the filtration of fluids (saline water or oil) started. Fluid filtration continued until the end of the discharge of emulsion, of oil (or water) and the stabilization of the pressure drop. In a number of experiments the direction of fluid filtration and emulsion coincides (modelling of bottom-hole zone of injection wells), in others it was opposite (modelling of the bottom-hole zone of producing wells). In the latter case, the emulsion was pumped through the outlet of the reservoir model. Filtration experiments were carried out at a constant filtration rate.

The effect of the emulsion on the permeability of porous media was evaluated by changes in filtration resistance of the porous medium model (reservoir model):

$$R=(\Delta P_i/Q_i)/(\Delta P_1/Q_1)\,, \qquad (1)$$

where R – resistance factor; ΔP_i and ΔQ_i – current pressure drop and flow rate, respectively; ΔP_1 and Q_1 – steady pressure drop and fluid flow rate during filtration prior to injection of emulsion, respectively. In the case of the steady filtration:

$$R = R_{ост} = k_1 / k_2 \ , \qquad (1)$$

where R_{ost} – the residual resistance factor, k_1 and k_2 – permeabilities of the porous medium before and after treatment, respectively. To characterize the filtration properties of the emulsion R_{ost} and the maximum resistance factor (R_{mak}) were used. Experiments were conducted at a temperature of 20-21 °C.

Rheological properties of emulsions

Research has shown that to describe rheological properties of the inverse emulsions based on the Devonian oil and Neftenol NZ at a shear rate more than 1 sec^{-1} the following equation can be used (Fig. 1, Table 1):

$$\delta = A \times \gamma n \ , \qquad (3)$$

where δ – shear stress, Pa; γ – shear rate, sec^{-1}; A – constant (consistency), n – constant ($n < 1$). Thus, the studied inverse emulsion properties are apparent viscous.

Viscosity (consistency) of emulsions increases with decreasing volume fraction of oil in the emulsion. Simultaneously, the deviation of the rheological properties of emulsions from the Newton equation (parameter n reduces) increases. Increase in the concentration of emulsifier favors the increases in the consistency of inverse emulsions.

Table 1

Rheological parameters of the inverse emulsion

№	Emulsion composition			Equation 1 parameters		
	Oil volume, ml	Water volume, ml	Neftenol NZ, g	*A*	*n*	Correlation coefficient
Effect of the volumetric ratio oil / water						
1	15	85	2.0	20.30	0.422	0.99
2	20	80	2.0	11.20	0.495	0.99
3	30	70	2.0	5.03	0.551	0.99
4	40	60	2.0	1.84	0.627	0.99
5	50	50	2.0	1.70	0.747	0.99
Effect of the emulsifier concentration						
6	15	85	3.0	49.8	0.306	0.99
7	15	85	4.0	58.8	0.274	0.98

The results of filtration studies

For the filtration study the inverse emulsion number 7 with a minimum content of the oil phase was chosen, because rheology of the emulsion number 7 deviates from the rheology of Newton fluids in the maximum degree among the studied emulsions. According to its rheological properties emulsion 7 approaches to hydrocarbon gels and should therefore be most effective in water isolation works in oil reservoirs.

Initially, the effect of the inverse emulsion on the permeability of water-saturated and the residual oil saturation of porous media was studied (Table 2). In experiments number 1 and 2, 0.4 pore volumes (p.v.) of emulsion was injected, what led to a rapid increase in pressure drop (Fig. 2). Subsequent injection of saline water was accompanied by a rapid decrease in pressure drop, but the initial permeability was not restored. Emulsions were not observed at the exit of the reservoir model. From a porous medium with residual oil (experiment number 2) emulsion and then water pushed out 16.5 % of residual oil (calculation of the change of oil saturation was carried out taking into account the oil injected into the model in the emulsion content). Sorting of the water saturated reservoir model (experiment number 1) showed that starting from the entrance 45-48 % of the model is filled with an emulsion, the remainder of the volume was water-bearing. Thus, emulsion destruction did not happen as a result of the emulsion movement in the highly permeable porous medium, i.e. pore sizes were larger in size than emulsion particles. In the case of the formation model with a residual oil emulsion filled 50-55 % of the reservoir model.

In experiments number 1 2, the values R_{ost} are close and the values R_{mak} differ: in the case of a porous medium with residual oil maximum resistivity factor is considerably lower than in the case of water-saturated porous medium (Table 2).

Results of experiments number 1 and 2 show the following:

1. The emulsion easily displaces water and residual oil from fractures and large pores, whose sizes exceed the size of emulsion particles. Part of the residual oil is pushed into the porous medium and is often mixed with the emulsion, reducing its viscosity. That decrease in emulsion viscosity (Table 1, Fig. 1) explains the smaller value R_{mak} in the experiment 2 compared with experiment 1.

2. Breakthrough of water through a porous medium filled with an emulsion occurs in narrow channels, apparently along the surface of the pores. Emulsion pinch in

the free pore volume (as it is the non-wetting fluid), which explains the high values R_{ost}. Channels volume through which water filtrates in emulsion area is low, as indicated by the closeness of emulsion injection and by occupied by it part of the model volume in experiment 1.

Experiment technique in 3 and 4 (Table 2, Fig. 3) differs from the experimental procedure in the experiments 1 and 2 in that the water and the emulsion filtrate in opposite directions (the emulsion was pumped through the outlet of the reservoir model). In experiment 3 (water-bearing reservoir model) breakthrough of water through the emulsion occurred after injection of 0.03-0.04 p.v. of mineralized water, and then ousting the emulsion quickly stopped. In experiment 4 (porous medium with residual oil) emulsion displacement by water happened quite easily and the type of emulsion at the outlet of the model was constantly changing. Originally, displaced was the emulsion hardly distinguishable in appearance from the original, then, the emulsion with oil stain was displaced. The degree of displacement of the emulsion of the porous medium was at least 80-90 %. When sorting of the reservoir model no significant amount of emulsion in a porous medium was found. In the case of a porous medium with residual oil (experiment 4) and R_{mak} and R_{ost} are significantly lower than in the case of water-bearing formation model (experiment 3). Thus, the water is almost unable to displace the original (unmodified) emulsion of the porous medium, but it displaces the emulsion mixed with residual oil in a porous medium.

In experiment 5 (Table 2) the effect of the inverse emulsion on the permeability of the porous medium of oil was investigated. Emulsion injection resulted in a decrease in permeability, but the oil easily displaced emulsion in the porous medium (Fig. 4). As a result, oil permeability for reservoir model rose by 5 % (R_{ost} = 0.955), i.e. hydrophobic emulsion had no adverse effect on the oil permeability of the model of "small" fractures.

Results of experiments 5, 4 and 3 indicate that the higher oil saturation of the porous medium, the lower the maximum and residual resistance factors were and the easier inverse emulsion is displaced from the porous medium. This reduction in cement properties of the inverse emulsion is due to the reduction of its viscosity by diluting by oil. Thus, data show that, for water isolation works in the production wells hydrophobic emulsion with a minimum content of the oil phase are most suitable.

In experiment 6, a porous medium with permeability of 38.5 μm^2, i.e. model of large cracks was used (Table 2). Injection of the emulsion followed by a constant growth in pressure drop, but after injecting of 1 v.p. increase in the pressure drop has slowed. At the exit of the reservoir model emulsion was observed, whose appearance did not differ from the original, i.e. emulsion was filtered without breaking. Water injection led to a gradual displacement of the emulsion from the porous medium. Water breakthrough occurred after injection of 0.26 p.v. of water, after which the displacement of an emulsion from a porous medium quickly stopped. Pressure drop stabilized and the permeability of the model decreased by 51 times after injecting of 1.5 p.v. of water. Analysis of the model showed that the entire volume of the model is filled with an emulsion. The experimental results show that the emulsion can reduce the permeability of large fractures.

Hydrophobic inverse emulsion can be used to align the front of oil displacement by water in fractured reservoirs (injection into injection wells) and for selective water isolation in producing wells. In the latter case it is recommended to use the emulsion compositions with low content of oil phase.

A similar conclusion can be drawn for the case of gas treatment in fractured reservoirs – hydrophobic inverse emulsion can effectively block the gas show in the wells.

Table 2

Filtration experiments results

№	Permeability, μm²			Oil saturation, %		Filtrated fluid	Emulsion injection volume, pore volume	Resistivity factors		Filtration speed, m/day
	in water	in oil with remaining water	in water with remaining water	initial	Before emulsion injection			maximum	remaining	
Emulsion filtration direction coincides with fluid filtration direction										
1	4.10	-	-	0.0	0.0	Water	0.40	354.0	11.0	3.7
2	4.46	1.79	1.37	78.6	28.1	Water	0.40	97.5	12.9	5.2*
Emulsion filtration direction is opposite to fluid filtration direction										
3	3.83	-	-	0.0	0.0	Water	0.50	850.0	12.4	3.7
4	3.90	1.88	1.46	79.4	21.5	Water	0.59	209.0	3.-	4.6*
5	3.41	1.05	-	77.4	77.4	Oil	0.67	35.9	0.955	4.9*
6	38.5	-	-	0.0	0.0	Water	1.33	2300.0	51.0	3.9

*Note: * - effective filtration velocity (remaining oil and water are considered unmovable)*

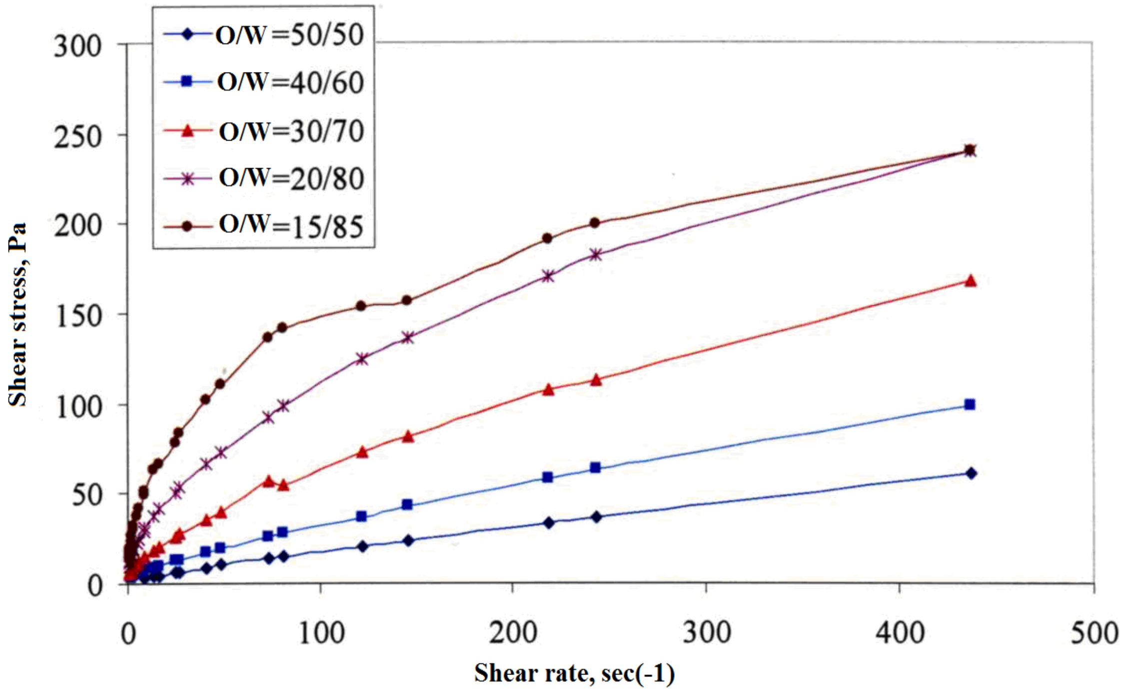

Figure 1. Influence of volumetric ratio oil / water (o/w)
on the rheology of the inverse emulsion (Neftenol NZ content – 2 g / 100 ml)

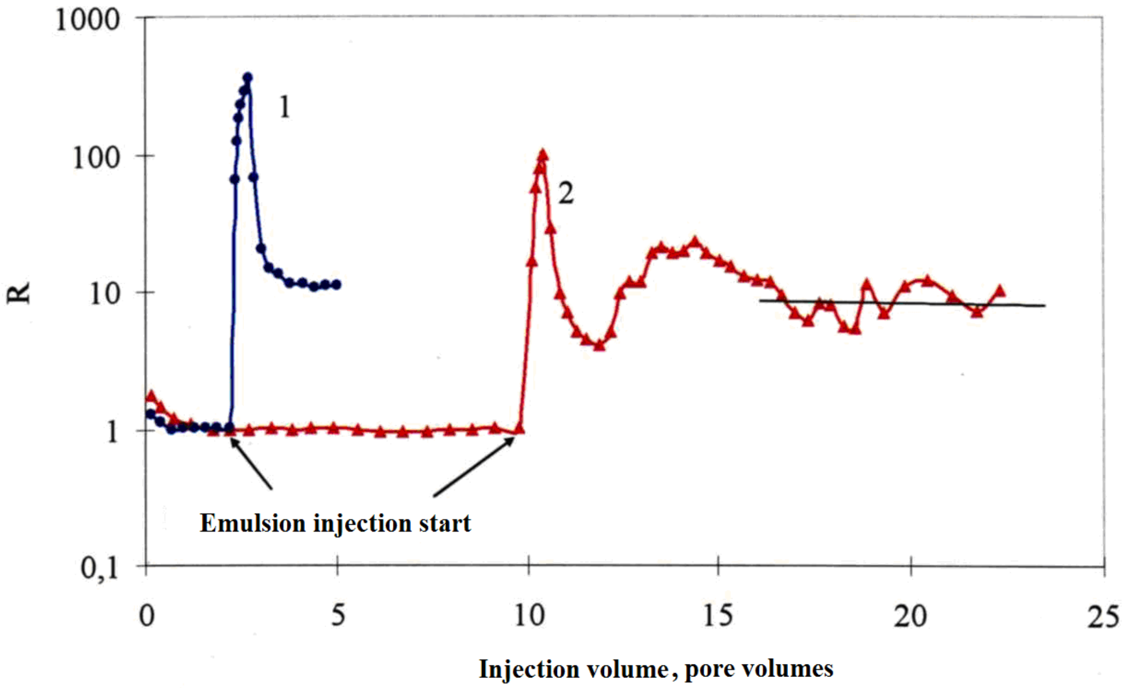

Figure 2. Filtration dynamics:

1 – water-saturated reservoir model (experiment 1);
2 – reservoir model with the remaining oil saturation (experiment 2)

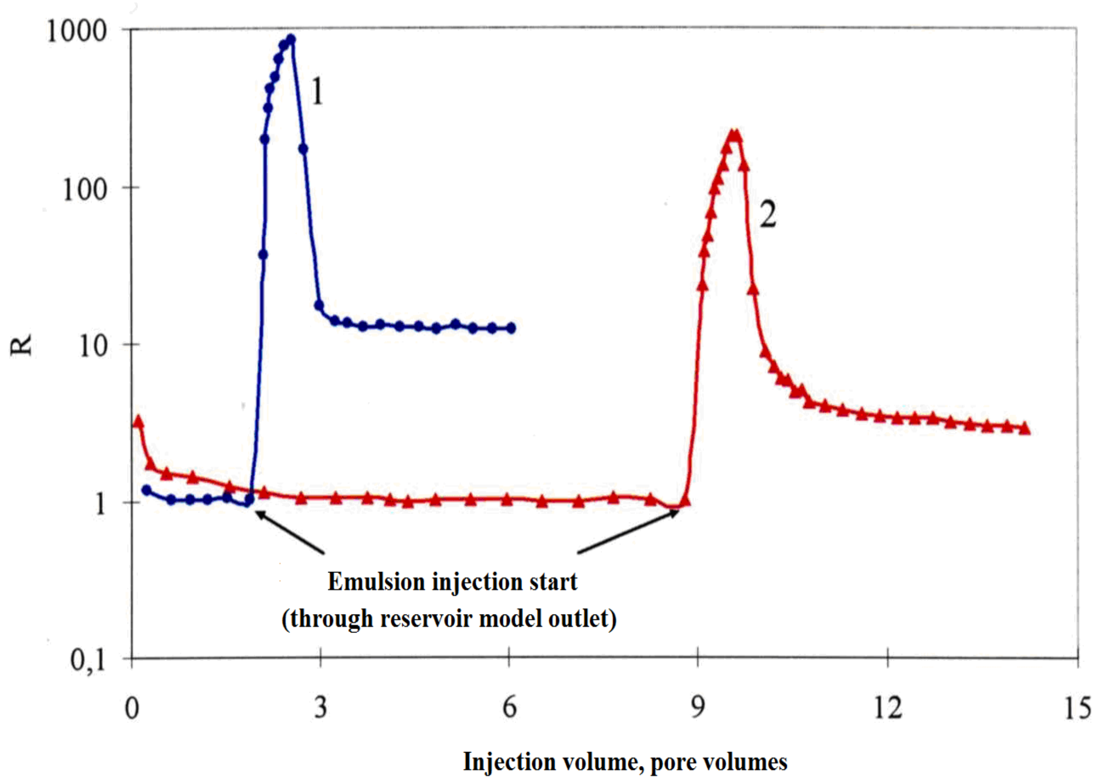

Figure 3. Filtration dynamics:

1 – water-saturated reservoir model (experiment 3);
2 – reservoir model with the remaining oil saturation (experiment 4)

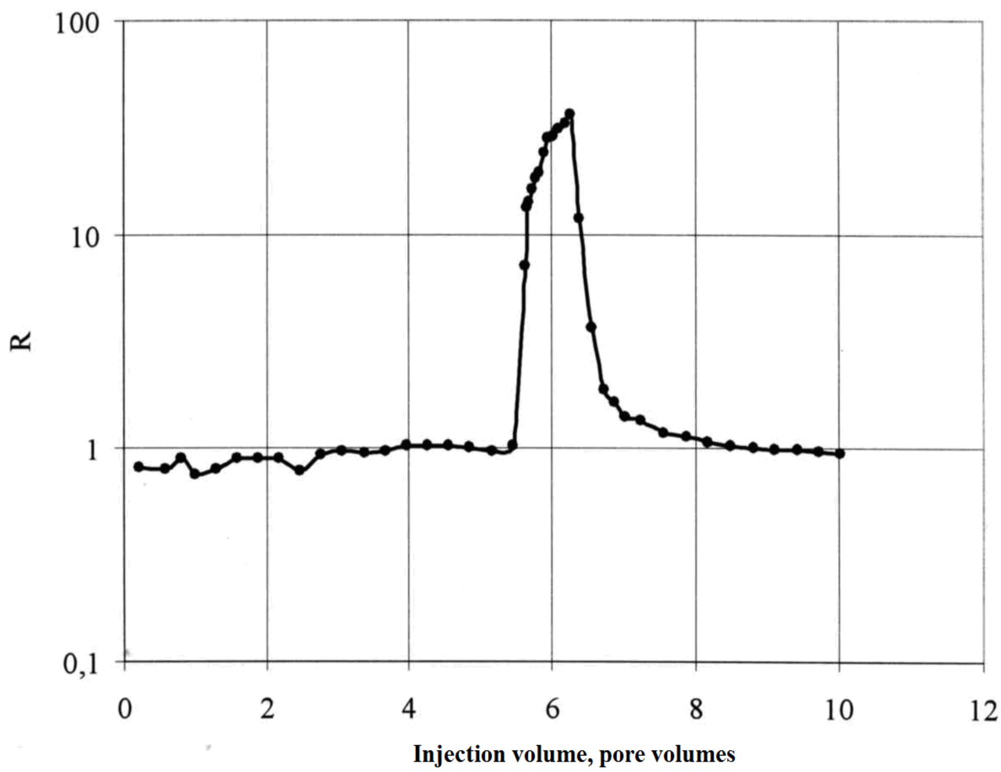

Figure 4. Oil filtration dynamics (experiment 5)

Modelling of the emulsion treatment

Phase equilibrium of inverse micro-emulsion systems

Used for enhanced oil recovery micro-emulsions are composed of four main components: water, hydrocarbons (oil and its various distillates), emulsifiers (surface active agent soluble in oil) and stabilizer (water soluble surfactant). Mixing these components in certain proportions leads to the formation of inverse micro-emulsions (water in the oil) with excess water and hydrocarbon phases. Hydrocarbon content in the proper micro-emulsion is 30-40 %. This state is relatively stable and is characterized by high viscosity and low surface tension on the border with water and oil. To describe the phase equilibrium of micro-emulsion systems at constant temperature and salinity it is proposed to use the standard technique of triangular phase diagrams (TPD) [2]. In addition, as a rule, oil, water with electrolytes and surfactants are picked for conditional elements[3]. TPD type depends on the composition of surfactant (ratio of emulsifier / stabilizer), mixture temperature and water salinity.

Use the inverse (water in oil) micro-emulsion is encouraged to use for enhanced oil recovery. Phase equilibrium of oil, water, emulsifiers (EM) and stabilizer (ST) were experimentally studied. According to research results, TPD, presented in Fig. 5, were designed and constructed for some concentrations of emulsifier + stabilizer.

Conducted laboratory studies have shown that the viscosity of the emulsion is slightly different from the oil viscosity, surface tension at the boundary of emulsion with water and oil decreases by 5-10 times (Table 3), the size of inclusions of water in the emulsion is distributed according to a certain law, with a maximum of 1-5 μm [4].

Inverse emulsions are relatively stable formations; they can from structures. Static shear stress depends on the ratio of emulsifier/stabilizer significantly, adding a stabilizer in the system decreases the shear stress to zero (Table 3).

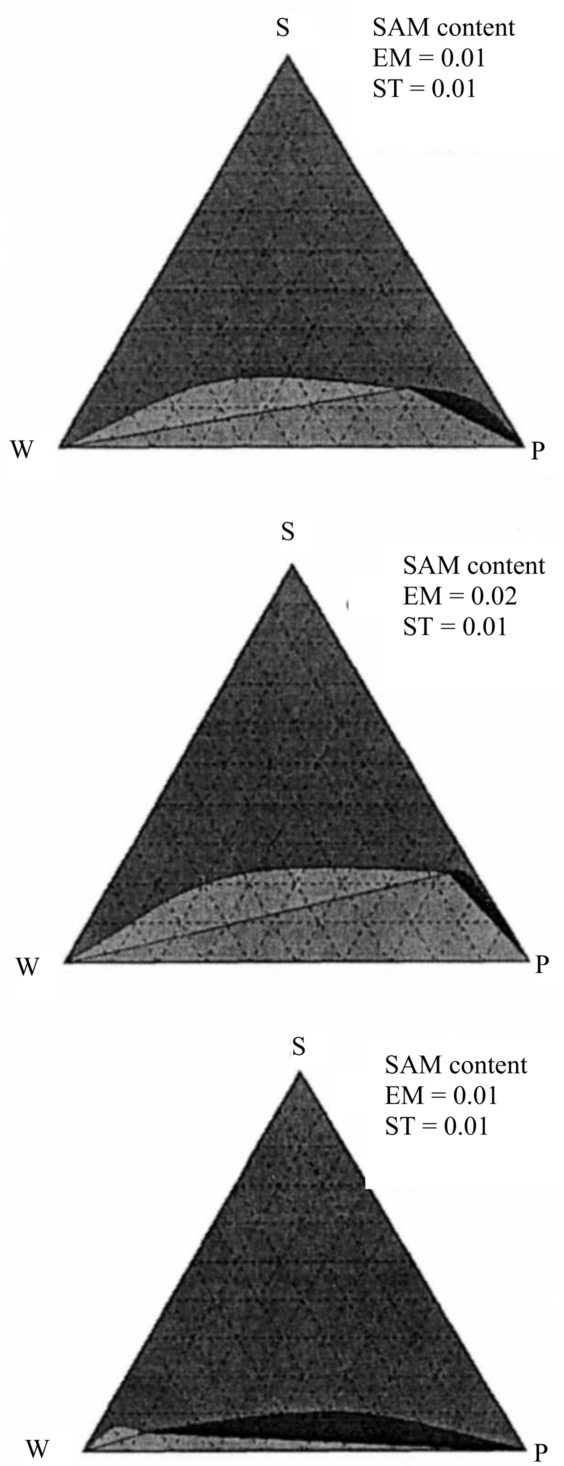

Figure 5. Calculated diagrams of the phase condition of oil-water-surface active agent system for various ratios of emulsifier/stabilizer in the system

Table 3

Phase behaviour and rheological characteristics of micro-emulsions (reservoir water)

Initial composition, %	Relative phase content,%	Effective viscosity, mPa·sec	Static shift voltage
ЭМ*- 1 СТ-1 Н-10 В-88	S1=6 S2=6 S3=88	38.75	0
ЭМ*- 2 СТ-1 Н-10 В-87	S1=2 S2=6 S3=92	29.62	0
ЭМ*-5 СТ-1 Н-10 В-85	Sl=2 S2=12 S3=86	7.06	0
ЭМ*-2 СТ-0 Н-10 В-88	S1=2 S2=40 S3=58	29.00	0
ЭМ*-5 СТ-0 Н-10 В-85	Sl=2 S2=93 S3=5	21.16	0
Э*-2 С-0.5 Н-20 В-77.5	S1=2 S2=30 S3=68	25.47	0
Э*-2 С-0 Н-30 В-68	S1=5 S2=35 S3-60	76.00	2712
Э'-2 С-0 Н-20 В-78	S1=20 S2=30 S3=50	49.00	2712
Э*-5 С-0 Н-30 В-65	S1=2 S2=93 S3=5	52.00	1695

Table 4

Surface tension on the oil-water boundary

Mixture composition	Surface tension coefficient, mN/m
Oil	52.50
Oil + 1 % emulsifier	20.06
Oil + 2 % emulsifier	16.85
Oil + 5 % emulsifier	8.32

In-situ production of inverse micro-emulsions

Micro-emulsion can be obtained in the reservoir itself. In this case, the solution of oil with an emulsifier was first pumped into the reservoir and then this mixture is pushed into the bed by water mixture with a stabilizer. Mixing of reagents and emulsion formation take place directly in the reservoir. Moreover, according to the phase diagram of the system given above, only part of the reagents leads to the formation of the micro-emulsion, i.e. emulsion yield is not 100 %. During injection of the oil solution into injection well in the first stage of the process diluting of the system with water takes place (it is assumed that it is mainly water in the bottom-hole zone); it occurs along a straight line connecting the point of the injected mixture on the side P-S of TPD with the point corresponding to 100 % of oil (W), Fig. 6. In the second stage of the injection of an aqueous solution into the injection well, dilution of the new solution in oil takes place: on a straight line on the TPD, which connects the point of this solution composition and a point of 100 % oil concentration (P) (it is assumed that during the second phase bottom zone is filled with oil phase). The final state of the system corresponds to point R, which is the intersection of straight lines P_0-W, W_0-P (Fig. 6).

The advantages of this technique include simplicity of wellhead equipment, requiring no apparatus for uniform mixing and pushing the viscous micro-emulsion via the borehole into the reservoir. The downside is that during mixing in the reservoir the emulsion yield is not complete, i.e. part of the injected into reservoir oil is not involved in the formation of the emulsion.

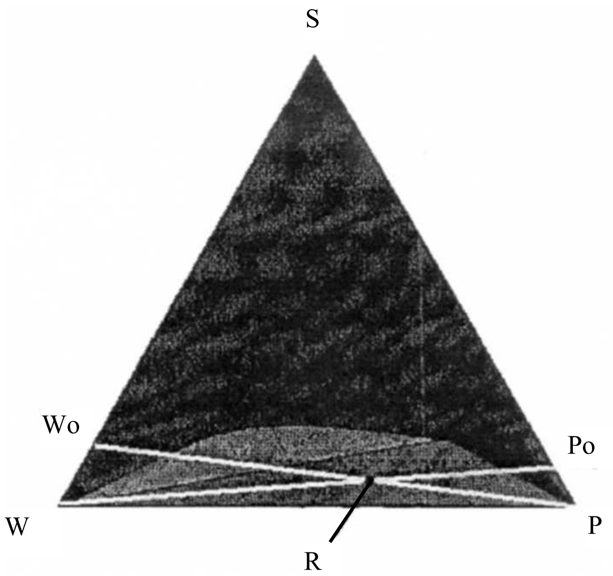

Figure 6. Diagram for determining the composition of the mixture obtained during in-situ micro-emulsion production. Initial compositions of the oil and aqueous solutions injected at various stages, labeled R_o, W_o, respectively

A mathematical model of emulsion stimulation

To describe the process of oil displacement by micro-emulsion, we use the two-phase filtration model [5]. The oil phase is the actual reservoir oil and it includes dispersed third phase – a micro-emulsion, which consists of oil, water and surface active materials as components. A micro-emulsion may stick in a porous medium and can be stationary. Difference in phase densities and speeds of moving micro-emulsion droplets and oil phase itself are neglected. Phase movement is described by a generalized Darcy'-s law [6].

In addition, we neglect the capillary pressure jump and the diffusion of components; phase equilibrium is established instantaneously. Then, in the 1-D case, the equation system of the phases and components conservation in the flow takes the form:

$$m\frac{\partial S}{\partial t}+U\frac{\partial F}{\partial x}=0\ , \tag{4}$$

$$m\frac{\partial S m}{\partial t}+U\frac{\partial}{\partial x}\left(\frac{1-F}{1-S}S_m\right)=-\frac{\partial a_m}{\partial t}\ , \tag{5}$$

$$U=const\ ,\ a_m=a_m(S_m)\ ,F=\left(1-\frac{f_p\mu_w}{f_w\mu_p}\right)^{-1}\ . \tag{6}$$

Here x – coordinate; t – time; m – porosity; U – the rate of filtration; S – water saturation; S_m – the volumetric content of mobile micro-emulsion in porous media; a_m – the volumetric content of the fixed micro-emulsion in a porous medium; F – Buckley-Leverett function; f_i, μ_i – relative phase permeability and viscosity of first phase (i: w for water; p for oil).

Concentrations of the components of the micro-emulsion are considered constant and are determined from the TPD. In a first approximation, the kinetics of micro-emulsion droplets stuck in the pores of the dispersed phase is determined by their concentration in the suspended state and does not depend on the saturation of the aqueous phase. Analysis is restricted to linear kinetics [7-11]:

$$\frac{\partial\beta}{\partial t}=\lambda S_m\ , \tag{4}$$

where λ – is a constant.

Further, we assume that λ does not depend on the size of droplets, but is determined mainly by the structure of the porous medium and filtration rate [7-10]. Thus, we have $\lambda\approx v_w/d$; v_w – the rate of filtration of the aqueous phase; d – geometrical characteristic of the porous medium. The system of equations (4-7) is transformed and contains three variables: water saturation, the volumetric concentrations of mobile and fixed emulsion.

Phase object permeabilities, planned for the application of new technology are modeled with the use of dependencies of the following form:

$$f_w=\begin{cases}\left(\dfrac{S-S_{wr}}{1-S_{wr}}\right)^n; \\ 0, S\le S_{wr} \quad S>S_{wr}.\end{cases} \tag{8}$$

$$f_p = \begin{cases} 1, S \le S_{wr}; \\ \left(\dfrac{1 - S - S_{pr}}{1 - S_{pr} - S_{wr}} \right)^p; \\ 0,\ S \ge S_{pr}\quad 1 - S_{pr} > S > S_{wr}. \end{cases} \qquad (9)$$

Empirical constants were determined by comparing the calculated and experimental data on the fractured reservoir and have the following values: S_{wr} = 0.22, S_{pr} = 0.27, n = 4.1, p = 2.3. Estimates of the relative permeability and the Buckley-Leverett function with viscosity of reservoir oil and water are shown in Fig. 7. Optimization of emulsion parameters impact on the mathematical model is made for conditions average over geological and physical properties, fluid composition and technology development of the porous-fractured reservoirs in the Carboniferous sediments of Bashkortostan.

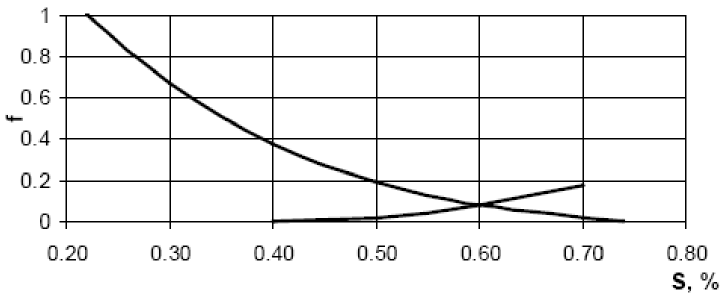

Figure 7. Modelling data on the relative phase permeabilities of fractured reservoir for oil and water

Algorithm for solving, the problem of oil displacement by inverse emulsion and study of the parametric sensitivity of the model

In view of the complexity of solving the general problem of displacement of oil by micro-emulsions we divide it into three sub-problems. The first sub-problem simulates the state of the reservoir at the start of injection of the micro-emulsion and is the traditional problem of oil displacement by water. The second problem simulates the process of displacement of residual oil from the reservoir during its displacement by micro-emulsion or micro-emulsion forefront movement. And finally, the last task – the micro-emulsion displacement by water – simulates the processes occurring at the rear edge of the micro-emulsion.

In the first problem, we assume that the initial time $t = 0$ reservoir ($0 < x < L$) is saturated with residual water Swr and oil. Solution to the Buckley-Leverett sum is done using graphical-analytical technique [11].

Parameters of the displacement front are determined by solving the following equation

$$D=\frac{U}{m}\frac{F(S_A)-F(S_{wr})}{S_A-S_{wr}}=\frac{U}{m}\frac{\partial F(S_A)}{\partial S}\ . \qquad (10)$$

Graphical method for determining the front saturation SA and speed of the front displacement D is shown in Fig. 8.

As a consequence of high-viscosity of oil, displacement front is moving with greater speed and core resources are extracted in a two-phase filtration.

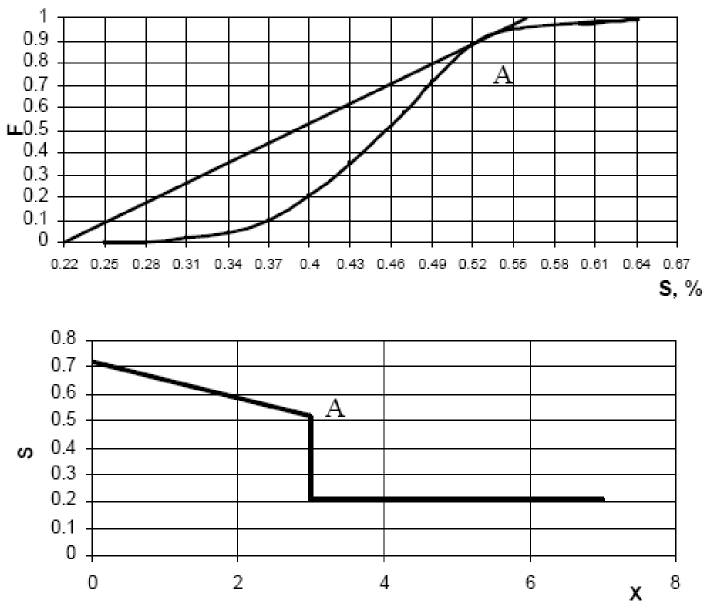

Figure 8. Graphical-analytical technique for solving
the of Buckley-Leverett problem. Schematic solution for the distribution
of water saturationin the reservoir at a fixed time

Injection into the reservoir of inverse micro-emulsion is planned at the moment when the oil displacement by water front already broke into the producing wells and production consists of 80 % water. The initial state of the reservoir at the start of injection is modelled by a uniform distribution of water and oil in the reservoir when the water saturation is equal to the frontline of SA from the solution to the first sub-problem. Solving the second problem is realized using the graphical-analytical technique developed in [11]. The method consists in solving the transcendental set of equations that determine the laws of the phase mass conservation on the Buckley-Leverett concentration jumps for water and the inverse emulsion. The latter function is constructed taking into account the viscosity of the emulsion to reduce surface tension at the inverse emulsion – water boundary. Form of these functions is shown in Fig. 9. Graphical method for determining water saturation on the oil displacement front by inverse emulsion SB and the front velocity D_2 is shown in Fig. 9.

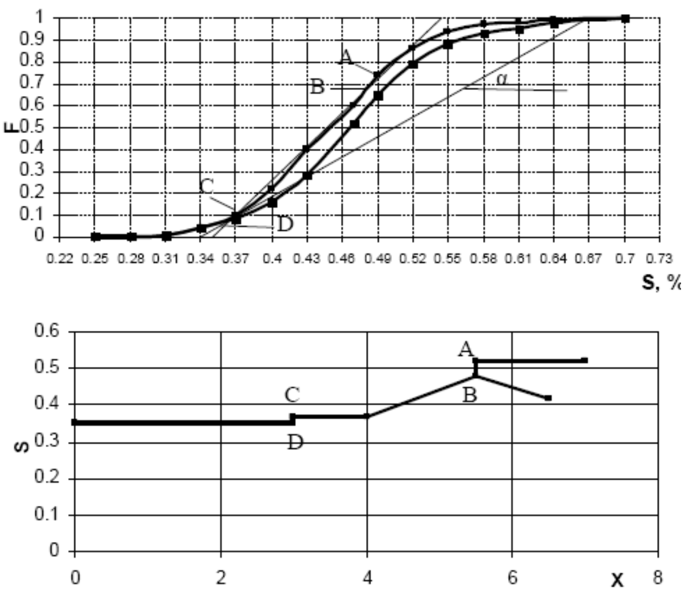

Figure 9. Buckley-Leverett function for water and oil F(S), water and the inverse emulsion F(S, S_m) and graphical method of the equation set solution (11). Schematic distribution of water saturation in the reservoir, created based on the graphical-analytical method

Initial conditions for the problem of micro-emulsion displacement by water are the saturation of the emulsion in the area of portion SD. The technology of the inversion emulsion includes a stepped reduction in its viscosity due to changes in the composition. Sequential injection of four portions of inverse emulsion with lower viscosity is provided in the proposed variant. Last portion has a composition which is characterized by a viscosity of 8 cP. It is the latter portion that is moved along the reservoir by water. Therefore, for the last sub-problem it is assumed that the viscosity of the emulsion is 8 cP and this value is used to evaluate the Buckley-Leverett function. Example of calculated function is shown in Fig. 10.

$$D_2 = \frac{U}{m}\frac{F(S_B, S_m) - F(S_A)}{S_B - S_A} = \frac{U}{m}\frac{\partial F(S_B, S_m)}{\partial S} = \frac{U}{m}\frac{F(S_A) - F(S_B, S_m)}{S_A - S_B - a_m(S_m^0)}, \quad (11)$$

where $F(S)$ – Buckley-Leverett function for water and oil; $F(S, S_m)$ - Buckley-Leverett function for water and inverse emulsion.

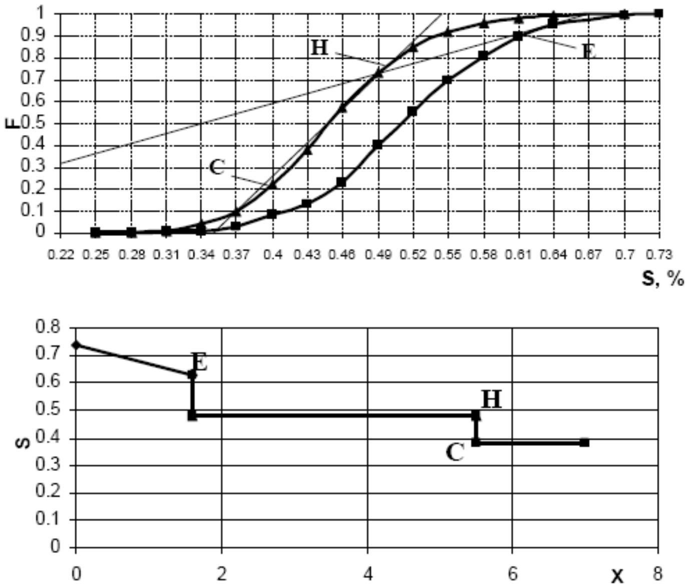

Figure 10. Graphical-analytical solution to the problem of micro-emulsion displacement by water. The structure of the reservoir water saturation: CH jump corresponds to the front of the micro-emulsion displacement by water

Graphic technique and the solution of the latter problem are presented on Fig. 10. Speed of the micro-emulsion displacement by water or the velocity of the "rear" edge of the portion is calculated according to this solution. Obtained solution shows that the velocity of the leading edge of the inverse emulsion is less than the velocity of the rear edge. Thus, the rear edge of the portion catches up front, schematic view of the trajectories of the portion edges is shown in Fig. 11.

Optimization of technology parameters on mathematical model

It is evident from Fig. 11 that the calculation of the portion optimal size is a simple geometric problem. A size at which the portion is completely destroyed at the outlet of the reservoir is meant under the optimum size of the portion. Optimum portion size as a fraction of the pore volume is determined from the formula

$$V = \text{tg}(\alpha) - \text{tg}(\beta)\ . \qquad (12)$$

The optimum size of portion is 20 % of the pore volume, but because of economic considerations the recommended portion size is underestimated.

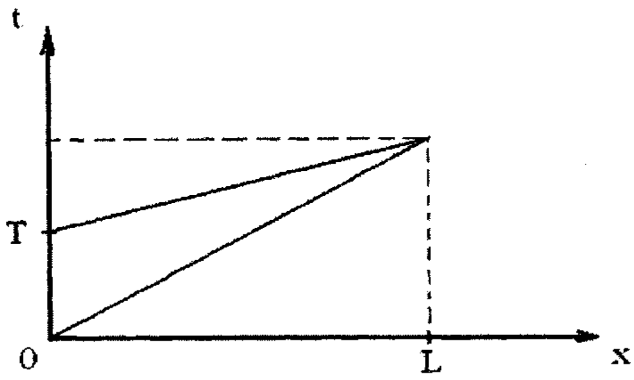

Figure 11. Schematic trajectory view of the forefront and rear front of inverse emulsion portion during its movement in the reservoir

The technology of oil displacement by micro-emulsion includes gradual decrease in viscosity of the inverse emulsion. It is proposed to inject the portion in three stages. The compositions of injected fluids are given in Table 5. Table 6 presents estimates of the composition and properties obtained in the formation of the micro-emulsion.

Table 5

Compositions of working reagents for injection

Stage number	Hydrocarbon portion composition, %		Water portion composition, %	
	oil	emulsifier	water	stabilizer
1	90	10	100	0
2	94	6	98	2
3	100	0	90	10

Table 6

In-situ produced emulsion composition and its rheological characteristics

Stage number	Produced emulsion composition, %				Rheological characteristics	
	Oil	Water	Emulsifier	Stabilizer	Static shift voltage, Pa	Effective viscosity, mPa·sec
1	30	66	4	0	2.700	71
2	10	85	5	0	0.678	21
3	26	69	0	5	0.000	8

Size and composition of fluids used in the process are obtained based on the calculation of technological parameters and economic characteristics. These data are presented in Table 7. After the injection of working compositions and in-situ production of inverse emulsion it is expected to push the portion in reservoir with water.

Table 7

Volume and composition of solutions for the in-situ production

Stage number	Total volume of the hydrocarbon portions, m^3		Total volume of water portions, m^3		Volume of emulsion produced in the reservoir, m^3
	нефть	эмульгатор	вода	стабилизатор	
1	75	10	165	-	250
2	50	25	425	0	500
3	260		690	50	1000
Total:	415	25	1205	55	1750

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