UDC 622.276.6

MODELLING OF OIL DISPLACEMENT PROCESS IN HETEROGENEOUS RESERVOIRS

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In order to calculate parameters of oil displacement by water flooding a mathematic model was built, considering joint and separate reservoir exploitation. Regression equations for Yasnopolyanskiy horizon of one large field of Permian-Bashkirian arch have been derived, which enable to forecast heterogeneity parameters, affecting degree of reserves recovery, as well as to identify zones with the highest oil recovery coefficients. Application of physical and chemical stimulation methods enable to increase length of well life and duration of profitable exploitation of productive reservoirs.

Kew words: permeability coefficient, heterogeneity, water-cut, regression model, surface-active substance

Water intrusion is extremely non-uniform during water flooding of layer-by-layer heterogeneous reservoir. Water breaks through to producing wells via high-perme-able layers leaving not displaced oil in low-permeable low-drained zones. Massive break of water leads to high water-cut of produced liquids and eventually results in necessity of such wells shut-in. With low hydrodynamic connectivity between layers and varying filtration parameters physical and chemical simulation methods are used in order to reduce water-cut. Main aim of these methods is to create gel barriers or dregs in drained water-bearing reservoir zones [1].

Modelling of oil recovery process by water-flooding has been accomplished for productive reservoirs of Yasnopolyanskiy suprahorizon of one large field of Permian-Bashkirian arch with geological and physical characteristics presented on Table 1.

Calculation of parameters of oil recovery from water-flooding is being done using two-dimensional with vertical cross-section numerical model of two-phase filtration in layer-by-layer heterogeneous reservoir. It is anticipated that formation is being developed by system of wells with distance between producing and injection rows of 500 m. Development of heterogeneous formation with varying reservoir properties is undertaken by means of reservoir pressure maintenance with water injection (Fig. 1). It is assumed that between layers there is mass exchange, liquids and formation skeleton are incompressible. With conventional water flooding approach, e.g. displacing oil by water via the most permeable layer, there is water enroachment of reservoir. In conditions of high variation in heterogeneity parameters and with the aim of the most precise identification of water-flooding efficiency several options of calculation for both joint and separate reservoir exploitation have been considered:

– permeability coefficient value of Formation Bb1 10 times exceed permeability of Formation Bb2;

– permeability coefficient value of Formation Bb1 100 times exceed permeability of Formation Bb2;

– permeability coefficient value of Formation Bb1 1000 times exceed permeability of Formation Bb2.

Table 1

Geological and physical characteristics of productive formations

Productive formation	Total thickness, m	Oil net pay, m	Number of permeable intervals	Porosity, %	Oil saturation, %	Permeability, μm^2
Formation Bb1						
Maximum	20.0	14.6	3.0	25.6	95.1	1993.4
Minimum	0.1	0.2	1.0	12.1	50.9	1.8
Average	8.1	0.3	1.3	16.7	79.2	158.8
Formation Bb2						
Maximum	39.0	25.4	10.0	25.9	95.3	2184.6
Minimum	4.7	0.2	1.0	12.1	50.9	1.8
Average	17.6	1.6	1.9	19.8	87.1	543.2

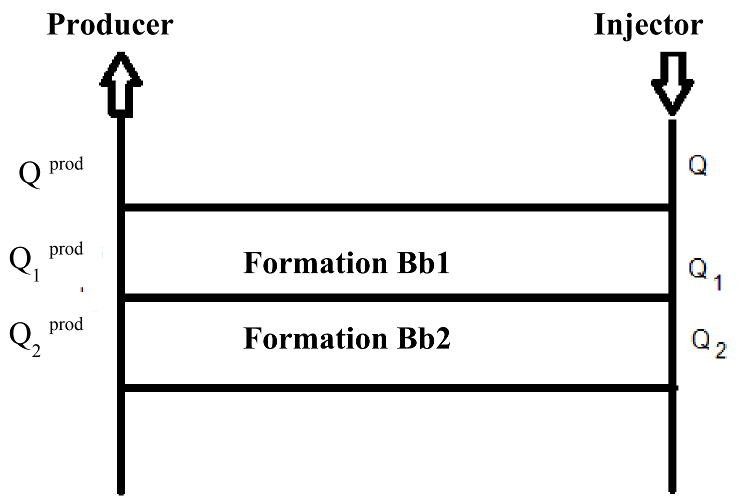

Figure 1. Task geometry. 1, 2 – layers with different permeability

Mathematical statement of a problem consists of system of equations of continuity and movement for each phase, supplemented by initial and boundary conditions. A task of flat displacement is considered corresponding to row system of water flooding.

Equations of continuity for phases with account of equation of movement in a form of Darcy law:

$$m^j \frac{\partial}{\partial t}\left(S_i^j\right)=\frac{\partial}{\partial x}\left(k^j \frac{k_i(S_2^j)}{\mu_i}\frac{\partial P^j}{\partial x}\right);\ i=1,2;\ j=1,2;\ 0\le x\le L\ , \qquad (1)$$

where index i – phase number (1 – oil, 2 – water) and index j – number of layer.

For simplicity of task solving with specified water-intake capacity on formation boundary this equations system can be re-arranged into the following form:

$$m^j \frac{\partial S_2^j}{\partial t}+q^j \frac{\partial}{\partial x}\left(F(S_2^j)\right)=0\ ; \qquad (2)$$

$$F(S_2)=\frac{k_2\left(S_2\right)}{k_2\left(S_2\right)+\frac{\mu_2}{\mu_1}k_1\left(S_2\right)}\ ,$$

where $q^j=\frac{Q^j}{H^j A}$; Q^j – water-intake capacity of one well into layer j; H^j –layer thickness, A – distance between wells in a row.

In order to compare results derived from separate and simultaneous injection into formation two tasks must be considered. For task of separate displacement a case of specified water-intake capacity of well is considered and for task of joint displacement a case of specified injection pressure is taken into account.

In first task boundary conditions for equation (2) will have the following view:

$$S_2^j|_{x=0}=1\ ,\ S_2^j|_{t=0}=0\ .$$

In second task boundary conditions for system (1) are:

$$S_2^j|_{t=0}=0\ ;$$

$$P^j|_{x=L}=P_{pr}\ ,\ \ P^j|_{x=0}=P_{inj}\left(t\right)\ ,\ S_2^j|_{x=0}=1\ .$$

In addition, conditions of equality of total water-intake capacity in first and second task must be considered:

$$\sum_j Q^j=Q\ ;$$

$$\sum_j \frac{k^j}{\mu_2}\left(\frac{\partial P^j}{\partial x}\right)_{x=0} H^j A=Q\ .$$

Results of water-cut in well production calculation for different exploitation conditions are presented in Fig. 2. For conventional scheme of water-flooding early water intrusion in a high permeable layer can be noted. Early water influx in well product can be prevented by water-intake capacity adjustment in each layer during separate exploitation of layers. Calculation parameters: formation thickness 5 m, ratio of oil/water viscosity – 5, porosity 20 %, distance between wells 500 m.

Therefore, based on existing graphs for conditions of productive beds of Bobrikovian horizon for fields of Permian-Bashkirian arch, it can be noted that with permeability ratio of two layers less than 10 times the effect from application of simultaneous separate exploitation may not be achieved. This approach will help to identify top-priority wells for application of separate independent exploitation technology.

While organizing separate water injection into formations with permeability ratio of 100 and 1000 times rates of water intrusion are reducing and oil displacement efficiency is increasing (Fig. 2).

Accomplished modelling of joint and separate exploitation efficiency enables to conclude that undertaking of separate exploitation technologically and therefore economically efficient only at specific permeability ratio – higher than 10 times. Thus, to reach the highest technological and economical efficiency while defining two jointly developing formations for separate objects of exploitation it is necessary to range drilled exploitation wells (firstly injection) based on permeability variation in each layer. It is also worth to differentiate production and injection when exceeding permeability ratio more than 10 times.

Degree of oil reserves recovery is determined by different geological and technological reasons. Complexity of field geological structure is often characterized by unfavourable reservoirs, such as: low-permeable, low-porous, discontinuous, highly compartmentalized reservoirs, beds with low oil net pay and low oil saturation, formations with dual porosity and permeability. All parameters mentioned to a greater or lesser extent have impact on oil reserves recovery degree.

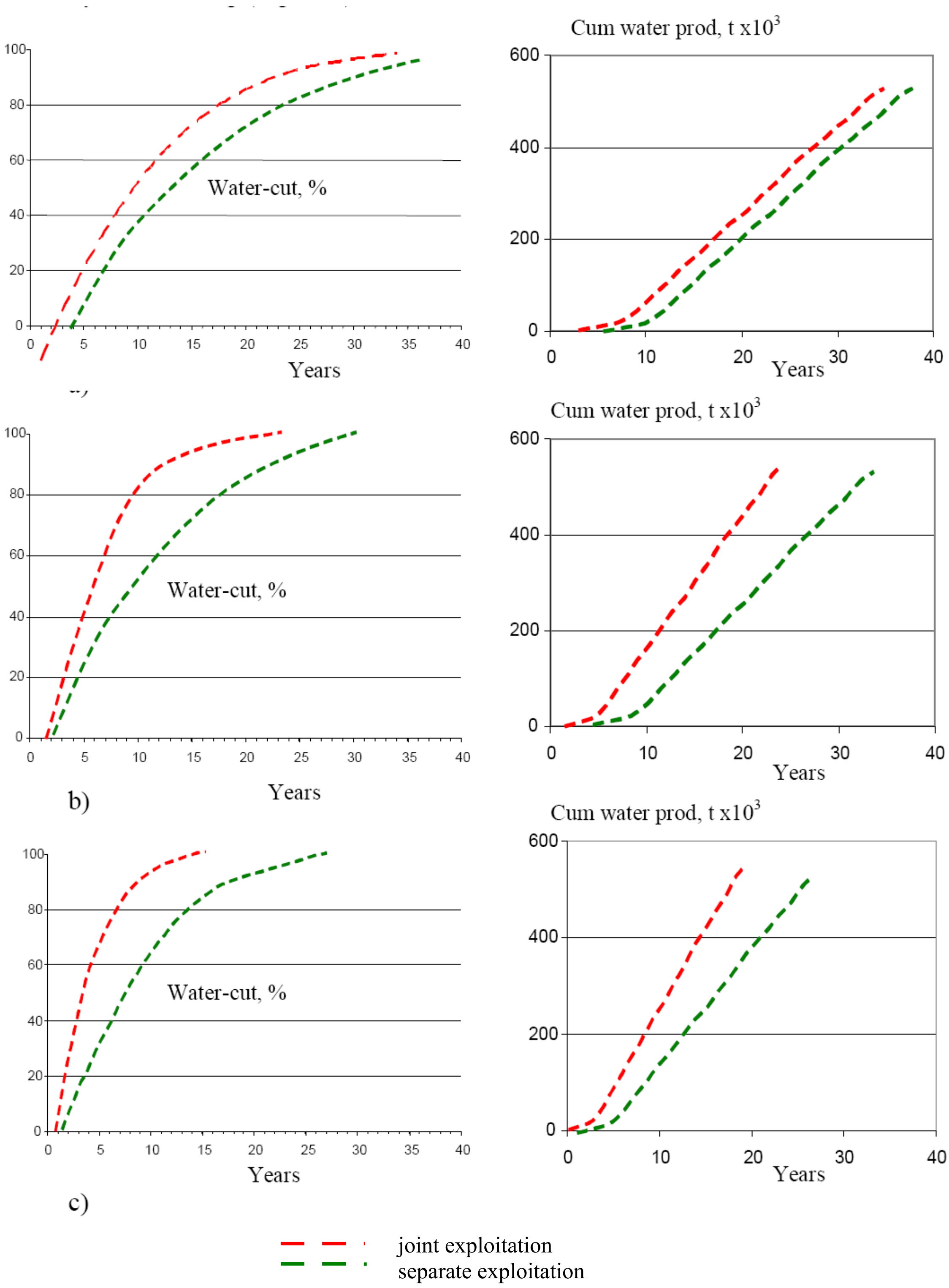

Figure 2. Calculation of water-cut in well production and cumulative water produced based on different permeability ratio of layers:

a) permeability of Bb1 formation 10 times exceed permeability of Bb2 formation;
b) permeability of Bb1 formation 100 times exceed permeability of Bb2 formation;
c) permeability of Bb1 formation 1000 times exceed permeability of Bb2 formation

Yasnopolyanskiy horizon on the studied field includes the following formations: $Tl_{2\text{-}a}$, $Tl_{2\text{-}b}$, Bb_1 and Bb_2. Some parts of productive formations with relatively homogeneous reservoir properties are characterized by high recovery and water-cut values. It is also worth to mention that within the field there are zones with unfavourable reservoir properties but with high degree of oil recovery which is due to high density of wells.

In order to quantitatively and qualitatively assess influence of heterogeneity parameters geostatistical modelling has been undertaken which comprised regression models building and their analysis. As heterogeneity parameters of productive formations that have impact on development efficiency the following were used: coefficient of compartmentalization, variation of oil net pay, permeability, porosity and oil saturation. Initial matrix of studied factors has been normalized. In statistical analysis 136 wells have been utilized. Regression analysis has been carried out in Statgraphics Plus 5.0 software. As a dependent parameter values of dispersion and variation of cumulative oil recovery (DQn and Vqn), oil production rates (Dqn, Vqn), water production rates (Dqv, Vqv) and water-cut (Df, Vf) were selected, while affecting parameters were: coefficient of compartmentalization (Rasch) and oil net pay variation (WHnnas), permeability (Wpron), porosity (Wpor) and oil saturation (Wnnas).

Dispersion values of technological parameters were calculated for wells during the period from start of oil production decline and up to current date.

Regression model building based on example of water-cut variation analysis includes the following stages.

On the first stage of statistical analysis all investigated objects have been used. Results have revealed that correlation coefficient for this set has low number – 1.7 % and coefficient of multiple correlation – 0 % as some values are quite far away from trend line, thus heavily reducing value of correlation coefficient and making obtained geostatistical model unreliable.

On the first stage in order to increase the model reliability it is necessary to exclude objects out of the common range. As a result if these objects exclusion, values are uniformly distributed along the trend line and values of correlation coefficients and multiple correlation have gone up – 65.4 % and 63 % respectively. After such removal reliability of the geostatistical model can be considered acceptable (Fig. 3).

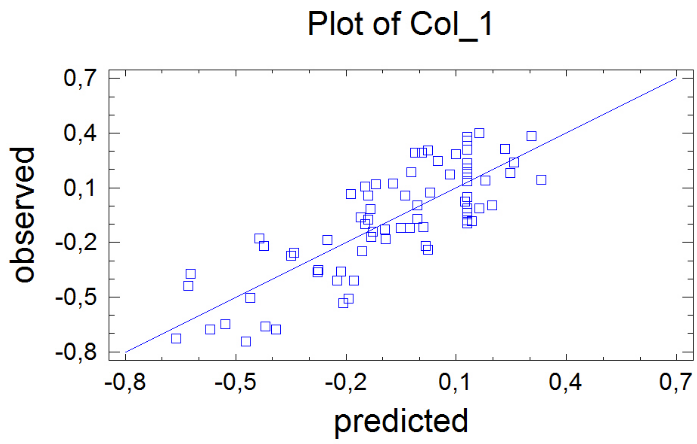

Figure 3. Wells (set) distribution with estimated and actual correlation coefficients.

On the third stage parameters that do not affect investigated factor are revealed. For this reason independent parameters are exposed to statistical analysis of Darbin-Watson, this statistics is based on the following formula: $DW = 2 - 2p$, where p – correlation coefficient between two values of random variable, for instance with total absence of correlation between errors $DW = 2$ and parameter p is equal to 0. If parameter p is less than 0.01, then statistically valuable relation between variables is 99 %; if parameter p is less than 0.05 then statistically valuable relation between variables is 95 %, which is acceptable. But if parameter p is more or equal 0.1 then the value is not statistically valuable more than 90 % and this value should be deleted from geostatistical model. Parameter p for compartmentalization values is equal to 0.96, therefore these values are statistically valuable only by 4 % and do not affect the reliability of geostatistical model [2].

For Yasnopolyanskiy horizon regression models have been built and are presented in Table 2.

Based on the results obtained it is possible to make the following conclusions: completed analysis and reserves recovery map juxtaposition with heterogeneity maps as well as geostatistical modelling for geological and physical conditions of one field of Permian-Bashkirian arch made it possible to accurately identify heterogeneity parameters which have the highest impact on reserves recovery degree, that is permeability and porosity variation.

Table 2

Regression models for Yasnopolyanskiy horizon

Regression model	Correlation coefficient	No of data in a set	Parameters that do not affect
DQn=–0.32 – 0.0469*Wpor+ 0.0136* WHnnas + 0.0095*Rasch + 0.38*Wnnas - 0.052*Wpron	60.7 %	58	WHnnas
Vqn=–0.46 – 0.84*Wpor + 0.67*WHnnas + 0.039* Rasch + 3.88*Wnnas – 0.696*Wpron	67.4 %	60	-
Dqn=–0.120712 + 0.00038*WHnnas + 0.00025*Rasch – 0.0014*Wpor + 0.00079*Wnnas – 0.00025*Wpron	66.5 %	50	Wnnas
Vqn=-0.296 + 1.095*Wpor + 0.154*WHnnas + 0.0137*Rasch – 0.889*Wnnas – 0.14*Wpron	63.6 %	65	Rasch
Dqv=– 0.097 + 0.0011*Wpor + 0.00024*WHnnas – 0.0000024*Rasch – 0.00038*Wnnas – 0.00018*Wpron	63 %	65	Rasch
Vqv=– 0.204 – 0.145*Wpor+0.0755*WHnnas+ 0.0098*Rasch + 0.286*Wnnas-0.065*Wpron	68.3 %	60	-
Df=-0.093 + 0.0155*Wpor + 0.00197*WHnnas- 0.000397*Rasch – 0.0277*Wnnas + 0.0016*Wpron	68.4 %	50	-
Vf=0.128 – 1.517*Wpor + 0.3349*WHnnas + 0.000776*Rasch + 3.468*Wnnas – 0.74*Wpron	65.4 %	75	Rasch

Using this approach it looks possible to predict what heterogeneity parameters affect the reserves recovery degree as well as to identify zones with the highest pre-dic-ted coefficients of oil recovery.

Development control of heterogeneous productive formations is possible by applying technologies orientated on increase of reservoir oil recovery and also by selective stimulation on near well bore zone of certain formations or layers in order to increase reservoir and well performance efficiency. For this aim stimulation methods for near well bore zone of reservoir have been developed:

– method of hydrophobic stimulation of near well bore zone of productive reservoir;

– stimulation method of near well bore zone of reservoir with application of acrylic range and corrosive substances.

Hydrophobic stimulation of near well bore zone of productive reservoir is a method of well productivity enhancement and control of formation water influx in order to increase reservoir oil recovery by applying physical and chemical stimulation methods. This technique enables to increase well life period and duration of profitable exploitation of productive formations.

Technical result could be increase of efficiency and reliability of water influx control, giving water repellency properties to surface of porous volume with no reduction in cross-section of transport channels. Method of hydrophobic stimulation of near well bore zone of productive reservoir includes mixture of surface active substances injection into porous and fractured volume of the near well bore zone and holding well in quite for capillary imbibition, conversion into regime of hydrocarbons inflow. As a mixture of surface active substances a solution of chemical products waste containing polyatomic spirits 96-75 % weight, concentrate of parent admixtures of ethanol from food raw material 1.0-4.0 % weight, intermediate fractions of ethanol from food raw material 0.5-4.0 % weight, fusel oil 1.0-3.0 % weight, surface active substances of neonol group 0.5-4.0 % weight, oxyethylated fatty acids 1.0-10.0 % weight are being used. Well hold in quite is undertaken for 24-60 hours, and upon completion liquids from the well are flared until stable well work, and then the well is converted into regime of hydrocarbons inflow.

Surface active substances (SAS) selection for water flooding is carried out, according to a task set, based on several methods (surface tension measurement, contact angle, adsorption, displacement from porous media etc.), which do not provide the full information on aggregate surface events in reservoir system "oil-displacement agent-porous media" and moreover on hydrodynamics of residual oil affected by external action. In this case even experiments on natural samples of porous media are not always informative, because they are normally carried out on unrepresentative samples with unknown porometric characteristics.

Absence of adequate information on modification of oil model by physical and chemical stimulation leads to errors early on stage of development and decrease in efficiency of simulation methods when they are applied.

This is why while developing method of stimulation along common methods a complex of special investigations on influence of some substances on structural and mechanical properties of oil and specifics of its flow in porous media has been undertaken.

There are some results of such investigations presented below for homologous series of SAS (AF-3, AF-5, AF-10) on naphtenic crude oil of well 45 of Arlanskoe oil field. The experiment was carried out on original installation of USPTU, enabling in pores – narrow gaps of micron size to measure structural and mechanical parameters of oil and to study the character of its flow [3].

Investigations of original oil, not stimulated by substances, in pores, sizes of which are similar to the studied deposit, have revealed that even after few hours of contact interaction of liquid with rock-building mineral (quartz) its viscosity is increasing by order in relation to the volumetric value of this parameter, which is 25 mPa•s.

The noted effect along with that is increasing by reducing the size of narrow gap, therefore depends on intensity of solid body area (Fig. 4). Close to the linear type the presented relationships present the independence of viscosity from the magnitude of applied stress, which is possible in Newtonian or in certain conditions viscoplastic flow regime.

Further analysis has revealed that the latter law of motion satisfies to capillary oil, which is normally typical for solid-like liquids. It is worth to mention that in volume conditions in rotary viscosimeter the same oil demonstrates qualities of low-structured liquid.

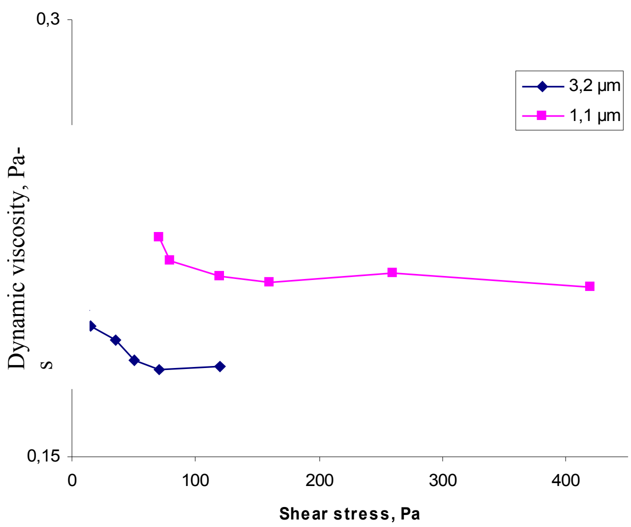

Figure 4. Studied oil dynamic viscosity relation with shear stress in narrow gaps of different size (curves code-gap size, micron)

Experiment data on oil flow in narrow gaps of different size in coordinates "shear speed-shear stress" are reliably approximated by straight-line equation V-A+BX (Table 3, Fig. 5).

Table 3

Parameters of regression equations

Coefficient A	Coefficient B	Correlation Coefficient	Notes
-13.865	4.796	0.998	Gap 1.1 micron
-1.045	5.308	0.997	Gap 3.2 micron

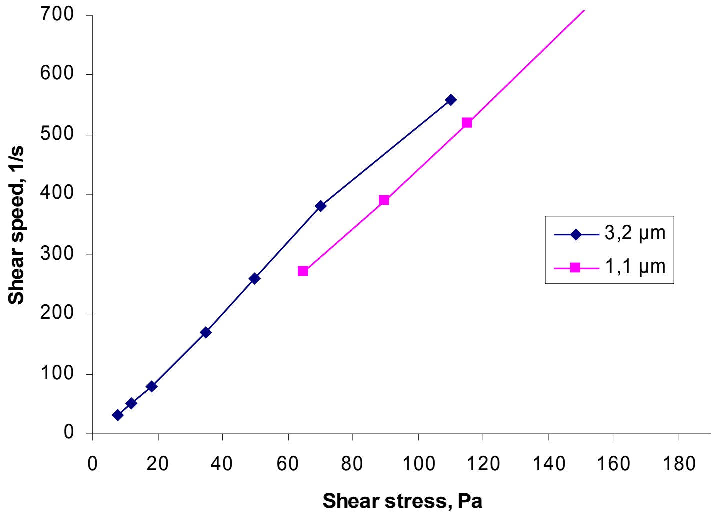

Figure 5. Studied oil flow curves in narrow gaps of different size
(curves code-gap size, micron)

Values of dynamic shear stress determining the beginning of plastic value of dynamic flow stress are equal to 2.89 and 0.197 Pa, respectively. By using the Buckingham equation it is possible to estimate the corresponding critical pressure gradients, which in this case are 10.51 and 0.246 MPa/m, respectively. It is quite evident that even in the latter case the derived value of critical gradient is one higher than existing pressure fluctuations in reservoir, which makes impossible to displace oil out of pores of this size without undertaking any preventing actions.

Based on the example of the most structured oil, accumulated in capillars of small diameter, influence of SAS on structural, mechanical and hydrodynamic properties of liquid can be shown. The methodology of the experiment comprised the following: certain quantity of SAS was brought to the oil sample, which then was put into the measuring cell of the installation – narrow gap of certain size, where after reaching the balanced state measurements of structural, mechanical and hydrodynamic properties of the liquid sample were carried out.

The obtained data show that this SAS within the whole range of concentrations (0.1 - 4 %) does not radically change viscoplastic supramolecular oil structure, affecting only its quantitative characteristics (Fig. 6). It is important to note the uncertainty of this effect; it is clear that the plot for oil with the minimum composition of AF-5 has the highest angle of slope and plastic flow in this case starts at gradients three times less than the existing oil has. Analysis of measurements in all range of concentrations shows that viscosity (Fig. 7) and critical shear stress (Fig. 8) actually depend on reagent concentration. The derived relationships show the existence of different mechanisms of SAS action – surface and volumetric, determined by SAS adsorption on outer and inner boundaries of phase division.

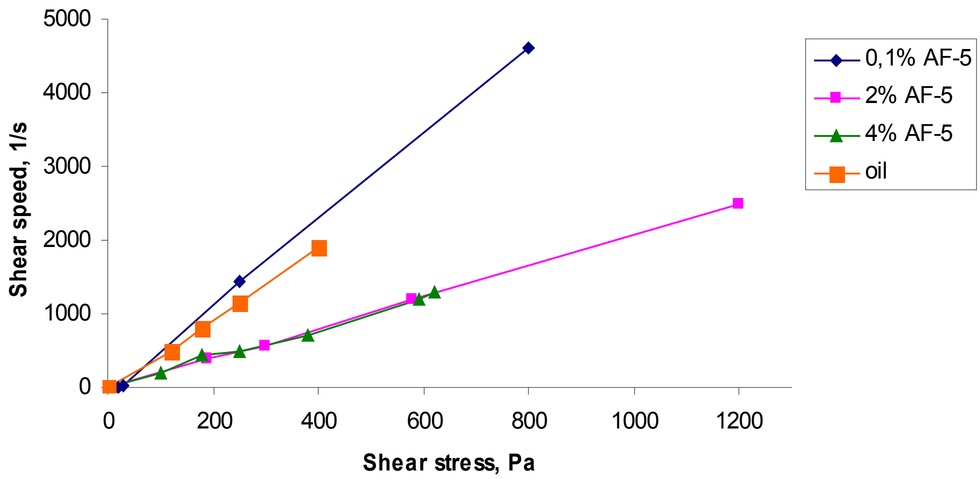

Figure 6. Flow curves of studied oil and treated by SAS in narrow gap of 1.1 micron

In first case, there is a blockage of active centres of solid body surface that weakens effect of surface forces on wall-adjacent layers of liquid and leading to reduction of non-Newtonian anomalies of the latter. In the second, molecules of reagent, diffusing in volume with increase in concentration, weaken in- and intermolecular links in liquid and therefore increase structural action of solid body that leads to strengthening of anomalies in liquid. With concentrations close to KKM solubility of micelle of outer SAS and their content in liquid are increasing and creating by them supramolecular structure due to larger sizes of body-building particles obtains more unconsolidated and plastic character.

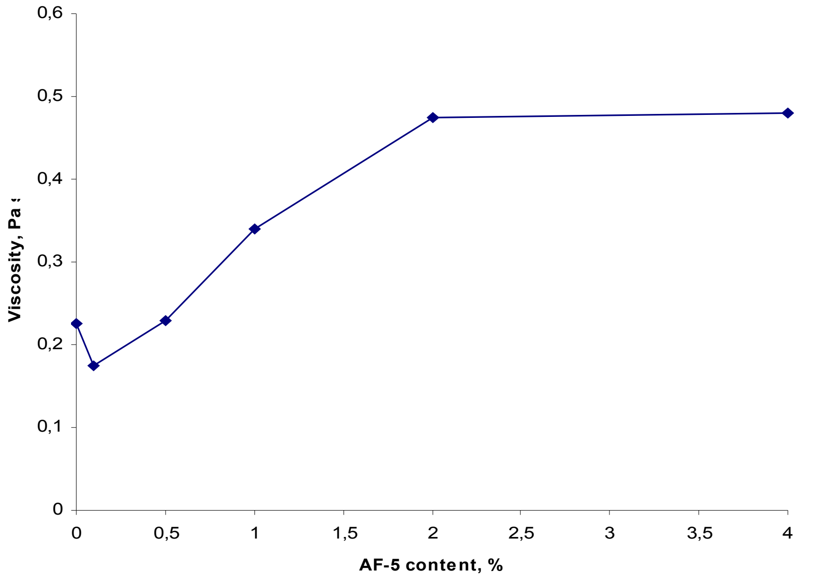

Figure 7. Dependence of oil viscosity in narrow gap of 1.1 micron on AF-5 content

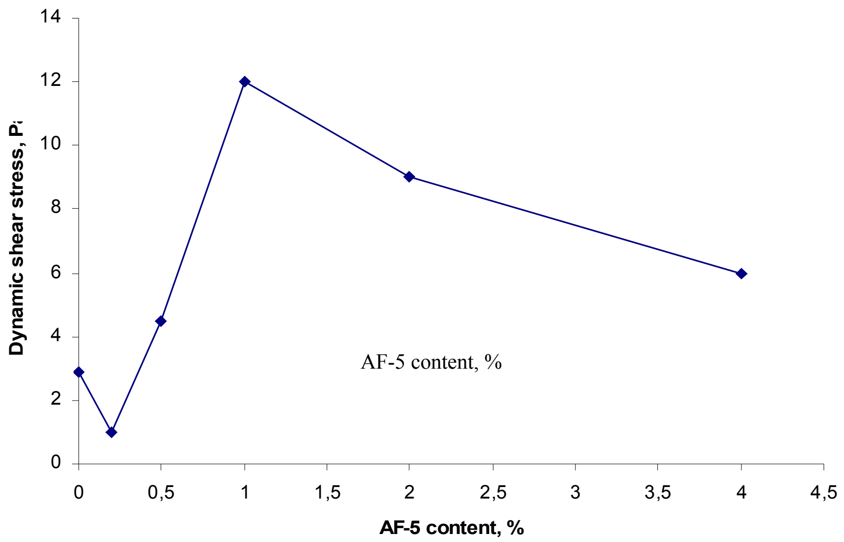

Figure 8. Dependence of dynamic shear stress on SAS content
in narrow gap of 1.1 micron

Described events determine the extreme character of relations presented above. Attention could be drawn to the distinctive points on the last figure – points of inversion, where the sign of effect changes. Qualitatively similar functions have been obtained for other SAS samples and different gaps. The revealed trends enable to promptly control properties of displacement agent by varying content of active substance; strengthen detergent properties of the latter in drained part of the deposit or, on the contrary, to block the latter, increasing non-Newtonian anomalies of the displaced oil there. From our point of view, absence of information about such character of SAS stimulation on oil is the main reason of not always effective application of SAS in reservoir conditions.

According to the mechanism of SAS action described above with the content of AF-5 up to 0.1 % there is a surface mechanism leading to shielding of solid body area and reducing structural and mechanical parameters of oil. With high concentrations (up to 1 %) modifying influence of solid phase is increasing due to break of the initial supramolecular net of oil. With further increase in concentration of AF-5 there are collective processes and building micelles of the latter form less stable own structure, which is shown by the corresponding reduction of critical shear stress value with some increase of viscous properties.

Equally uncertain is the influence of nature of the outer SAS on capillary oil characteristics, because components of homologous series of reagents affect parameters of oil flow in pores differently (Fig. 9).

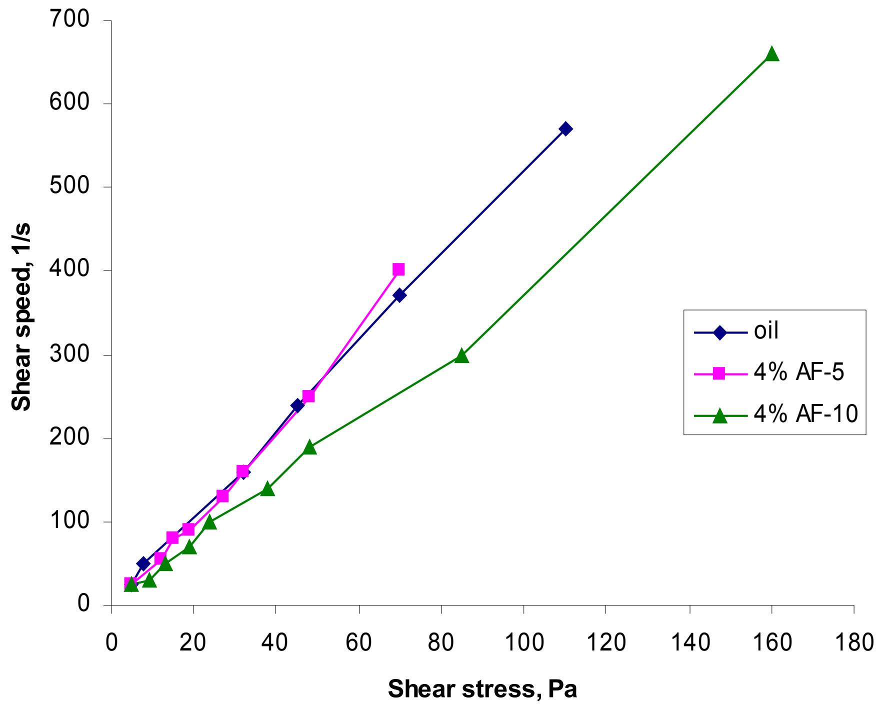

Figure 9. Curves of the studied oil flow and with SAS additives in narrow gap of 5 micron

Summarizing everything mentioned above it is possible to note that extreme character of concentrate functions of hydrodynamic parameters of capillary oil suggests about the possibility of the stimulation mechanism on oil by varying the SAS content in displacing liquid. However, the application of the noted fact requires adequate information about variation of oil hydrodynamics by the reagent action that may be provided by application of modern methods of interphase events studies along with known methods at stage of development of intensification technologies and precise accomplishment at the stage of implementation.

For performance regulation of permeability heterogeneous reservoirs at the later stages of oil field development by means of water influx isolation method with gel-forming technologies application based on polymer of acrylic series and corrosive substances has been developed. This technology can be used for performing jobs on inflow profile aligning in producing wells and intake profile in injection wells, water influx isolation, and intensification of oil and gas production. It also provides more full alignment of inflow profile in producing well and intake profile in injection well.

According to this method sequential injection of the first portion of the aluminous liquid mixed with water in 1:4 ratio is undertaken, followed by fresh water; mixture of hydrolyzed in alkali waste of fibers or polyacrilonitrile fabrics; fresh water; second portion of the aluminous liquid; acid; as aluminous liquid a mixture of aluminium chloride is used – waste of chemical products, for example waste of catalytic production in obtaining alkyl benzenes, additionally containing polyglycols, carbamide, surface active substance and universal acid inhibitor in the following ratios % weight:

18-23 % water mixture A1C13, waste of chemical production	75-80
polyglycols	8-10
carbamide	8-10
surface active substance + universal acid inhibitor	2-5

As hydrolyzed in alkali waste of fibers or polyacrilonitrile fabrics a water-polymer composition is used containing additionally non-ionic surface active substance that has low temperature of cooling from -25°C to +35°C and forming larger quantity of solid material in fractured porous reservoir volume, containing components in the following ratios, % weight:

hydrolyzed polyacrilonitrile (waste of fibers or polyacrilonitrile fabrics or otherpolyacrilonitrile material), % weight	10-20
non-ionic surface active substance, % weight	0.1-0.5
caustic soda (NaOH), % weight	20-40
water, % weight	remaining

Besides after finishing the first portion of aluminous liquid there is a break and leave the well at rest for 60-72 hours for gel-forming. As acid it is possible to use the mentioned a mixture of aluminium chloride – waste of chemical products additionally containing polyglycols, carbamide, non-ionic surface active substance and universal acid inhibitor mixed with water in ratios 1:4 or 1:5. Acid injection or instead of acid of aluminous liquid containing polyglycols, carbamide, surface active substance and inhibitor mixed with water in ratios 1:4 or 1:5 can be performed in two parts, between which a solvent is injected, for example methanol or acetone or other hydrocarbon solvent.

Gel and precipitated polymer created in water-filled interval of the reservoir are stable to water washing in reservoir conditions.

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