

Study and determination of regularities in variability of oil rheological properties to enhance oil recovery

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ABSTRACT

The processes of oil production, collection and treatment are complicated by a complex of problems associated with the formation of stable oil emulsions, deposits of asphalt-resin substances and paraffinic hydrocarbons, inorganic salts. Moreover, the formed sediments often have a complex blend composition. Especially, at the late stage of oil field development, as a rule, procedures of gathering and processing of oil are complicated, in particular, by wall mud cake, low pressure, and also by an increase in the water cut of the product, with an increase in the volume of chemicals used during repair works and for production stimulation. Under these conditions, it becomes relevant to determine the regularities in changes of the rheological properties of oil to prevent complications in pumping equipment and flow strings, pipelines, equipment, and tank farm of oil gathering systems. The use of ultrasonic waves in electrophysical advanced recovery has a number of advantages, including simple and fast application, protection from wellbore damage, high profitability, low operating costs, significant compatibility with other enhanced oil recovery methods, and widespread application. This paper provides a technical and economic assessment of the effectiveness of electrophysical stimulation in the production field in Western Kazakhstan. The use of electrophysical stimulation technology in the production fields shows high technological efficiency. A decrease in the oil viscosity in a bottomhole zone of a production well during the use of ultrasound leads to an increase in the flood front during the water-driven operation of the reservoir. This matter was addressed in the present paper.

Keywords: Viscosity reduction, Oil recovery factor (ORF), Hard-to-recover reserves, Oil and gas complex.

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1. Introduction

In recent decades, hard-to-recover oil reserves in the Republic of Kazakhstan have been attracting more and more attention. In this regard, it is relevant to develop innovative methods for increasing production, which can significantly increase the oil recovery factor (ORF) from the oil-producing formation. At the enterprises of oil and gas complex, methods of intensifying oil production are being introduced quite intensively, nevertheless, the choice of one or the other method requires a scientifically based approach. One of the electrophysical methods is the ultrasonic wave emission, which supports the method of enhanced oil recovery (EOR), while preventing damage to the collapsing reservoir and also reduces the viscosity [1-15].

Nowadays, the direction of the combined application of ultrasound together with thermal, chemical and hydrodynamic methods is promising. However, this requires comprehensive research and development (R&D) and field trials. It is also very promising to use ultrasonic treatment in order to reduce the viscosity of oil in high-viscosity deposits and to increase the productivity of marginal wells [16-40].

The processes of oil production, collection and treatment are complicated by a complex of problems associated with the formation of stable oil emulsions, deposits of asphalt-resin substances and paraffinic

hydrocarbons, inorganic salts. Moreover, the formed sediments often have a complex blend composition [41; 42; 43-60]. Especially, at the late stage of oil field development, as a rule, procedures of gathering and processing of oil are complicated, in particular, by wall mud cake, low pressure, and also by an increase in the water cut of the product, with an increase in the volume of chemicals used during repair works and for stimulation of production [61-80]. Under these conditions, it becomes relevant to determine the regularities in changes of the rheological properties of oil to prevent complications in pumping equipment and flow strings, pipelines, equipment, and tank farm of oil gathering systems. The use of ultrasonic waves in electrophysical advanced recovery method has a number of advantages, including simple and fast application, protection from wellbore damage, high profitability, low operating costs, significant compatibility with other enhanced oil recovery methods, and widespread application [81; 82-100].

Compared to other methods of enhanced oil recovery, the electrophysical stimulation technology, namely ultrasonic treatment, has a number of significant advantages, such as:

- cheaper, more effective, as it has better results;
- no pollution, chemicals, and water contamination;
- in all three phases, production is effective if fluid is present at the stimulation depth;
- compared to other methods, there is much less non-productive time.

In order for the use of these technologies to give positive results, the following measures are important:

- removal of salt formations in capillaries;
- removal of deposits of asphaltenes, paraffins, resins;
- removal of colloidal formations;
- disinfection of the well.
- lowering interfacial tension in the capillaries;

These measures revitalize oil wells with low margin, stimulate oil wells with declining flow rates, and maintain the maximum well production [101-110].

2. Materials and methods

The use of high-power ultrasound technology at one field in the Mangistau region of the Republic of Kazakhstan was carried out as part of field trials. The field was at the late stage of development. The development of this field was carried out using waterflooding. The main problem in the development of this field was to eliminate the negative impact of the high viscosity ratio of oil and water, as well as non-Newtonian oil properties in the current and final oil recovery (Figure 1) [111; 112-120].

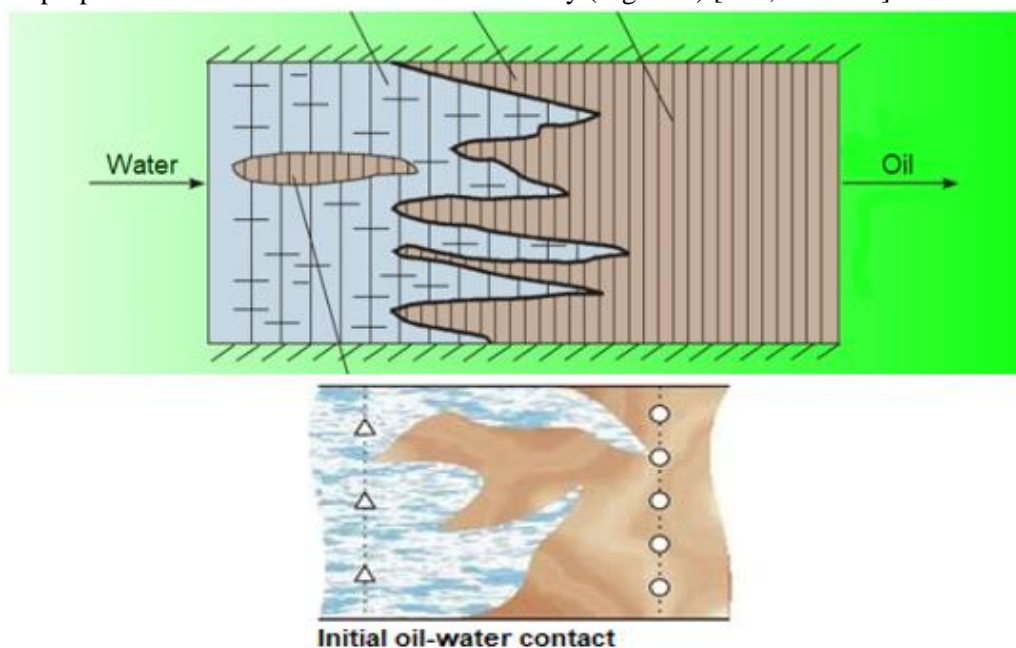


Figure 1. The movement of the oil-water contact in the reservoir at $\mu = 20\text{-}30 \cdot 10 \text{ Pa/s}$

To reduce the viscosity of the produced fluid, as well as to assess the effect of changes in viscosity on the final oil recovery factor, the technology of using ultrasound in the bottomhole zone was chosen [121-123]. A

production well with a high viscosity of the produced fluid (30-50 cP) was selected. For the calculation in Excel, the following initial field data was used (Table 1). Initial well performance model [124-126].

Table 1. Initial data

Efficiency of microscopic bias of the Buckley-Leverett function			
mo	Oil viscosity	50	cP
mw	Water viscosity	1.23	cP
S_{wirr}	Irreducible water saturation	0.25	fraction
S_{or}	Residual oil saturation	0.3	fraction
k_{rwor}	Relative permeability to water @ $S_w = 1 - S_{or}$	0.7	fraction
k_{rowr}	Relative permeability to oil @ $S_w = S_{wirr}$	1	fraction
n_w	Corey coefficient for water	3.5	fraction
n_o	Corey coefficient for oil	2.5	fraction
a_o	Coefficient = k_{rowr}/m_o	0.02	1/cP
a_w	Coefficient = k_{rwor}/m_w	0.569106	1/cP
b	Coefficient = $1 - S_{or} - S_{wirr}$	0.45	fraction
On breakthrough			
S_{BLE}	Front water saturation	0.401	fraction
S_{BL}	Front water saturation	0.430	fraction
m	Slope	4.469	fraction
S_{wavg}	Average water saturation behind the front	0.474	fraction
TB	Breakthrough time (pore volume introduced)	0.224	fraction
R	Oil recovery at breakthrough	29.84	%

3. Results and discussion

High-power ultrasonic stimulation technology has been applied to various onshore and offshore production fields. Table 2 provides extensive ultrasonic tests for Field X, which show that oil production increases from 38% to 380% based on average bbl/day production rates.

Table 2. Comparison of production rates before/after the application of high-power ultrasound stimulation technology in test wells

Field	No. of well	Country	Damage	Flowrate before	Flowrate after	Growth
Oil field X	643	Country X	Resins, paraffins, asphaltenes, bacteria, and emulsions	49	235	380%
	632			60	274	357 %
	654			39	116	197 %
	2003			899	1896	111 %
	62			7	13	86 %
	133			71	129	82 %
	1484			83	137	65 %
	1177			26	41	58 %
	912			6	9	50 %
	2474			13	19	46 %
	10-21-25			65	92	42 %
1473	102	141	38 %			

Also, in all tested wells, the following advantages were noted when applying ultrasonic stimulation to the well:

- short downtime – less than 2 hours;
- no risks for the environment;
- cheaper and more efficient than conventional chemical methods.

Water saturation in the flood front is only 40%. This low value of water saturation is explained by the high difference in the viscosities of oil and injected water, and as a consequence, the water tonguing. The recovery factor for this method is 29.84% (Tables 3-4).

An analytical formula for calculating the oil recovery factor in two cases:

1. Exhaustion:

– material balance calculates the oil recovery factor of depletion drive; from initial reservoir pressure to saturation pressure is defined as Equation (1):

$$r_b = B_{oi}/B_{ob} * c_e (P_i - P_b) \tag{1}$$

where Equation (2):

$$c_e = c_o + c_w S_{wi} / (1 - S_{wi}) + c_f / (1 - S_{wi}) \tag{2}$$

and Equation (3)

$$c_o = (B_{ob} - B_{oi}) / B_{oi} / \Delta P \tag{3}$$

– material balance calculates oil recovery factor of depletion drive; from saturation pressure to storage pressure is defined as Equation (4):

$$r_2 = (B_{oa} - B_{ob} + B_{ga} (R_{si} - R_{sa})) / (B_{oa} + B_{ga} (R_p - R_{sa})) \tag{4}$$

2. Water injection. API correlation gives Equation (5):

$$r_1 = 54.9 * [\phi (1 - S_{wi}) / B_{oi}]^{0.0422} + [k \mu_w / \mu_o]^{0.077} + [S_{wi}]^{-0.19} [P_i / P_a]^{0.216} \tag{5}$$

Table 3. Primary oil recovery – direct depletion

B_{oi}	Volumetric coefficient of initial pressure	1.029	rb/stb
B_{ob}	Volumetric coefficient at saturation pressure	1.034	rb/stb
B_{oa}	Volumetric coefficient at conservation pressure	1.027	rb/stb
B_{ga}	Volumetric-gas coefficient of conservation pressure	0.00491	rb/stb
R_{si}	Initial gas/oil ratio	49.4	scft/stb
R_p	Gas/oil ratio	49.4	scft/stb
R_{sa}	Gas/oil ratio at conservation pressure	6.3	scft/stb
P_i	Initial pressure	1310.8	psi
P_b	Saturation pressure	597	psi
P_a	Conservation pressure	300	psi
S_{wi}	Initial water saturation	0.25	fraction
c_w	Water compressibility	3.100E-06	1/psi
c_f	Formation compressibility	3.175E-06	1/psi
c_o	Oil compressibility	6.807E-06	1/psi
c_e	Effective compressibility	1.207E-05	1/psi
r_1	Oil recovery factor before P_b	0.86	%
r_2	Oil recovery factor from P_b to P_a	16.52	%
r	Total % of oil recovery	17.38	%

Table 4. Oil recovery factor for water injection

S_{wi}	Initial water saturation	0.25	fraction
B_{oi}	Volumetric coefficient of initial oil formation	1.029	rb/stb
ϕ	Porosity	0.27	fraction
k	Water permeability	100	md
μ_o	Oil viscosity	50	cP
μ_w	Water viscosity	1.23	cP
P_i	Initial pressure	1310.8	psi
P_a	Conservation pressure	300	psi
r_1	Oil recovery factor (part 1)	51.26	%
r_2	Oil recovery factor (part 2)	1.07	%
r_3	Oil recovery factor (part 3)	0.95	%
r	Total oil recovery factor	53.28	%

Analytical calculation of microscopic oil recovery factor through Buckley-Leverett method. Relative permeability is a function of normalised water saturation in the following way:

– relative permeability of water Equation (6):

$$k_{rw} = k_{rwor} * [S_e]^{no}; \quad (6)$$

– relative permeability of oil Equation (7):

$$k_{ro} = k_{rwor} * [1-S_e]^{nw}; \quad (7)$$

– normalised water saturation Equation (8):

$$S_e = (S_w - S_{wirr}) / (1 - S_{or} - S_{wirr}); \quad (8)$$

where: no and nw – the Corey coefficient for oil and water, respectively.

From these equations before the breakthrough, we can deduce the following Equation (9):

$$df_w/dS_w = (\alpha_w \alpha_o / \beta) * [S_e^{(nw-1)} (1-S_e)^{(no-1)} (n_w + S_e (n_o - n_w))] / [\alpha_w S_e^{nw} + \alpha_o (1-S_e)^{no}]^2. \quad (9)$$

Front saturation SBL is derived by numerically solving the following Equation (10):

$$\alpha_w S_e^{nw} + \alpha_o (1-S_e)^{(no-1)} * [1 - n_w - S_e (1 + n_o - n_w)] = 0, \quad (10)$$

further Equation (11-14):

$$S_{BL} = \beta S_{BLe} + S_{wirr} \quad (11)$$

$$m = \alpha_w / \beta * \alpha S_{BLe}^{(nw-1)} / [\alpha_w S_{BLe}^{nw} + \alpha_o (1-S_{BLe})^{no}] \quad (12)$$

$$S_{wavg} = 1/m + S_{wirr} \quad (13)$$

$$TB = 1/m \quad (14)$$

with: $\alpha_o = k_{rowr}/\mu_o$; $\alpha_w = k_{rwor}/\mu_w$; $\beta = 1 - S_{or} - S_{wirr}$ and BL – Buckley-Leverett water saturation at the front, and SBL, its normalised analogue; Swavg – the average water saturation behind the front; TB – time for pore volume breakthrough.

NB1: if no <= 1, then this definition of dfw / dSw has a feature for Se = 1.0 and is replaced by Equation (15-16):

$$df_w/dS_w |_{Se=1.0 \& no=1} = \alpha_w / \alpha_o / \beta; \tag{15}$$

$$df_w/dS_w |_{Se=1.0 \& no<1} = \text{infinite}. \tag{16}$$

If $nw \leq 1$, then this definition of df_w / dS_w has a singularity for $Se = 0.0$ and is replaced by Equation (17-18):

$$df_w/dS_w |_{Se=0.0 \& nw=1} = \alpha_o / \alpha_w / \beta; \tag{17}$$

$$df_w/dS_w |_{Se=0.0 \& nw<1} = \text{infinite}. \tag{18}$$

For numeric purposes, 1000.0 is assumed to be infinity.

NB2: solving the SBL equation may result in more than one solution or none. Calculate the slope m for each solution and also for $Se = 0.0$ and $Se = 1.0$ Equation (19-20):

$$m |_{Se=0.0} = df_w/dS_w |_{Se=0.0} \tag{19}$$

$$m |_{Se=1.0} = 1/\beta \tag{20}$$

The solution remains the one that leads to the greater bias. Note that if $nw < 1$, $m |_{Se = 0.0}$ is infinite (1000.0) and therefore has a greater slope, and $SBL = 0.0$; no front. After the breakthrough, the average water saturation is defined as Equation (21):

$$S_{wavg} = S_w + (1 - f_w) / (df_w/dS_w), \tag{21}$$

where: S_w , f_w and df_w / dS_w – the values at the output $x / L = 1$. Since df_w / dS_w – is the front speed, the ratio Equation (22):

$$x/L = (df_w/dS_w)^* \tag{22}$$

the injection volume gives the position of any saturation S_w depending on the injected pore volume. If $S_w = SBL$, then the edge position as a function of the injection volume can be obtained (Tables 5-6).

Table 5. Fractional flow

S_w	S_e	k_{rw}	k_{ro}	f_w	df_w/dS_w	tangent				
0.250	0.000	0.000	1.000	0.0000	0.0000	0.00				
0.295	0.100	0.000	0.768	0.0023	0.1957	0.15				
0.340	0.200	0.003	0.572	0.0343	1.5202	0.30				
0.385	0.300	0.010	0.410	0.1703	4.7853	0.46				
0.430	0.400	0.028	0.279	0.4524	7.1108	0.61				
0.475	0.500	0.062	0.177	0.7400	5.1312	0.76				
0.520	0.600	0.117	0.101	0.9039	2.3317	0.91				
0.565	0.700	0.201	0.049	0.9707	0.8427	1.07				
0.610	0.800	0.321	0.018	0.9932	0.2539	1.22				
0.655	0.900	0.484	0.003	0.9992	0.0515	1.37				
0.700	1.000	0.700	0.000	1.0000	0.0000	1.52				
$S_w _{x/L=1}$	$S_e _{x/L=1}$	k_{rw}	k_{ro}	f_w	S_o	df_w/dS_w	S_{wavg}	injection volume	R, %	R_{MAX} , %
0.25	0.000	0.000	1.000	0.0000	0.750	0.0000	0.250	0	0	60.00
0.25	0.000	0.000	1.000	0.0000	0.750	0.0000	0.545	0.30	39.37	60.00
0.501	0.557	0.091	0.130	0.8496	0.499	3.3876	0.545	0.30	39.37	60.00
0.551	0.668	0.171	0.063	0.9562	0.449	1.1877	0.587	0.84	45.00	60.00

0.600	0.779	0.292	0.023	0.9904	0.400	0.3344	0.629	2.99	50.56	60.00
0.650	0.889	0.464	0.004	0.9989	0.350	0.0635	0.667	15.76	55.63	60.00
0.700	1.000	0.700	0.000	1.0000	0.300	0.0000	0.700	Infinite	60.00	60.00

Table 6. Injected pore volume

Sw	0.07	0.15	0.22	0.30	0.84	2.99	15.76
x/L	x/L	x/L	x/L	x/L	x/L	x/L	x/L
0.250	1.000	1.000	1.000	1.000	2.852	10.131	53.385
0.250	0.250	0.500	0.750	1.000	2.852	10.131	53.385
0.501	0.250	0.500	0.750	1.000	2.852	10.131	53.385
0.551	0.088	0.175	0.263	0.351	1.000	3.552	18.717
0.600	0.025	0.049	0.074	0.099	0.282	1.000	5.269
0.650	0.005	0.009	0.014	0.019	0.053	0.190	1.000
0.700	0.000	0.000	0.000	0.000	0.000	0.000	0.000

The calculation was performed in Excel. According to the results, after the application of ultrasound in the bottomhole zone, it was possible to achieve a decrease in the viscosity of the produced oil to 10 cP. This change led to an increase in water saturation in the flood front to 55.7%, and an increase in the field development efficiency. At the same time, the oil recovery factor increased to 39.37% (Table 7; Figures 2-5).

Table 7. Calculation results

On the breakthrough			
$S_{BL,e}$	Front water saturation	0.557	fraction
S_{BL}	Front water saturation	0.501	fraction
m	Slope	3.387	fraction
$S_{w,avg}$	Average water saturation behind the front	0.545	fraction
TB	Breakthrough time (pore volume introduced)	0.295	fraction
R	Oil recovery factor at breakthrough	39.37	%

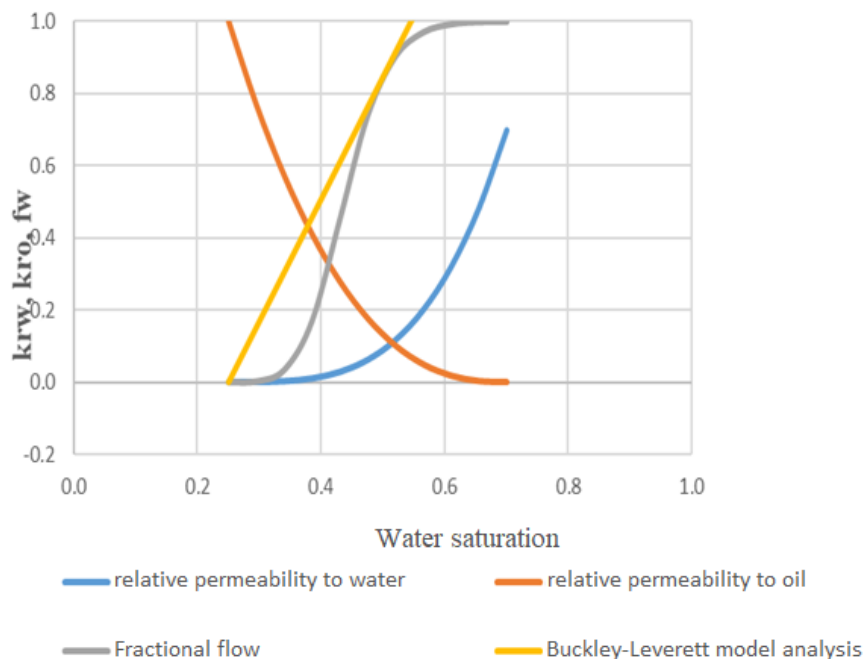


Figure 2. Fractional flow curve

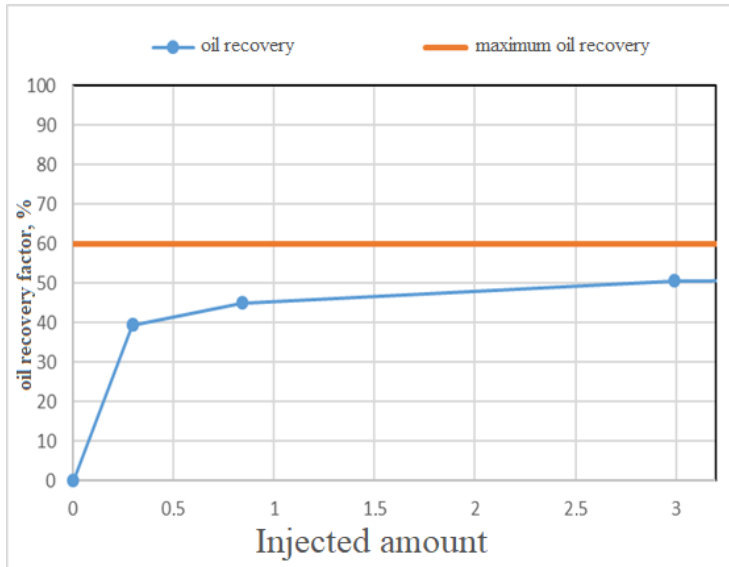


Figure 3. Oil recovery factor by injected amount

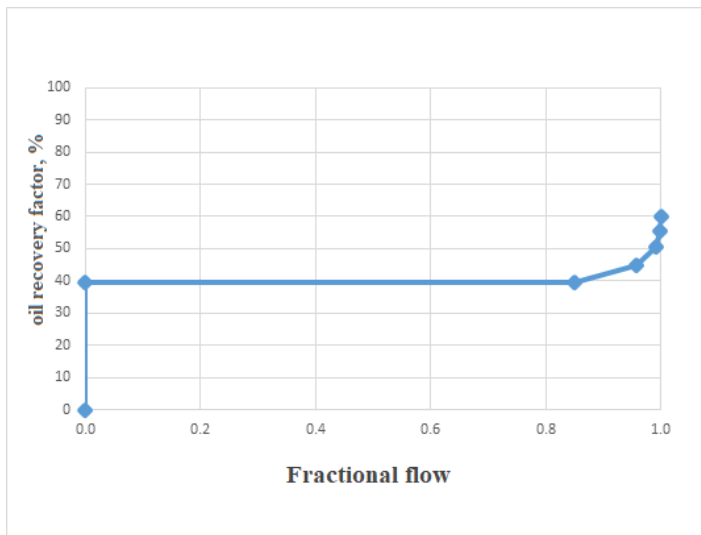


Figure 4. Oil recovery factor by fractional flow, Buckley-Leverett model

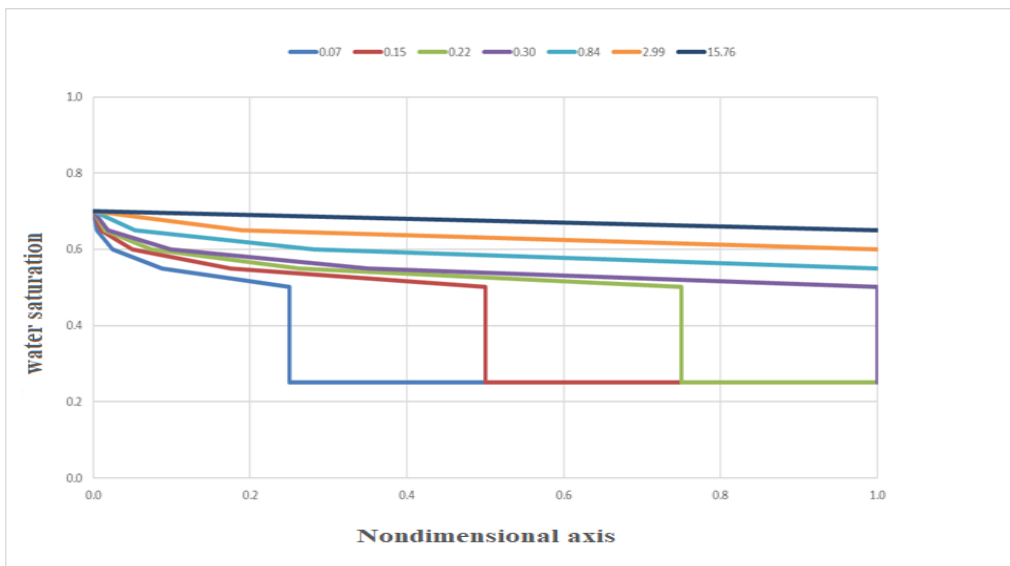


Figure 5. Saturation profile by different injection volumes

4. Conclusions

The studies conducted by many scientists focused on the investigation of the acoustic methods of influence on the viscosity and temperature characteristics of oil, show that these methods lead to an increase in oil recovery. The electrophysical stimulation is the most effective and environmentally friendly method for well stimulation, which has been proven by an increase in oil production from 30% to 380% on land and at sea.

Electrophysical stimulation is a highly effective way of cleaning the bottomhole zone of a well from typical contaminants such as tar, mud cake, and salt deposits, thereby significantly increasing the flow of oil into the borehole. The technology of electrophysical stimulation does not provide for the use of any chemicals and the like, it also allows the well to be in the production mode during the purification. At the same time, this technology is not distinguished by environmental harm, high cost and technical difficulties.

The use of this technology in the framework of field trials on the territory of the Republic of Kazakhstan has shown a positive effect on increasing the efficiency of the water drive operation, as well as increasing the oil recovery factor.

Taking into account the results of this study, such as reducing the viscosity of the produced oil to 10 cP, increasing the water saturation in the flood front to 55.7%, as well as increasing the oil recovery factor to 39.37%. It is recommended to apply the technology of electrophysical stimulation of the bottomhole zone in wells with high viscosity, as well as with a large difference in the viscosities of the produced and injected fluids during the water drive.

It is recommended for use in many oil fields in Western Kazakhstan. Since the creation of new combined effective technologies for increasing the oil recovery, for example, as electrophysical stimulation will provide an increase in oil production, at the same time, it will provide a sufficient effect reducing the viscosity and minimize the environmental burden.

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