CONTROLS OF CO_2 FILTRATION IN HETEROGENEOUS RESERVOIRS WITH FOAM-EMULSION SYSTEMS

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Abstract: Pumping CO_2 into oil reservoirs is one of the most promising methods to increase oil recovery. A significant drawback of the method is channelled flow of CO_2 through the most permeable intervals in heterogeneous reservoirs. To control flow we used foam-emulsion systems generated both before pumping into the reservoir model and directly in the reservoir. This allows us to double the driving medium from high- to low-permeability reservoirs and presents a likely mechanism of flow redirection. Studying the regulating effect of foam-emulsion systems using a transparent micro-model of the reservoir and the Hele-Shaw cell revealed a previously unknown effect of dynamic blocking of porous mediums and fractured structures during transformation of emulsions filtering through it.

Key words: channelled flow during CO_2 flooding; heterogeneous reservoir; porous structure; foam-emulsion system; driving medium; redirection of flow; interchanged injection; dynamic blocking

1. INTRODUCTION

Pumping carbon dioxide into oil reservoirs is one of the most promising and quickly developing methods to increase oil recovery. A large-scale introduction of the method in the USA showed its effectiveness for oilfields during different stages of development and in reservoirs having a wide range of geology, structure and oil properties.

Data published in the international press and results of trial CO_2 injection into Russian oilfields shows that the main technological factor that limits the

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development of the method is the quick inrush or channelling of CO_2 into producing wells along strata or structures with high permeability. The main instrument to control the process of oil extraction is sequential injection of CO_2 and water slugs. Recently, surfactant-water solutions have been used to push CO_2 to increase the effectiveness of the technology.

2. RESULTS AND DISCUSSION

Trial pumping of CO_2 in the Radayevskoye and Sergeyevskoye oilfields has shown the technical effectiveness of this method. Injection of CO_2 has also been conducted in the Kozlovskoye (PO Kuybyshevneft) and Yelabuzhskoye (PO Tatneft) oilfields, while preliminary studies are being performed on the Olkhovskoye oilfield (PO Permneft). Technical indices are listed in table 1.

Table 1. Technical indices of carbon dioxide injection.

Parameters	Oilfield				
	Radayevskoye	**Kozlovs - koye**	**Sergeevskoye**	**Yelabuzhskoye**	**Olkhovskoye**
Predicted oil output increase, %	12.80	10.40	10.40	8.00	12.40
Additional output, million tons	6.90	3.21	0.89	0.40	3.10
Yearly injection of CO_2, thous. tons	430.0	400.0	165.0	140.0	400.0
Actual injection by 01/07/89, thous. tons	787.2	110.1	73.8	58.3	-
Injection started	August 1984	May 1986	September 1986	July 1987	-

The largest quantity of CO_2 was injected into the reservoir within the Radayevskoye oilfield. Results of a four year trial indicate the effectiveness of the method, with the injection of 787.2 thousand tons of CO_2 during this period. Despite the fact that this was 2.6 times less than the planned amount for this time period an additional 218 thousand tons of oil were produced due to CO_2 injection by 01/07/89, which amounts to 0.28 tons per 1 ton of injected reactant. As a result the obtained recovery rate was higher than the predicted rate (0.21 ton/ton).

In this paper results are presented on water-saturated model experiments of non-communicated heterogeneous reservoirs having water permeability ratios equal to 15.7. Experiments were conducted at a pressure of 10.5 MPa, temperatures equal to 26.5 and 40°C, and an average fluid flow velocity of 201 m/year.

The experimental setup (Figure 1) used to study the distribution of CO_2 in heterogeneous reservoirs consists of standard equipment and devices used to investigate processes of fluid and gas filtration under reservoir conditions. Detailed descriptions of the equipment, as well as the preparation of the porous mediums can be found in OST (1986).

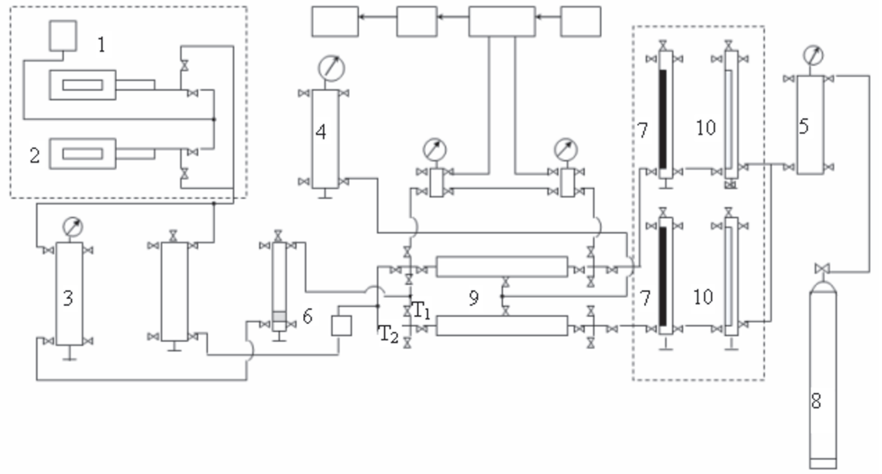

Figure 1. The experimental setup used to investigate the distribution of CO_2 in heterogeneous reservoirs: 1, 2 –constant flow rate sensors; 3,4,5 – columns for distilled water, reservoir water and compressed air or nitrogen, respectively; 6 – filters; 7, 10 – measuring tanks to determine the yield rate of the reservoir and volume of the delivered CO_2 visually; 8 – balloon with air or nitrogen; 9 – core-holder.

The plant, excluding the constant flow rate sensors (SCF), is thermostatted. Each experiment consisted of three stages. The first stage was to deliver water (using SCF-1 through assembly T_1) with a constant flow rate (measured using measuring tank 7) up to the establishment of a constant yield rate. The second stage was to study the influence of one of the investigated parameters. Water was delivered into reservoir models as done during the first stage, while CO_2 was delivered using SCF-2 from tank 10 through assembly T_2. The third stage was to wash the porous medium separately using water to remove the CO_2.

Table 2. Characteristics of reservoir models.

Model number	Length, cm		Permeability, mcm^2		Permeability ratios, K_0
	HPR	LPR	K_B	K_H	
1	58	54.8	0.144	0.018	7.8
2	52	54.8	0.158	0.026	6.0
3	54.8	54.8	0.133	0.039	3.41
4	101.8	54.8	5.001	0.039	128.2

All the presented dependencies were produced via no fewer than 5 experiments. A total of 4 porous medium models were used in the experiments (Table 2). A conditional value was introduced and used to simplify the calculation and plotting of the graphs; this consists of the CO_2 (R_{CO2}) and water (R_B) distribution parameters, which are equal to the ratio of yield rates for high- (Q_B) and low-permeability (Q_H) reservoirs.

The obtained results (Figure 2) show that using the non-ionic surfactants sufficiently increases the reservoir coverage of both carbon dioxide and water, via alternating injection of the two reactants. The supply of liquid CO_2 into the low-permeability reservoir increased from 16.67% and 17.01% (after injection of mineralised (140 g/l) and distilled water, respectively) to 36-38% when using the solution of Neonol AF_9-12 in concentrations of 0.25-2.00%. The injection of gaseous carbon dioxide (10.0 MPa, 40°C) also increases into low-permeability reservoirs from 15.4% (water) to 36.5-37.7% (0.25-1.00% solution of AF_9-12). Coverage of the reservoir in the case of alternating injection of CO_2 slugs and surfactant water solutions increases due to the formation of water-carbon dioxide emulsions and foams at the water/CO_2 interfaces within the porous medium. Because of the different mobilities of carbon dioxide and water, the volume of emulsion formed in pores will be maximal in intervals with higher permeabilities. Accumulation of specific volumes of emulsion (foam) in these intervals will cause partial (temporary) blocking of the pores, which allows for the redistribution of flow from high- to low-permeability intervals.

The influence of gas mixture composition on its reservoir distribution was studied in two models (1 and 2). The characteristics of the porous mediums (represented by natural sandstones) are listed in Table 3. Experiments were conducted at 26.5°C and 10.5 MPa.

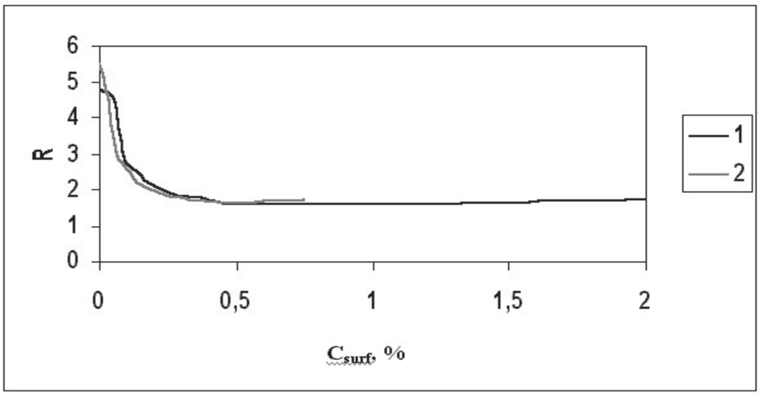

Figure 2. Dependence of CO_2 and water distribution parameters on the concentration of Neonol AF9-12, where R is a dimensionless distribution parameter, while QB and QH are the quantity of fluid (gas) entering the low- and high-permeability porous mediums, respectively.

Table 3. Characteristics of reservoir models.

№ of the well	Porous medium*		Ratio K_B/ K_H
	Length, cm	Permeability, mcm^2	
1	57.9/57.1**	0.55/0.035	15.7
2	57.6/57.7	0.48/0.096	5.0

* Diameter of porous mediums – 50 mm;

** The numerator – high permeability (K_B), the denominator – low permeability porous medium (K_H).

The results of complex filtration testing to optimise the technical parameters during alternating carbon dioxide – water injection were used as the basis for the current work. These include a total gas-mixture volume of 12% ΣV_n, a gas-mixture / water volume ratio of 3 and the number of gas mixture divisions equal to 20.

As a result of eight experiments (Figure 3) (four for both reservoir models) it can be stated that the distribution parameter increases linearly with the increase of petroleum gas content, i.e. the intake of gas mixture into the low-permeable reservoir decreases linearly. Obtained data are in good agreement with data described in previous works which studied the viscous and rheological properties of water-gas systems and experiments to determine the stability of foam-emulsion systems.

The next group of experiments involved regulating gas mixture filtration using the foam-emulsion mixtures. Parameters of the alternating injection in these experiments were kept constant. The CO_2 content in the gas mixture was 50%, while a mixture of Neonol AF_9-12 and KOBS was used for the surfactant (the mass ratio of each component in water was 0.125%).

It was found that the alternating injection of the gas mixture and water solution of the indicated composition into model №2 caused the distribution parameter R to decrease from 3.30 to 2.91, which corresponds to an increase of reactant ingress into the low-permeable reservoir from 23.26 to 25.58% (Figure 3). If one compares the obtained redistribution of gas mixture filtration in the heterogeneous reservoirs with the distribution of the clear carbon dioxide in model №1, it can be seen that regulation of the gas mixture filtration has limited effectiveness. For clear CO_2 the distribution parameter R decreased from 5.50 to 2.06 with the injection of the AF_9-12 / KOBS solution in water instead of simple water slugs.

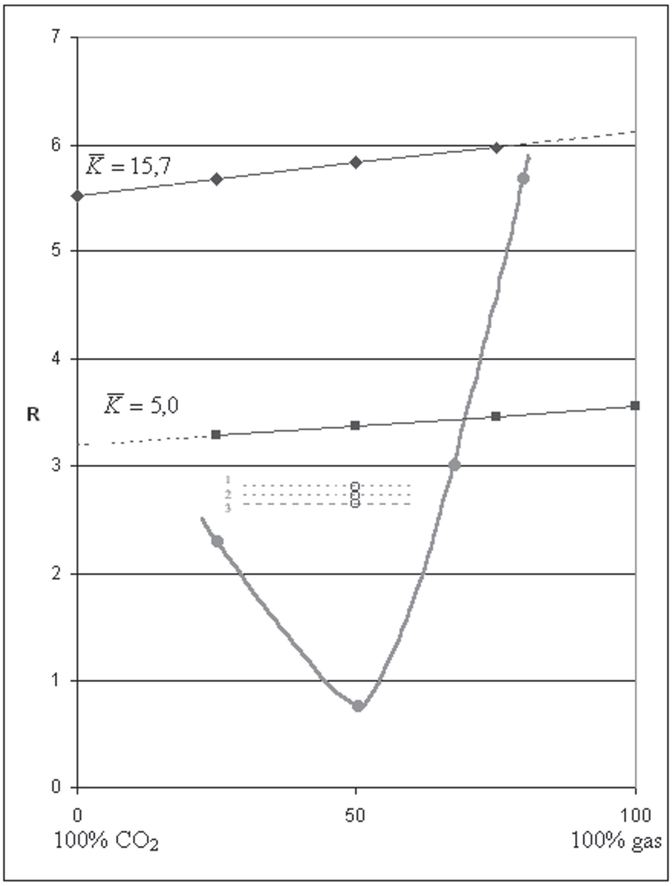

Figure 3. Distribution of CO_2 and gas mixtures during alternating water and surfactant water solutions injection and combined injection, respectively.

The increase of AF_9-12 concentration to 0.25% did not lead to a sufficient improvement of the gas mixture filtration alternating with the surfactant solution. The distribution parameter in this case was 2.88, which corresponds to 25.77% ingress of reactant into the low-permeable reservoir.

The increased division of the gas mixture into 40 portions also did not bring about sufficient increases in the coverage of the reservoir model. The distribution parameter in this case decreased to only a value of 2.82 (Q_H=26.18%).

Thus earlier results that allowed the increase of reservoir coverage by CO_2 with the alternating injection of surfactant water solution slugs was not repeated for the mixture of CO_2 and petroleum gas. As gases have a low solubility in water foam-emulsion systems form on the interface of the slugs of the filtering phases. Evidently in this case the decrease of the foam-emulsion system stability, consisting of gas mixture and water compared to the dispersion of CO_2 and water, has a decisive impact on the regulation of the filtration process.

The following experiments on the technology of water-gas mixture combined-injection were conducted to increase the contact surface of gas mixture and surfactant water solution. The content of CO_2 in the gas mixture was in all cases 50%, the gas mixture slug volume was 12% ΣV_{pore} while the detergent was a 0.25% Neonol AF_9-12 water solution. The investigated parameter in these experiments was the ratio of water solution to gas mixture volumes.

The increase of the gas mixture ratio from 25 to 50% at the combined injection with 0.25% surfactant solution decreased the distribution parameter from 2.26 to 0.89 and increased the intake of the reactant into the low-permeable reservoir from 30.67% to 52.91%, respectively. This result clearly supports the previous assumption regarding the primary influence of foam-emulsion system stability on the surfactant solution regulating properties. In this case the combined injection of the gas mixture and the surfactant water solution results in direct foam filtration, and the pore cells work as the centers of foam formation.

An additional increase in the foam's aeration extent (ratios of water and gas mixture volumes 1:2.3; 1:3) causes the sudden decrease of reactant intake into the low-permeable reservoir – 25.32 and 8.05% respectively. The dependence of the distribution parameter on the water and gas mixture volumes ratio has a strongly pronounced maximum. Its presence can be explained by the increase of the foam-emulsion system's stability which causes the decrease of R from 2.26 to 0.89 with the increase of the gas mixture ratio during injected dispersion. Appearance of a free gas phase during the continued increase of the gas ratio in the injected mixture to 75% causes the temporary blocking of small pores and the growth of the distribution parameter. The distribution parameter minimum, R=0.89, was obtained with the combined injection of the gas mixture slug and the 0.25% Neonol AF_9-12 solution into reservoir model №2.

The technical parameters have been optimised based on the results of the conducted filtration experiments, and the main principles needed to increase coverage of reservoirs with heterogeneous permeability using foam-emulsion systems have been shown.

The next experiments were devoted to studying the mechanism of emulsion filtration in fractured and porous structures (reservoir micromodel experiments were conducted under the direction of Dr. A.T. Akhmetov).

The reactant Neftenol NZ 40M (designed by the company “Chimeko-GANG”) was used to stabilize the inverted water-oil emulsions. The experiments conducted on physical models of the reservoir elements (i.e. fractured and porous structures) were conducted in order to understand what happens with the emulsion during flow through the reservoir.

A Hele-Shaw cell was used to study processes occurring in a fracture. It consisted of two parallel optical glass plates with a clearance of 17 or 35 microns and a size of 4 x 2 cm, restricted by a foil. The processes taking place in the porous structure were studied using a micro-model.

The porous structure micro-model is a two-dimensional transparent porous system, representing the pore structure in the plane of the polished section of the oil-bearing core sample. The micro-model working section is the same as in the Hele-Shaw cell (i.e. 4 x 2 cm) and has channel depths equal to 15 microns.

To measure the liquid flow rate an HM200 scale was used (interval 0.1 mg) and the data were automatically transferred to a computer. The fluid flowing out of the model displaced distilled water from a tube and was deposited into a receptacle on the scale, thereby allowing the volume flow through the model to be calculated. To avoid capillary effects the end of the outlet tube was put into liquid, while evaporization errors were minimized by covering the water with a thin layer of light oil.

Injection of the highly-concentrated oil emulsion, stabilized by Neftenol, into the Hele-Shaw cell at pressure drops of 150–200 kPa caused exuding of some aqueous phase volume from the emulsion. Decreasing the pressure drop to 50–100 kPa resulted in a stable emulsion. In all cases, however, cell blockage occurred over time, though the pressure drop remained constant.

The emulsion volume which flowed through the model over time was calculated via the computer according to the scale data. The flow structure changed over time, and it was most precisely exhibited at the greater gap of the cell, equal to 35 microns. The curve describing the blocking of the cell is shown in Figure 4, as are various video images of the flow structure at different emulsion discharge rates. The flow structure changes are shown at a greater scale in Figure 5. Complete blockage, discovered using the scale data and verified with careful microscopic study, has shown the presence of small fluid flow at the inlet and outlet (Figure 6.).

The flow rate value is four orders of magnitude lower than the initial flow rate and does not increase with time, although the emulsion structure in the cell and in the micro-model change considerably after a long period of time (a day and more) and resemble the composite emulsion, formed during flow of the non-stabilized emulsion. As emulsion micro-flow is always present, the observed "blocking" effect has been termed "*the dynamic blocking effect"*.

The same dynamic blocking effect was found in the study of stabilized emulsion flow in the porous structure micro-model. In this case the consumption of the emulsion is much less, but the relationship between emulsion volume flow and time have the same nature and blocking as in the case of the Hele-Shaw cell, which happens within about one hour. Under dynamic blocking the emulsion has the property of "the fluid nipple", i.e. at the pressure build-up in the reverse direction the motion of the emulsion is restored (curve 4 in Figure 7). In the case of both the micro-model and the Hele-Shaw cell there is micro-flow at the inlet and outlet of the model.

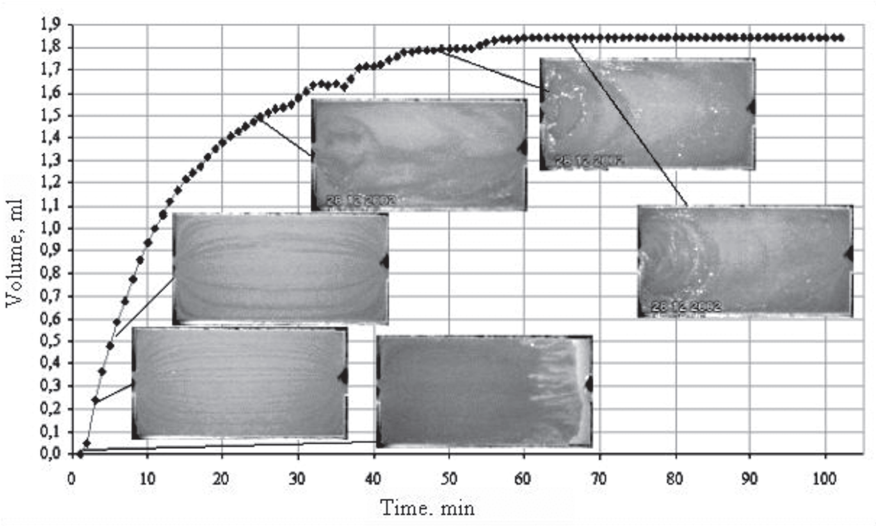

Figure 4. Stabilized emulsion volume passed through the fracture model versus time at a constant pressure drop. The video images of flow structure are shown at different moments of time.

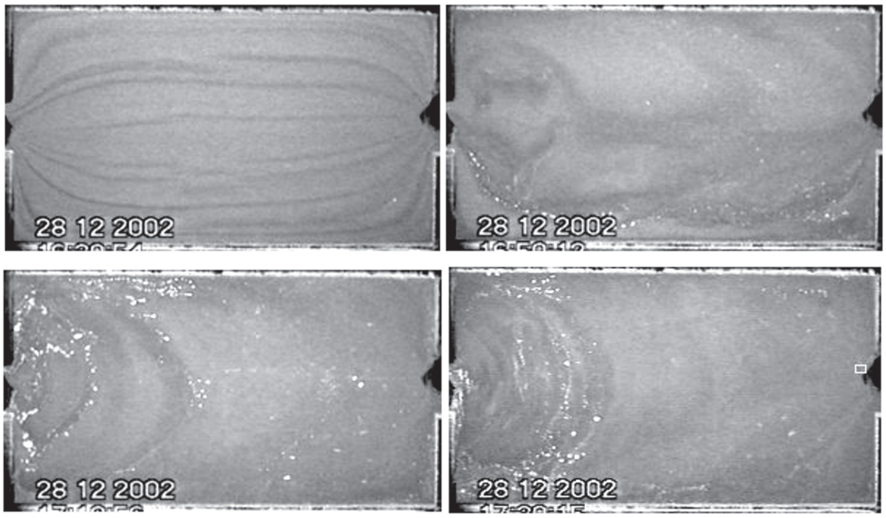

Figure 5. The modification of the flow structure due to the dynamic blocking of the Hele-Show cell (pressure drop is 100 kPa, on the right lower video image the rectangle at the outlet corresponds to the field observed under a microscope).

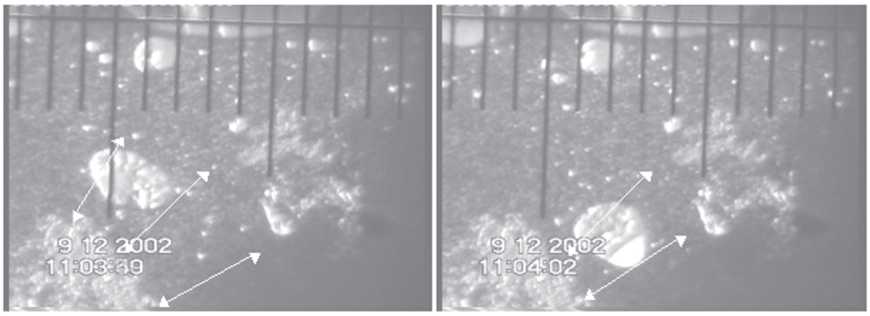

Figure 6. Micro video image of the single site, at the outlet, on which the motion is observed, the flow parameters are indicated by arrows. Screen width 700 microns, flow 200 microns, movement 80 microns per 12 seconds.

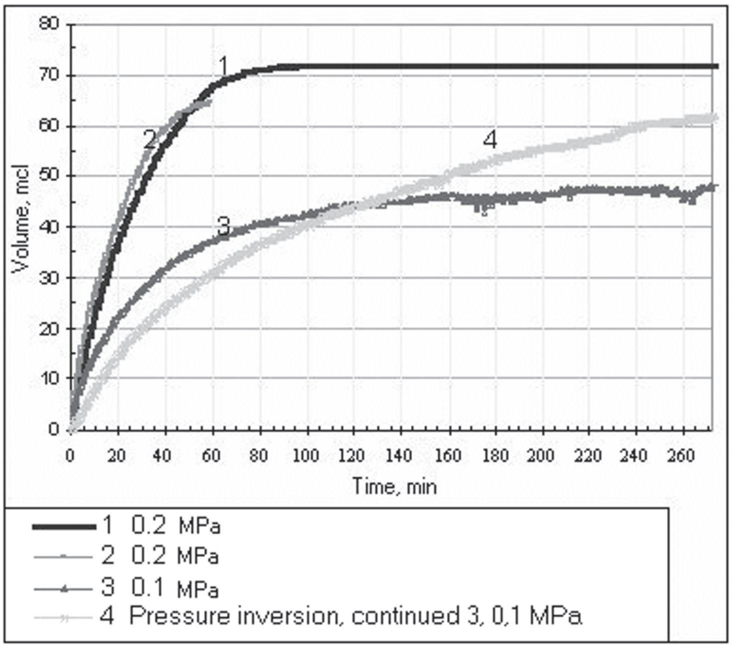

Figure 7. The volume of the stabilized emulsion, passed through the micro model at a constant pressure drop.

3. CONCLUSIONS

In conclusion it can be stated that one of the most interesting experimental result is the observed dynamic blocking effect, which practically ceases flow despite the considerable (up to 5 MPa/m) constant average pressure gradient. It is hoped that this effect can be successfully exploited in different versions of the technologies of the levelling of the well injection capacity profile and waterproofs in porous, fractured porous and fractured reservoir types.

REFERENCES

OST, 1986, Oil. The method to determine the index of oil displacement by water in laboratory conditions, *OST Report 39-195-86*.