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ЕКСПЕРИМЕНТАЛЬНЕ ВИВЧЕННЯ ПРОЦЕСУ ЗВОРОТНОГО ПРОСОЧЕННЯ ПРИ ПАДІННІ ТИСКУ В ПОКЛАДІ

Анотація. *В міру відбору газу в ході розробки покладів падає пластовий тиск і починається підйом води, тобто відбувається просочення колектора підошовною водою. Якщо процес витіснення води з колектору вивчений досить добре, то процес поглинання води або вуглеводневого флюїду колектором вивчений досить слабо. Слабо розроблена і методична база для таких досліджень. Значною мірою це обумовлено великою тривалістю необхідних експериментів, що становила в нашому випадку до 6 місяців. У даній роботі розроблялася методика донасичення зразка вуглеводневим флюїдом при зниженні пластового тиску з метою моделювання процесів, які відбуваються в покладі, що розроблюють. В результаті роботи, на основі методу напівпроникної мембрани, що застосовується в режимі "дренування-просочення", на зразках порід-колекторів продуктивного горизонту Г-7-10 Більського родовища доведено фактичне існування зворотного просочення зразка вуглеводнями з падінням тиску витіснення, вирішені методичні питання, пов'язані з особливостями просочення саме вуглеводневим флюїдом, виявлені основні особливості процесу і встановлені його основні закономірності. З метою зменшення тривалості часу дослідження рекомендована заміна на етапі дренування, методу напівпроникної мембрани на метод центрифугування. Наведено вихідні теоретичні уявлення, коротко описана методика досліджень та використаний керновий матеріал, наведено графіки, що ілюструють протікання процесів дренування і просочення в часі, зв'язок поточної водонасиченості зразка з тиском витіснення і поровою характеристикою зразка, коротко сформульовані висновки. Результати проведеної роботи знайдуть застосування при вивченні процесів витіснення газу нафтою з нафтових облямівок, витіснення нафти чи газу водою, витіснення нафтогазової суміші при сайклінг-процесі та ін.*

Ключові слова: *обводнення свердловин; підйом газоводоконтакту; зона газоводоконтакту; перехідна зона покладу; лабораторна петрофізика; дослідження керна; порода-колектор; напівпроникна мембрана; капіляриметр; зворотне просочення; донасичення.*

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ЭКСПЕРИМЕНТАЛЬНОЕ ИЗУЧЕНИЕ ПРОЦЕССА ОБРАТНОЙ ПРОПИТКИ ПРИ ПАДЕНИИ ДАВЛЕНИЯ В ЗАЛЕЖИ

Аннотация. *В ходе разработки залежи, по мере отбора газа, падает пластовое давление и начинается подъём воды, то есть происходит обратная пропитка коллектора подошвенной водой. Если процесс вытеснения воды из коллектора изучен довольно хорошо, то процесс поглощения воды или углеводородного флюида коллектором изучен сравнительно слабо. Слабо проработана и методическая база для таких исследований. В значительной степени это обусловлено большой длительностью необходимых экспериментов, составлявшей в нашем случае до 6 месяцев. В данной работе разрабатывалась методика обратной пропитки образца углеводородным флюидом при понижении давления вытеснения с целью моделирования процессов, происходящих в разрабатываемой залежи. В результате работы, на основе метода полупроницаемой мембраны, применяемого в режиме «дренирование-пропитка», на образцах пород-коллекторов продуктивного горизонта Г-7-10 Бельского месторождения доказано фактическое существование обратной пропитки образца углеводородами с падением давления вытеснения, решены методические вопросы, связанные с особенностями пропитки именно углеводородным флюидом, выявлены основные особенности процесса и качественно установлены его основные закономерности. С целью уменьшения продолжительности времени исследования рекомендована замена на этапе дренирования метода полупроницаемой мембраны на метод центрифугирования. Приведены исходные теоретические представления, кратко описана методика исследований и использованный керновый материал, приведены графики, иллюстрирующие протекание процессов дренирования и пропитки во времени, связь текущей водонасыщенности образца с давлением вытеснения и поровой характеристикой образца, кратко сформулированы выводы. Результаты проведенной работы найдут применение при изучении процессов вытеснения газа нефтью из нефтяных оторочек, вытеснения нефти или газа водой, вытеснения нефтегазовой смеси при сайклинг-процессе и др.*

Ключевые слова: *обводнение скважин; подъём газоводоконтакта; зона газоводоконтакта; переходная зона залежи; исследования керна; лабораторная петрофизика; порода-коллектор; полупроницаемая мембрана; капилляриметр; обратная пропитка; донасыщение.*

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EXPERIMENTAL STUDY OF THE REVERSE IMPREGNATION PROCESS WHEN THE PRESSURE DROPS IN THE DEPOSIT

Annotation. *During the development of the deposit, as the gas is extracted, the reservoir pressure drops and water rise begins, that is, the reservoir is impregnated in reverse with bottom water .If the process of water displacing from the reservoir is well understood, then the process of water or hydrocarbon fluid absorbing by the reservoir is relatively poorly studied. The methodological basis for such studiesis also e laborated poorly. This is largely caused by the long duration of the necessary experiments, which in our case amounted to 6 months. In this work, a methodology of sample reverse impregnation with a hydrocarbon fluid was developed at a displacement pressured drop in order to simulate the processes occurring in the developed deposit. As a result of the work, on the basis of the semi-permeable membrane method used in the "drainage-impregnation" mode, the actual existence of the reverse impregnation of a sample by hydrocarbons at a displacement pressured drop is proved on rock collectors samples of the Belsky field productive horizon G-7-10, methodological issues related to the specifics of impregnation with specifically hydrocarbon fluid have been solved, main features of the process have been recognized and its main regularities have been determinate qualitatively. In order to reduce the duration of the study, it is recommended to substitute the semi-permeable membrane method with the centrifugation method at the stage of drainage. The parent theoretical ideas are given, the method of research and the used core material are described briefly, graphs illustrating the conduct of drainage and impregnation processes over time are given, the correlation of the current sample water saturation with the displacement pressure and pore characteristic of the sample, the inferences are enunciated briefly. The results of the carried out work will be used in the study of the processes of gas displacement by oil from oil rims, oil or gas displacement by water, oil and gas mixture displacement during the cycling process, etc.*

Descriptors: *drowning; gas-water contact rise; gas-water contact zone; reservoir transition zone; laboratoria petrophysics; core examination; reservoir rock; semi-permeable membrane; capillarimeter; reverse impregnation; resaturation.*

Introduction. During the development of deposits, as a measure of gas extraction, the formation pressure drops and the water rise begins, that is, the reservoir reverse impregnation with bottom water occurs. If the process of displacing water from the reservoir is studied fairly well, then the process of re-absorption of water or hydrocarbon fluid by the reservoir is studied poorly. In the complex of laboratory works on the physics of oil and gas reservoirs, capillary displacement of the reservoir water model by air is usually carried out in order to model the conditions for the formation of gas and oil deposits. Concurrently, a capillary pressure curve (CPC) is plotted and important for counting reserves and designing the development of deposits parameters are determined. These are the residual water saturation, the structure of the pore space, the distribution of water saturation in the transition zone near the gas-water contact (GWC) or gas-oil contact (GOC). This information is important primarily at the search and exploration stages, although it is also used at the development stage. However, the conditions and results of these works show the state of the deposit at the maximum at the beginning of development. During development, the formation pressure drops gradually and instead of displacing the formation water from the reservoir, it is absorbed. Approximately the same happens on GOC. The previously published work [1] was devoted to the development of a semi-permeable membrane method for use in the "drainage - impregnation" mode of the water-gas system, that is, regarding the conditions of the gas field. The procedure of investigation with hydrocarbon (HC) resaturation has its own specificity, and this work is devoted to its development.

The purpose of the work is to develop a method of a semi-permeable membrane in the "drainage-impregnation" mode for the gas-water-HC system using it in modeling the processes that take place in the HC deposits at the development stage, in conditions of decreasing formation pressure. Conducting test studies of reverse impregnation with liquid HCs, finding of the general nature of the process.

Theoretical ideas. What does the process look if you proceed from the model of ideal pores (Fig. 1), on the basis of which practical porometry works? During preparation, the sample was primarily saturated with water. In the process of achieving residual water saturation, under the influence of a growing displacement pressure, water is removed first from large and then from massively smaller pores. Samples used for the experiment have hydrophilic or mainly hydrophilic properties: index "M" [2] with a coefficient of 0.77 - 0.96. A thin water film remains along the walls of the capillaries when the water recedes. According to modern views, this film is not continuous, interrupted, sections of hydrophilic surface are covered with it, and sections of hydrophobic surface are free from water [3]. This does not conflict with the values of the indicator "M". As the displacement pressure decreases, the moment comes when this pressure becomes less than the lifting force that influences the water in the capillary, and the water begins to rise in reverse order - first in thinner, then in larger capillaries. A water film that remains on the walls of the pores is promotive of it.

As previously carried out experiments [1] showed, water rise is slower than its displacement, and water saturation under experimental conditions does not reach initial values by 5-8% with a total duration of experiment up to 4 months. The reason for this is structural complications in the form of variable intersection pores and the presence of sorbed and clamped air in large pores cleaned of water. Whether air can penetrate through a film of water is a debatable issue. However, there are water-free hydrophobic centers at which air is sorbed.

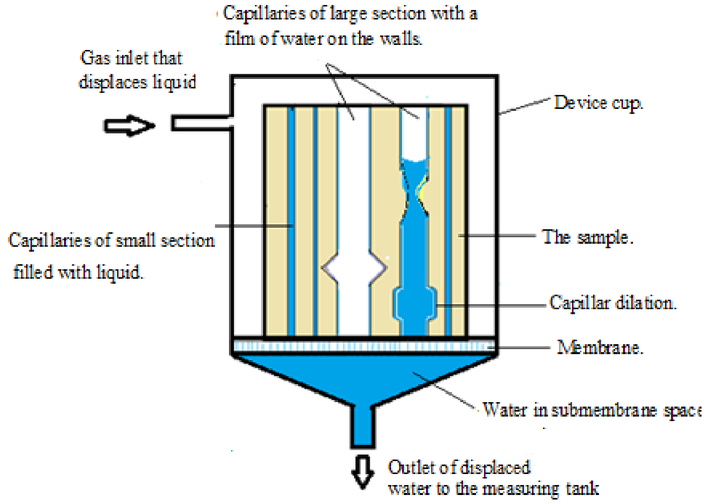

Fig. 1 - Draining stage experiment diagram

In the case of a reverse impregnation experiment with a hydrocarbon fluid modelled on kerosene, after the residual water saturation has been achieved and the drainage has been completed, the cylinder is placed into a prepared cup filled with kerosene and the displacement pressure is set to match the displacement pressure of kerosene from the smallest pores previously purified from water. During the experience, we gradually reduce this pressure. In large pores released from water, the surface is covered with a thin water film. For resaturation of the sample with kerosene, this film serves as an obstacle, since capillary lifting requires contact of kerosene with a solid surface. Two options are possible: displacement of water by kerosene from hydrophilic surfaces and the use of kerosene for capillary lifting of hydrophobic areas. Long experience in determining wettability according to the method of M. Yu. Nesterenko [4, 5] shows that in the typical case, our rocks are equally well wetted with water and kerosene, but with water a little better. In this case, most likely, spontaneous displacement of water by kerosene is difficult. Indeed, in the course of experiments, the water displacement with kerosene was not noticed and, therefore, the process is not carried out as displacement, but as resaturation. Kerosene performs capillary lifting using hydrophobic areas not wetted with water. Following the theory of bunch-like adsorption [3], the molecules of the outer layers of the clusters, distant from the surface of the pores, merge, forming an "arched ceiling" over the hydrophilic areas, and a central pore space free of water is filled with kerosene completely. In this case, the filling of the pore space free of residual water also does not happen completely, taking into account the actions of the same factors: variable-section pores and clamped and sorbed air.

Method of operation. The test is carried out on a capillarimeter, the membranes of which are designed for a maximum pressure of 1.5 kgf/cm^2. In general, the experiment consists of four stages: 1) preparatory, during which the samples are saturated with a model of produced water (NaCI solution); 2) displacement of water by gas (which is air) until residual water saturation is obtained; 3) reverse impregnation of the sample with oil (the role of which is kerosene), which occurs until the maximum possible saturation is obtained, against the background of a gradual decrease in displacement pressure; 4) exposure on the saturated kerosene membrane outside the cup of the device. The latter is done just to release the device, the exposure conditions are the same [1]. The preparation and saturation of the samples with the produced water model were carried out according to [6.7], the displacement of water by air, and the construction of the CPC - according to conventional methods of working on a capillarimeter, which, unfortunately, were never standardized. At this (1.5 kgf/cm^2) pressure, water is displaced from the pores with a radius of 1 µm and more, that is, almost all capillary water is removed. Water that remains in the sample is characterized as physically strong- and friable-linked [8]. Reverse impregnation was carried out according to the original methodology developed during these researches. The maximum pressure that can be applied to kerosene at the beginning of the experiment was calculated using the Laplace formula with the substitution of the kerosene surface tension value. If for water it is 1103.4 mm Hg, then for kerosene it is 363.7 mmHg. If the same pressure is applied to membranes designed for a breakthrough pressure of 1.5 kgf/cm^2 (for water), but saturated with kerosene, the membrane will be broken because the surface tension of kerosene is three times less. After exposure at the maximum pressure, which in time is twice as much against as the interval exposure during drainage [1], the pressure was decreased gradually, in stages, to atmospheric, with the determination of the sample mass at each stage. At zero pressure, the sample exposed in the cup of the device for several more hourly intervals, after which it was moved to the membrane in hermetic dishes outside the cup and exposed for several more hourly intervals, with weighing at the end of each.

Used core material. In our work, we used samples from the wells No. 171 and No. 403 of the Bilske field, taken from the horizon Г-7-10 gas-productive deposits of the araucarite formation of the Upper Carbonic at intervals of 2317-2324 and 2286-2294 m. Prepared samples [6] were preliminary used to carry out an expanded set of researches [9], which includes determination of carbonate content, density, porosity, permeability [7,10,11], residual water saturation [12] and porometry (capillarimeter). After that, the samples were saturated with a model of produced water, and the actual experience was carried out on them, which includes the displacement of water with air and further reverse impregnation with kerosene. Please note that the experiments conducted are quite long: up to 5 months (taking into account preparatory operations). With such duration, experiments cannot be any mass either in the sense of the number of experiments, or in the sense of the number of experimenters who can afford it. This circumstance forces attention to the results for each sample. The basic input data for the samples are shown in Table 1. As can be seen from this table, the samples are class IV and III collectors according to [13]. The lithological feature of these collectors is the significant content of finely-spotted carbonate cement, which nevertheless allows to maintain the sufficiently good collector properties of the samples that ensure their productivity.

Table 1. Main characteristics of used samples

Sample No.	Grain	Carbonate content, %	C_{per}, mD	C_{por}, %	Me (μm)	Mo (μm)	C_{rw}, %
28172	с/з	10,6	63,42	18,1	4,2	5	32,3
28169	к-с/з	16,6	60,25	17,2	2,4	4	35,0
27820	с-др/з	23,0	12,23	14,5	2,7	5	39,4
27830	с/з	22,5	16,5	2,24	5,3	10	23,0
28181	с-к/з	9,4	190,9	18,8	5,1	5; 21	26,8

Note: Me - median diameter of the sample pores, Mo - modal diameter, both are measured by porometry diagrams.

Results of test researches. Limited space of this article does not allow us to give results for all the studied samples, that is why we will choose one, the most indicative sample and, using this example, we will show how the process of reverse impregnation or resaturation of the sample proceeds. As the most representative, we will choose the sample No. 27830. The main characteristics of the sample are given above in Table 1, hereunder, for completeness of the pattern, its CPC (Fig. 2) and porometry diagram (Fig. 3) are given.

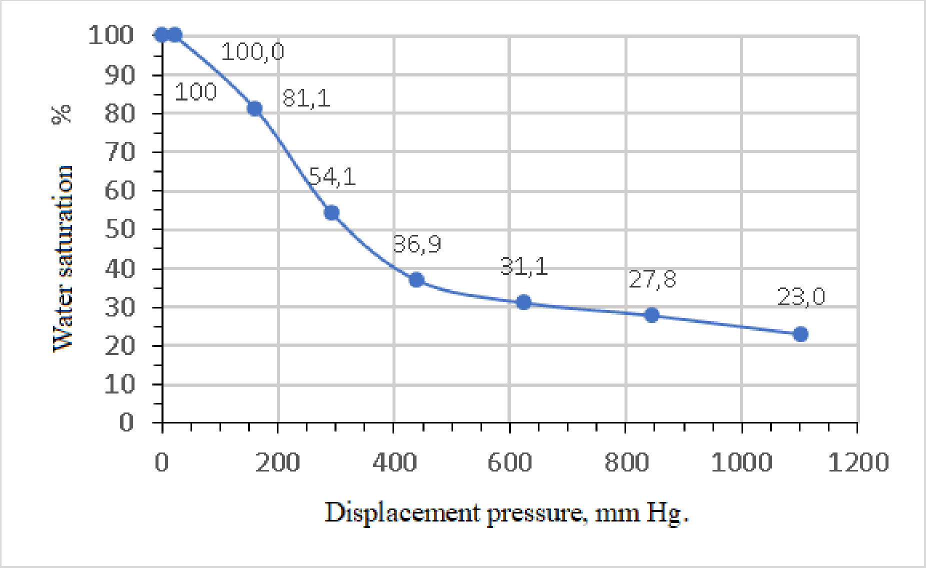

Fig. 2 - Capillary pressure curve of the sample No. 27830

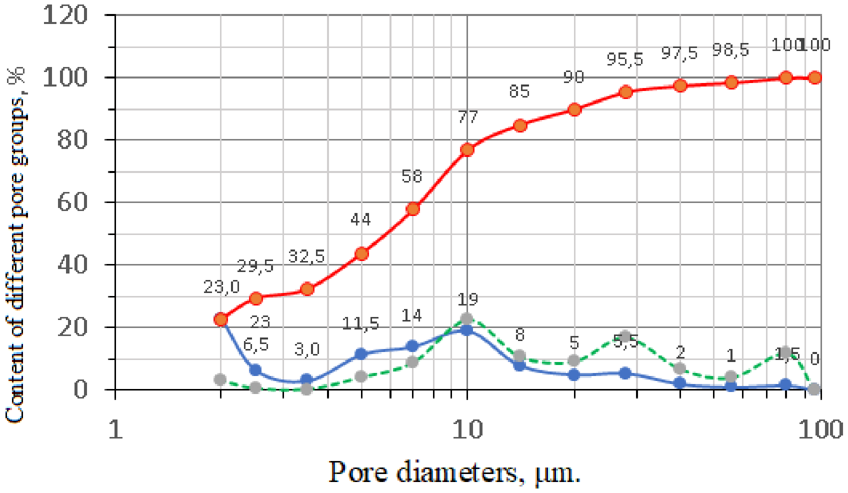

Fig. 3 – Porometry diagram of the sample No. 27830

The CPC of the sample is taken at 8 points, has a typical shape, an inlet pressure of about 20 mm Hg (max diameter - 109 µm), residual water saturation - 23.0%. The porometry diagram consists of three curves: red - a cumulative curve with which Me is determined, blue - a differential curve that shows the content of pore groups of different diameters and with which Mo is determined, green dotted - a curve that shows the percentage contribution of each pore group to the permeability of the sample. For this sample, Me = 5.9 µm, Mo = 10 µm. The Trask homogeneity coefficient is 2.138, that is, the homogeneity of the pore space is between medium and little [14]. The maximum contribution to permeability is made by pores of the prevailing diameter in this sample - 10 µm, less - pores of about 30 µm and even less - pores of about 80 µm. The small contribution of the largest pores, which usually determine permeability, is due to their little amount.

Now let's look at the progress of the process over time. The directly measured value that characterizes the process over time is the mass of the water and kerosene saturated cylinder. Let's see how the mass of the cylinder changes over time during the experiment (Fig. 4).

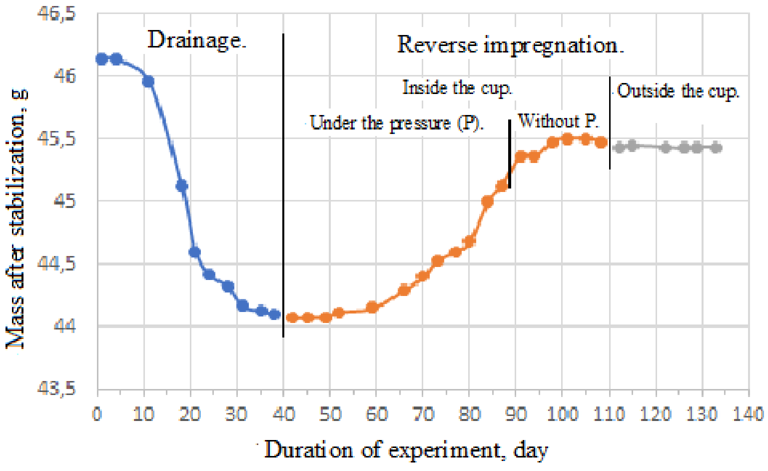

Fig. 4 - Change in mass of sample No. 27830 over time, impregnation with kerosene

In Fig. 4, we see a blue drainage curve that corresponds to the CPC, an orange resaturation curve inside the cup, first under pressure that slowly decreases, then without excessive pressure and, at the end, a gray curve that corresponds to exposition in a hermetic vessel outside the cup. The capillary impregnation curve (CIC) is not uniform completely, saturation breaks and jerks (the transition to zero pressure) are noted in the resaturation, most likely due to the poor capillary contact of the sample with the membrane, but perhaps the features of the structure of the pore space also play a role. On the CPC of this sample, these defects are small, on others they can be expressed much more strongly (No. 28169). The maximum mass of the sample (45.5 g) was reached on the sample, which was in the cup under zero pressure, then there is a gradual decrease in mass, which is explained by losses during periodic weighing, but, possibly, there is a slow displacement of water with kerosene. Compare the change in mass during the water reverse impregnation test with sample No. 28185 taken from the same horizon (Fig. 5).

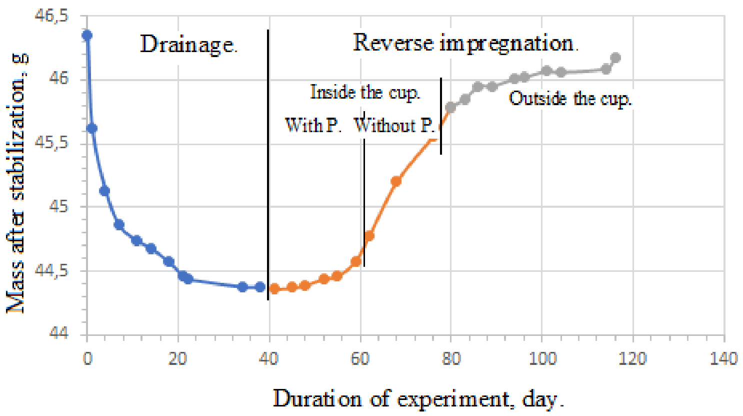

Fig. 5 - Change in mass of sample No. 28185 over time, impregnation with water

From the comparison of Fig. 4 to Fig. 5, it can be concluded that the process proceeds approximately the same, approximately for the same time. The difference is that during water impregnation, after transfer to the membrane outside the cup, water saturation continues to increase. In this case, it reaches 93.8%, occurs up to 94.4%, however, there is a suspicion that, if you continue the experience, over time it can reach 100%, which can hardly be expected for kerosene. A possible reason is the hydrophilicity of the samples.

Now let's see how saturation with both phases depends on displacement pressure and capillary pressure (Fig. 6). The blue curve is the CPC of the water drainage stage, the red – kerosene one. We see that at first, when the displacement pressure decreases, impregnation does not occur, but after the displacement pressure drops below 200 mm Hg the process of reverse impregnation begins. It is especially accelerated in the last section, when the displacement pressure drops below 50 mm Hg. The process continues at zero displacement pressure, concurrently the maximum saturation with kerosene reaches 89.7% (we have in mind the saturation of the pore space, free from residual water, with kerosene).

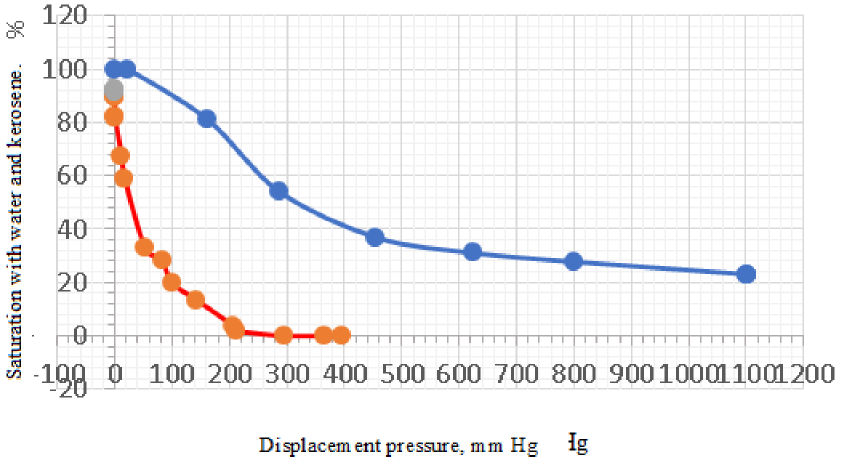

Fig. 6 - Saturation of sample No. 27830 with water and kerosene depending on displacement pressure

Let’s compare to how the reverse impregnation with water takes place using the example of the same sample No. 28185 (Fig. 7).

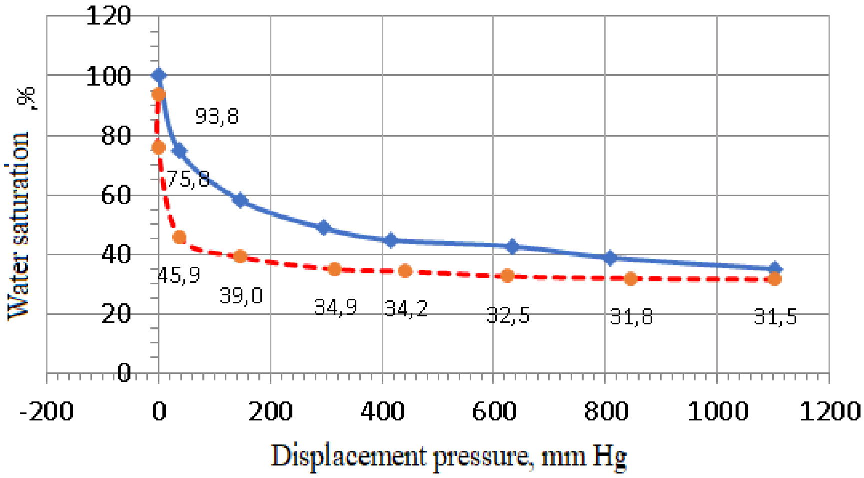

Fig. 7 - Drainage and reverse impregnation with water of sample No. 28185

The general pattern of curves is the same. The main difference is in the pressure at which we begin reverse impregnation. For water it equals the maximum drainage pressure, for kerosene it is much less - about 400 mm Hg. The reason is explained above. A characteristic feature of the "water" diagrams is the delay in the start of reverse impregnation by the time the pressure drops to about 400-300 mm Hg. Only after this impregnation is more or less intensive, reaching a maximum at a pressure of less than 50 mm Hg. The same delay is observed on the "kerosene" diagram, but the pressure of the impregnation start is even lower - 200 mm. Hg. Considering the “kerosene” diagram, it can be assumed that if we could create an initial kerosene impregnation pressure equal to that for water, the impregnation would also start at 200 mm Hg, that is, reverse impregnation with kerosene begins at lower displacement pressures or, to start it a greater pressure drop in the deposit is needed.

Consider how water and kerosene saturation relate to pore size (Fig. 8).

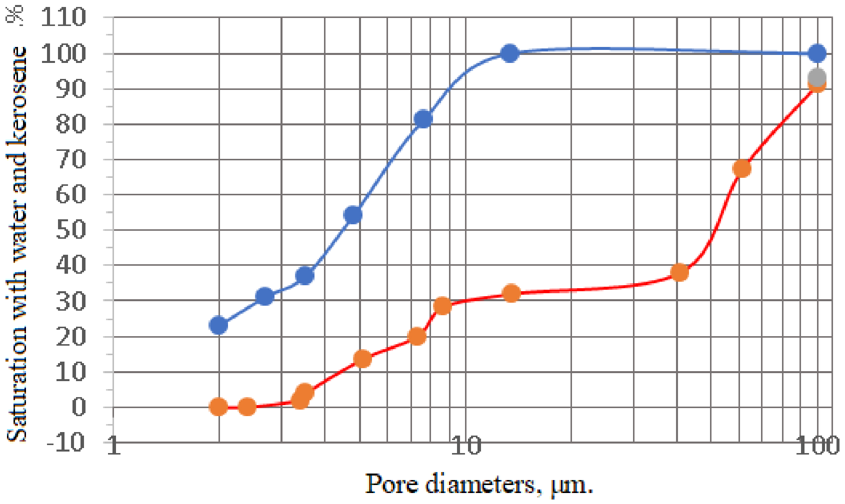

Fig. 8 - Change in saturation with water and kerosene of the sample No. 27830 depending on pore size

The blue line refers to drainage, the red line refers to reverse impregnation. At the drainage stage, when cleaning pores with a diameter of up to 12-13 µm, water saturation practically does not decrease, that is, there are almost no (see sample porometry diagram). Most rapidly, water saturation drops when cleaning pores with a diameter of 3.5-12 µm, which corresponds to the most widespread pores. Then, with the pore less than 3.5 µm number decreasing, the amount of displaced water also drops. In the impregnation stage, before filling the pores with a diameter of 2.5 µm, reverse impregnation does not occur, it occurs quite vigorously when filling the pores with a diameter of 3.5-10 µm, then it slows down until filling the pores with a diameter of 40 µm, after which its speed again increases. Interestingly, impregnation of the largest pores causes a significant change in kerosene saturation, which contradicts the small number of these large pores. Probably, filling the pore space does not happen as linearly as the ideal pore model provides.

Compare how water saturation during drainage (blue curve) and impregnation (red dotted curve) is related to the pore size of sample No. 28185 (Fig. 9).

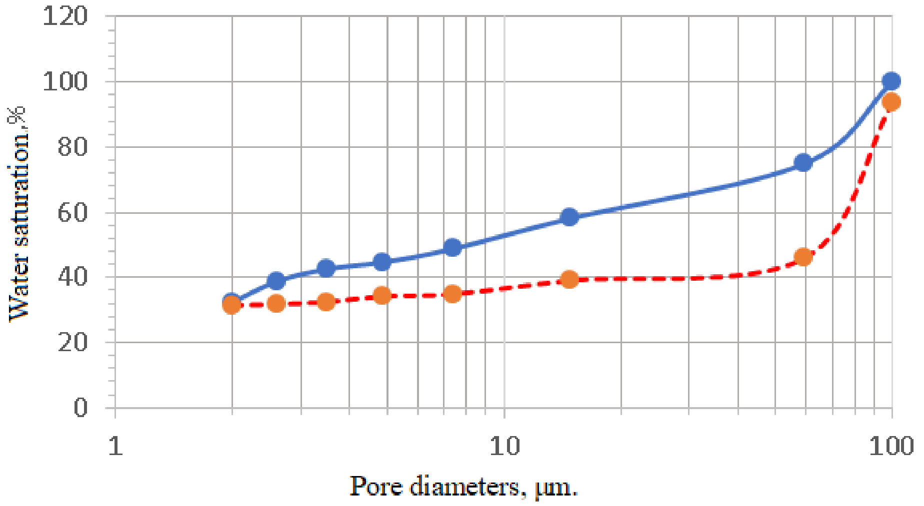

Fig. 9 - Change in water saturation of the sample No. 28185 depending on pore sizes during drainage (blue curve) and impregnation (red dotted curve)

This sample is characterized by a fairly steady decrease in water saturation during drainage, which is explained by its porometry diagram (Fig. 10). A relatively large number of large pores causes a sharp drop in water saturation during their cleaning, further displacement occurs evenly, until residual water is obtained. Approximately the same pattern with reverse impregnation: a slow steady increase in water saturation from residual to that corresponding to filling pores with a diameter of about 60 μm, and if you look at the porometry diagram, then it seems corresponding to filling pores with a diameter of about 80 μm, after which the process is sharply accelerated at large pores.

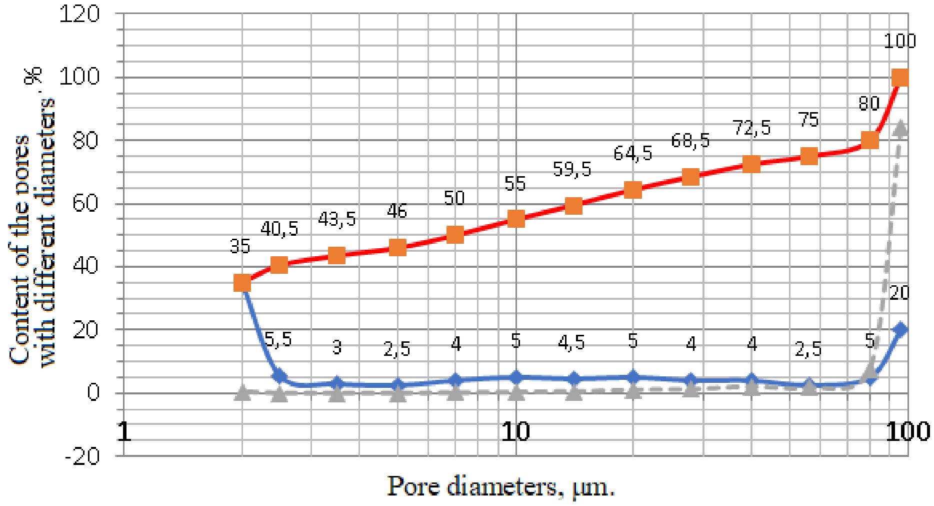

Fig. 10 – Porometry diagram of the sample No. 28185.

Thus, as a result of the carried out work, the main methodological features of the experimental work on reverse impregnation modelling with both water and hydrocarbon fluid become clear. The test researches afford the opportunity to qualitatively evaluate the main characteristics of the reverse impregnation process with hydrocarbons under conditions of displacement pressure decreasing. It should be noted that the work was carried out using hydrophilic samples. It can be assumed that on hydrophobic samples, or even on samples with neutral wettability, the process will proceed differently. In addition, on test experiments, it is not possible to define a more or less stable relationship between the characteristics of reverse impregnation and the capacitive filtration properties of rocks. There is reason to believe that the most significant influence on the process has the nature of the pore space surface wetting. This means that while the process of research it is necessary to determine, at a minimum, the integral wettability of the samples, by which these researches are carried out, according to the methods [2] or [4].

It has been noted above that the duration of the time experiments is very long, so the possibility of reducing the research time by substitute the semipermeable membrane method with a centrifugation method in the drainage stage is theoretically considered. The process of water displacement during centrifugation differs slightly from the process of capillary displacement on the capillarimeter and, therefore, centrifugation is not recommended by some authors for the plotting of a CPC [15]. However, laboratory practice shows that CPC, plotted on the base of the centrifugation method results and CPC, plotted on the base of the semipermeable membrane method ones, are quite close to each other. In addition, two options for the use of centrifugation are possible: both with and without the plotting of CPC. In both cases, centrifugation should be carried out until residual water saturation is obtained, but if there is a goal to plot a CPC, we work according to [12], and if there isn't this goal, we work according to [16]. Centrifugation with the plotting of the CPC will take 1 day, without the plotting of the CPC - 1 hour. In any case, the use of centrifugation will reduce the test time by about 4-6 weeks, depending on the characteristics of the sample. Thus, centrifugation can be recommended to substitute the semipermeable membrane method in the drainage stage.

Conclusions.

1. Reverse impregnation of the sample drained to residual water with both water and kerosene actually takes place, which confirms the existence of this process and in conditions of the deposit with decreasing pressure and selective watering.
2. Reverse impregnation with water and kerosene is fundamentally the same, with slight differences.
3. Both cases are characterized by a delay in the start of impregnation until the displacement pressure is below the capillary pressure. The delay is due to surface tension and more during impregnation with kerosene (under experimental conditions, impregnation with water begins when the displacement pressure drops to 300-450 mm Hg, and impregnation with kerosene - to 200 mm Hg). Under the conditions of the deposit, oil lifting will require a greater drop in formation pressure than water lifting.
4. Experiments show that the reverse impregnation in the time limits of the experiment is precisely as impregnation, and not as displacement. But, at large hourly intervals, the possibility of displacing water from hydrophilic areas or those that have neutral wettability is not excluded.
5. As a minimum, the integral mean wettability must be determined on the samples on which the researches are carried out.
6. Since all processes are associated with surface phenomena, with wettability, in experiments it is better to use not models, but combinations of specific, coexisting formation fluids, that is, formation gas, water and oil of this particular deposit.
7. The method of operation by the semipermeable membrane method in the "drainage-impregnation" mode is sufficiently developed for both reverse impregnation with water and for impregnation with kerosene, it opens up the possibility of switching from test studies to main researches.

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