Indian Journal of Science and Technology, Vol 9(42), DOI: 10.17485/ijst/2016/v9i42/104219, November 2016
ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Revisiting the Development of Oil Deposits with Low Permeability Reservoirs

Sumbat N. Zakirov*, Azariy A. Barenbaum, Ernest S. Zakirov, Ilya M. Indrupskiy, Vladimir A. Serebryakov and Dmitriy S. Klimov

Oil and Gas Research Institute of the Russian Academy of Sciences; ezakirov@ogri.ru, azary@mail.ru, ezakirov@ogri.ru, i-ind@ipng.ru, vladimir.serebryakov@gmail.com, seydem@mail.ru

Abstract

Background/Objectives: The study considers the results of the scientific revolution that started in Russia a quarter of a century ago and referred to solving the problem of oil and gas genesis. **Methods:** The revolution resulted in the development of the new oil and gas paradigm. The essence of this paradigm is that oil and gas are in fact renewable natural resources that should be produced taking into account the balance of the generated hydrocarbons (HC) and the possibilities for their recovery in the process of field development. **Findings:** These new ideas have gained the required theoretical and experimental justification within the biosphere concept of oil and gas generation (BCOG). However, neither the scientific revolution in oil and gas geology nor the implications that follow from the biosphere concept and that directly affect future oil and gas science and practices have been fully perceived in the West. Employing the biosphere concept ideas in the processes of developing oil and gas fields with low permeability reservoirs reveals new and better opportunities. These ideas have been confirmed by the results of the undertaken laboratory investigations and numerical simulation studies. **Applications/Improvements:** The results of the study make it possible to improve the efficiency of oil recovery considerably.

Keywords: Biosphere Concept of Oil and Gas Generation, Carbon Dioxide, Carbonized Water Injection, Dynamic and Stationary Experiments, Hard to Recover Hydrocarbons, Hydrocarbons, Hydrogen Generation, Low Permeability Reservoirs, Pressure Maintenance

1. Introduction

The experts in oil and gas field development, especially those in the countries of the West, seem to have been poorly informed about the revolutionary ideas of oil and gas genesis[1] that have been developed in Russia almost a quarter of a century ago. As a result, both “organic” and “mineral” theory of hydrocarbon formation that used to compete with each other over the last one hundred years gave way to the new oil and gas paradigm[2,3] that radically changes the earlier ideas about the nature of oil and gas and about the origins of their formations.

The essence of this paradigm was for the first time formulated in 1993 by Russian scientists Sokolov and Guseva[4], who claimed that “oil and gas are renewable natural resources and thus they should be developed based on the existing balance of HC generation and given the opportunities for their extraction in the process of field exploitation”.

Thus, it was suggested for the first time that oil and gas fields should be developed as renewable sources of hydrocarbons which repletion rates depend on the conditions of the field development. These ideas have gained the required theoretical substantiation and development within the framework of the biosphere concept of oil and gas generation[3,5] that associates oil and gas origins with the modern carbon and water cycles on this planet that occur in the biosphere, according to V.I. Vernadskiy[6–8].

*Author for correspondence

2. Concept Headings

In order to explain the processes of oil and gas formation the experts of Oil and Gas Research Institute of the Russian Academy of Sciences have suggested the Biosphere concept that unified the existing theories about the origins of oil and gas supplementing them with the ideas about the role of the biosphere and land surface carbon cycle in oil and gas formation and with new chemical mechanisms of low temperature synthesis of hydrocarbons in the crustal rocks which is of particular importance for the purposes of this study.

2.1 Biosphere Concept

By contrast to the biogenic and mineral theories of oil and gas formation the biosphere concept does not use the notions of "organic" and "inorganic" carbon replacing them with the ideas about the role of the carbon cycle in the process of oil and gas hydrocarbon generation. Circulating through the land surface within several cycles (Figure 1) the movable carbon of the biosphere participates in the processes of oxidation-reduction many times. Constituting a component of the living organisms at one time and of the mineral aggregates at another, carbon changes its chemical form and isotopic composition.

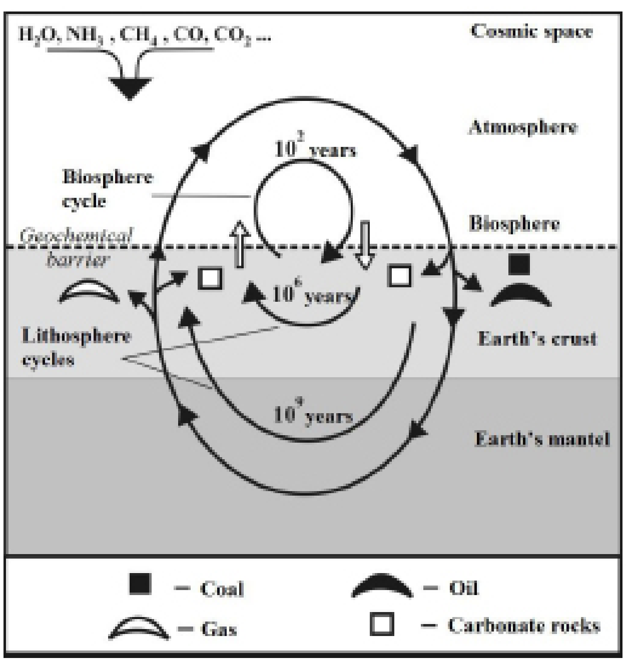

Figure 1. Schematic layout of biosphere carbon geochemical cycle of the Earth

The schematic layout show three main circuits of the cycle as the biosphere carbon circulates through the land surface: two lithosphere circuits: "slow" and "fast", and the biosphere circuit. The first cycle with the characteristic period of τ_1 ~10^8-10^9 years is caused by the deep penetration of the carbon containing rocks into the mantel of the earth under the conditions of subduction of lithosphere plates. The second cycle is associated with the transformation of the Organic Substance (OS) of sedimentary rocks together with the carbon of the carbonate sediments into HC in the crust of the Earth within the characteristic period of τ_2 ~10^5-10^6 years. The third, the biosphere cycle of τ_3 ~10-100 years, is responsible for the carbon cycle in the biosphere, including its underground part. This cycle is mostly caused by the transmission of the water dissolved CO_2 under the land surface by meteoric waters within the framework of their regional circulation.

All three cycles are interconnected with each other and they occur in such a way that above the land surface that plays the part of geochemical barrier carbon in the biosphere mostly circulates as CO_2. Under the land surface a considerable part of carbon as CO_2 and OS is transformed into HC of oil and gas. Because of their poor solubility in water oil and gas form their deposits in geological structures, in the traps of the crust of the Earth. Whether it will be gas or oil depends upon the temperature and pressure conditions of HC accumulations and upon the quality of the traps. Within the "good" traps both oil and gas can accumulate and within the traps that are not that good only oil is accumulated.

Thus, according to the biosphere concept, industrial deposits of oil and gas represent quite large and comparatively long existing traps of the movable carbon of the biosphere that is reduced to HC and that circulates through the land surface within all three circuits of the cycle.

An important element of BCOG is represented by the conclusion that there is an efficient mechanism that transforms within the rocks of the Earth's crust the water dissolved CO_2 and the dissipated OS into HC of oil and gas.[2,5] This mechanism is represented by polycondensation synthesis of HC on the surface of the water saturated mineral matrix of the rocks that has been mechanically agitated in the course of seismic micro-tectonic processes. The possibility of such HC synthesis has been theoretically substantiated and experimentally proven by Molchanov[9–11] and, separately, by Cherskiy and Tsarev[12,13]. The donors of carbon in the process of synthesis are water dissolved CO_2 and OS, and the donor of hydrogen is water.

In order to provide more profound proofs of the Biosphere concept several laboratory experiments have been carried out and are described below.

3. Results

3.1 Experiments within the Framework of the Biosphere Concept

It is obvious that laboratory investigations of meteoric waters flow in the earth crust interior that is affected by multiple natural factors represent a considerable problem. Therefore, naturally, some assumptions had to be made. The carbonized water used for the experiments was prepared by way of saturating the drilled well water with CO_2. It was used as the model of meteoric natural water. The crushed iron turnings were used as the model of the porous medium of rocks.

Experimental investigations were carried out in two modes: stationary and dynamic. In case of dynamic experiments, the physical and chemical processes were investigated under the conditions when carbonized water was continuously flowing through the model of porous medium. That is, the gas-liquid mixture was pumped at a specified rate through the model of porous medium in the reaction column. Thus, the process was reproduced when the carbon was transmitted by meteoric waters through rock formations, according to the ideas about the circuits of geochemical cycle of carbon that is a part of the Biosphere concept of oil and gas genesis[3,5].

In cases of stationary experiments, the investigations were focused on the behavior of the pressure in the system water+CO_2+catalyst with no fluids flow followed by chromatographic analysis of the generated gaseous products. Thus, the process was modeled when the meteoric waters interacted with rocks under the mode of stagnation.

Figure 2 shows the schematic layout of the plant for the dynamic mode testing that was fundamental for the experiments.

The experimental investigations started with the preparation of carbonized water. For this purpose, a gas bottle of CO_2 (1) and the mixing bottle (3) were used. The operating gauge pressure in the course of preparing the saturated solution was varying within the range of 1 to 15 atm, which was predetermined by technical reasons. Upon being saturated with CO_2 the carbonized water

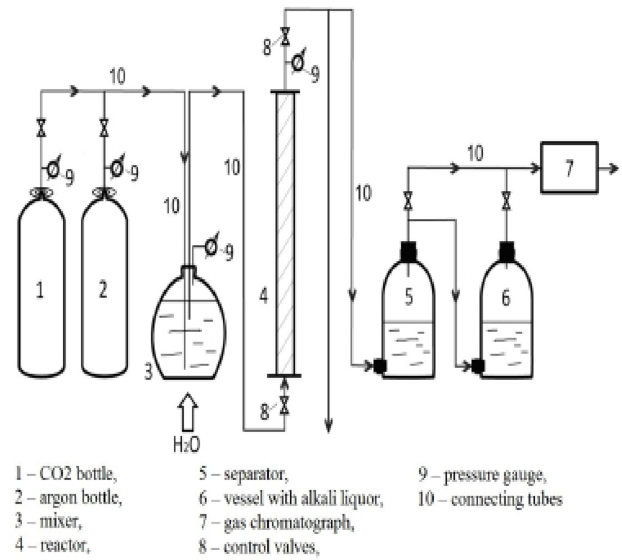

Figure 2. Schematic layout of laboratory plant for dynamic experiments.

from the bottle (3) was pumped at the constant preset rate through the reactor (4) filled with the model of porous medium (iron filler or shale). The reactor column (4) of 1 m length was made of a reinforced plastic tube. Upon passing through the reactor (4) the carbonized water together with the products of the reaction entered the separator (5) represented by the glass Woulff bottle. The separator (5) served for separating gaseous and liquid phases. After the separator (5) the gaseous phase, if required, was fed into the Woulff bottle (6) filled with dilute alkali solution, where it underwent additional treatment in order to remove the unreacted CO_2. The final gaseous products were tapped off and analyzed in the chromatograph (7).

The results of chromatographic analysis of one of the experiments are presented in Table 1.

Table 1 shows that the gaseous phase contains the gases that were not initially present in the carbonized water. They are hydrogen, methane and its homologs and also carbon oxide. Thereat, in terms of quantity, hydrogen dominates considerably. The presence of nitrogen can be explained by the fact that the air entered into the system during sampling and that some of it was contained in the water. Thereat, oxygen to nitrogen ratio decreased 1.5 times (to 0.18) as compared to the air ($O_2/N_2 = 0.27$) which can be related to its losses for Fe (iron turnings) oxidation in the reactor.

In explaining the obtained results some earlier investigations described in scientific literature[9-13] proved to be

Table 1. Chemical composition of gas phase upon alkali treatment

Component	Hydrogen	Nitrogen	Oxygen	Methane	Ethane	Propane	Butane	CO_2	CO
Contents, %	95.562	3.688	0.657	0.039	0.018	0.012	0.0004	0.007	0.017

useful. Those studies experimentally confirmed that the reactions of hydrocarbon synthesis from carbon oxides (CO, CO_2) and hydrogen (from H_2O) were thermodynamically possible under the temperatures higher than 200-400°C and could occur in the sedimentary cover even at lower temperatures when the rocks were agitated by mechanical energy.

In the experiments of Molchanov[9-11] mechanical agitation of the medium was achieved by crushing the carbon containing substances. In the experiments of Cherskiy and Tsarev[12,13] agitation was modeled by frictions and by feeding sea water through the rock samples. Based on the experiments and calculations those authors came to the conclusion that the required agitation in real geological environment was created by seismic vibrations, tectonic shifts and circulation of the subsoil waters. This conclusion was qualified by the authors as new natural phenomenon discovered by them.

The experiments carried out by the authors of this study aim to continue the abovementioned investigations but the tasks are different: the fundamental tasks are associated with identifying physical and chemical mechanism of hydrocarbon formation and the applied tasks are focused on improving modern technologies for increasing oil recovery factor of the oil beds, facilitating oil recovery under complicated geological conditions, carbon dioxide sequestration, etc.

Thus, within the proprietary reactor column the authors observed the phenomena of the carbonated water disintegration on the surface of the mechanically agitated mineral matrix of rocks that was accompanied by the formation of free hydrogen (H_2) and the low temperature synthesis of hydrocarbons from carbon dioxide (CO_2) and water (H_2O).

The formula of polycondensation synthesis of normal alkanes C_nH_{2n+2} that is considered most realistic can be represented as follows:

$$nCO_2+(n+\mu+1)H_2O+æFe = C_nH_{2n+2}+\mu H_2+ æ(FeO) + (½)(3n+\mu+1- æ)O_2,$$

where æ and μ are stoichiometric coefficients and "Fe" is used to designate not only iron but also other materials that act as catalyst and as O_2 absorber in this reaction.

Apart from the dynamic mode testing, as it has been already mentioned, stationary investigations were also carried out. This mode is characteristic, for instance, for the deposits that were earlier mothballed or abandoned. Upon performing the activities on increasing the oil recovery factor of the oil beds applying the injections of CO_2 either with or without water the beds of such fields can contain oil together with water and dissolved CO_2. In this case the speed of carbonated water flow can vary from zero (in stationary mode) up to the high values (in dynamic mode).

The plant for the stationary experiments was somewhat different from the plant for dynamic investigations because a number of constructive features have been changed (alkali treatment bottle was removed and the reactor was replaced). Therefore, the authors of this study would just describe the experiments. In the course of the dynamic experiments the principle parameter under observation was represented by the volumetric content of hydrogen in the products of the reaction. In the course of the stationary experiments the observations were focused on the dynamics of the pressure increase and also on the component compositions of the products of the reaction.

Figure 3 shows the example of the results obtained in the course of the experiments; it presents the dependencies of the pressure in the reactor on time under conditions of two different values of the initial pressure. Indeed, upon sealing the reactor the process of the pressure increase has been observed within it. It appears that the preset values of the initial pressure (2 or 4 atm) predetermine the intensity of the process under observation and the pressure achieves the value of 25 atm in 20 hours. This fact can be explained as follows. As the pressure in the mixer increases so does CO_2 concentration in the operational agent. This in turn affects the intensity of water disintegration releasing hydrogen which predetermines the pressure difference and the rate of pressure changes.

The results of some experiments carried out at the proprietary laboratory plants have been double-checked at the certified laboratory plant "Parr Multiple Reactor Heater System 5000 Series" (Figure 4) at the Department of Physical and Colloidal Chemistry of Gubkin Russian

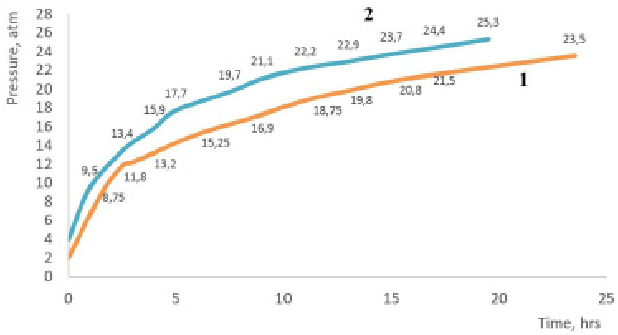

Figure 3. Dynamics of reactor pressure during stationary experiments with initial pressure values of (1) 2 atm and (2) 4 atm.

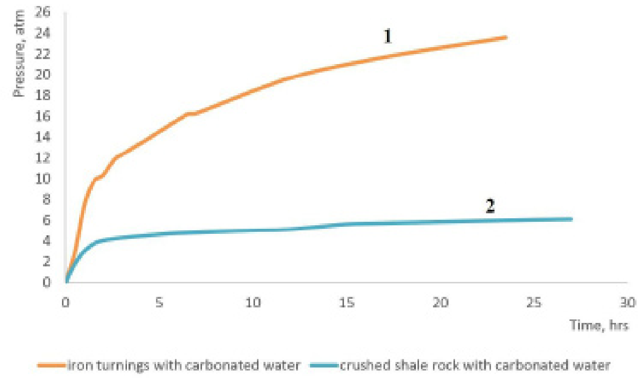

Figure 5. Pressure dynamics in the experiments with iron turnings and crushed shale rock.

Figure 4. General view of multi-cell laboratory station "Parr Multiple Reactor Heater System 5000 Series".

State University of Oil and Gas. The results of the experiments proved to be comparable.

For the purposes of approximating the experiments to the real oil bed conditions the investigations have been performed using the crushed shale of the natural deposits as the filler of the reactor. The investigations showed that in stationary mode the pressure used to increase at all the models of the pumped fluids. However, by contrast to the stationary investigations with iron catalyst, the increase in pressure in the experiments with natural shale is characterized by the lower rate of change (Figure 5). This can be explained by the fact that in the shale sample affected by the atmosphere the contents and the concentration of Fe and of other catalyst active elements are much lower than in the iron turnings. That is, there are scale and time factors that affect the durations of the informative investigations with shale rocks. In the course of the laboratory studies it was rather difficult to take into account time scales of the natural processes. Therefore, the choice of iron turnings in a number of cases was rather forcedly imposed. According to Figure 5, even small amount of shale rock was enough to activate the processes of water disintegration and hydrocarbon synthesis.

From the perspectives of practical application, the dynamic mode of the experiments is directly related to the technology of oil field development with pressure maintenance using CO_2 as operating agent. Thereat, the stationary mode together with the physical and chemical processes under investigation are important for developing the technologies of CO_2 sequestration in the depleted oil and gas fields and in the aquifers. Besides, they can be used for improving the technologies of tertiary oil production from the depleting fields.

The obtained results of the laboratory experiments[14] have been used as foundations for the oil field development method that is described below and they also made the basis for several patents[15,16].

3.2 On Improving ORF in Low Permeability Reservoirs

Below the study will consider the low permeability reservoirs of oil without specifying any geological information. There are a great number of different approaches to developing such reservoirs. However, the scope of the study is limited and thus no literary review of the existing methods will be given. Instead, the authors will concentrate on the suggested alternative method.

The results of the laboratory experiments incite interest in injecting CO_2 into the oil bed in that or another phase conditions. However, the idea of injecting CO_2 into the oil bearing beds faces the limits determined by the permeability values. Therefore, it is for a good reason that most shale deposits are developed under of reservoir energy depletion. Unfortunately, the oil recovery factor (ORF) in such cases does not, as a rule, exceed ten percent.

Therefore, the computer assisted experiments have been performed for the oil carrying bed with the limit value of the effective permeability of 1 md.

For the objectives of the study the model of multidimensional multiphase flow was used implemented within the commercial software package tNavigator developed by Rock Flow Dynamics[33].

The modeled productive bed is of low permeability (1 mD), it is not profitable by definition and belongs to "non-reservoirs" (non-pay reservoirs). Other initial data are as follows: initial reservoir pressure – 230 bar (1 bar = 10^{-1} MPa), oil saturation pressure – 5 bar, oil viscosity – 1 cP (1 cP = 10^{-3} Pa·s), oil formation volume factor – 1.6 m^3/m^3, formation thickness – 20 m. As the bottom-hole pressure in the producing wells decreases down to 30 bar further on it is kept unchanged. The bottom-hole pressure in the injection well is constant and it is equal to 300 bar. The producing wells are shut when the oil production rate is reduced to 1 m^3/day (per a whole well). The relative permeability curves are assumed to be diagonal because of the high solubility of carbon dioxide in oil. The flow simulation model was represented by the Black Oil model. With such initial data the comparative calculations for alternative scenarios have been performed and are described.

An element of a 5-spot development pattern is 500×500 m in size. It has been drilled with horizontal wells with lengths of 200 m. Around the horizontal part of the well bore the one-cell ring of the grid has been refined and the permeability values of these cells are 10 times higher than the permeability of the reservoir itself which simulates the technogenic fractures resulting from the multistage hydraulic fracturing. The schematic layout of the simulation element is shown in Figure 6.

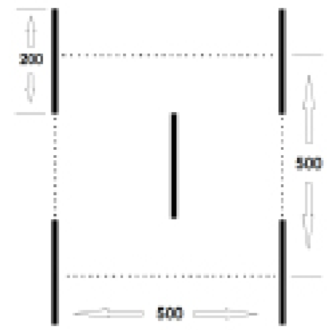

Figure 6. Schematic layout of 5-spot development element.

The effect of CO_2 interphase exchange accompanied by dissolution in water and oil was not taken into account. No account was made for the volumetric properties of the phases depending on the amount of the dissolved CO_2. The ability of the water dissolved CO_2 to mix with oil was approximately accounted for by means of the diagonal relative permeabilities for the oil-water system.

The dimensions of the simulation grid were 43×43×10 grid cells. The grid is not uniform in the horizontal plane, with cell sizes being reduced down to 1 m × 1 m in the area of each well. Then the sizes of the cells were increasing exponentially preserving the preset total distance between the wells. Over the vertical plane the grid is uniform.

In case ***I*** all wells in the development element are producing wells, i.e. the development is carried out under the depletion drive, the wells are producing at the bottom-hole pressure of 30 bar.

In case ***II*** one of the wells (the central one in the development element) becomes an injection well. Carbonized water of 1 cP viscosity is injected under the bottom-hole pressure of 300 bar.

The results of the simulations for the cases under consideration are shown graphically in Figures 7–8.

Figure 7 is of special interest here; it presents the comparison of the dynamics of ORF in the case with the depletion drive and in the case with the pressure maintenance. Hence, it is advisable to maintain the reservoir pressure in the low permeability reservoir under consideration. Though, here the dynamics of ORF in the case with the maintained pressure is somewhat too high, because the simulations were based on the model where the permeability of the oil reservoir was homogeneous and also some other assumptions have been made. However, there are several technological methods for taking into account the inhomogeneity of the reservoir and for alleviating its negative implications. There are still additional reserves when, for example, the lengths of the horizontal wells are assumed to be equal to 1000 or 2000 m, etc. The reserves can be even better when the results of the laboratory studies above are taken into account.

The results presented in Figure 7 can be understood in more detail upon considering Figure 8 that shows the

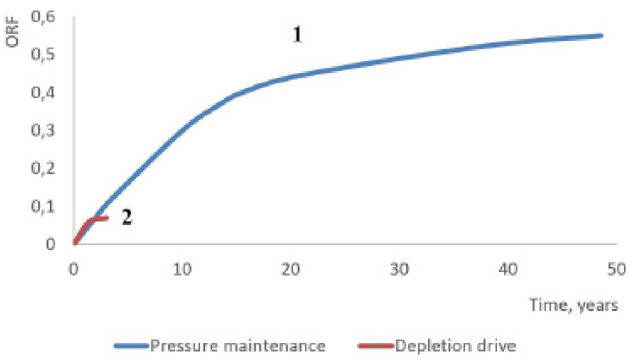

Figure 7. Dynamics of ORF.

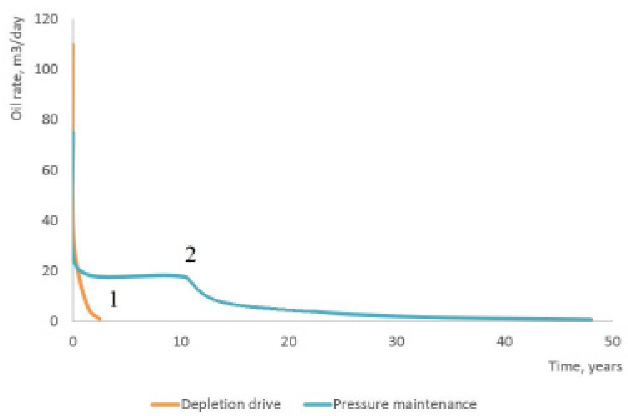

Figure 8. Dynamics of oil production rate.

comparison of the oil production dynamics in different modes for the same development element. Here, it has to be noted that in the depletion mode the oil production from the development element appears to be somewhat higher in the beginning as compared to the case of pressure maintenance, because in the depletion mode a larger number of producing wells are in operation.

4. Discussion

Given the considerable depletion of oil and gas reserves in the producing oil fields with commercial reservoirs, the oil and gas sector is forced to commence development of the oil and gas deposits in hard-to-reach areas and also in the fields with hard-to-recover hydrocarbons. It is a well-known fact that the most significant characteristic of commercial oil beds is represented by its permeability. It is the value of permeability of the reservoir that predetermines the oil, gas and condensate production rates as well as the overall economics of the development.

Until quite recently the formations of 1 millidarcy (mD) permeability and even more were not regarded as profitable objects of development. (Other criteria will be omitted for the purposes of this study). Today the situation has changed. Thus, the USA commenced successful development of oil and gas deposits featuring shale, low permeability oil beds. In these beds the value of permeability amounts to circa 1 mD or considerably lower[17]. Shale oil and gas extraction has started progressing in other regions as well.

This approach to low permeability formations has generated in many deposit fields what can be called non-commercial hydrocarbons. By definition, they used to belong and they still belong to the category of hard-to-recover hydrocarbons. However, due to the current situation in the world they should not be neglected.

- The authors of this study believe that the hydrocarbons-in-place are not estimated and recovered properly, at least in Russia.

The indiscretion starts with the fact that the State Balance Sheet of Mineral Reserves (SBSMR) covers actual hydrocarbons-in-place (called in Russian - geological reserves). In fact, geological reserves should be understood as the hydrocarbons “down to the last molecule”. However, SBSMR accounts for commercial (pay) hydrocarbons only. They do not include the hydrocarbons in the layers which permeability is lower than the adopted threshold values. Thus, the authors of this study suggest that these hydrocarbons should be taken into account and should be called non-commercial hydrocarbons.

The problem (if we forget the shale revolution) is that the non-commercial hydrocarbons have never been developed in Russia. In the authors’ opinion, these hard-to-recover hydrocarbons are the priority objects of development. Moreover, these types of hydrocarbons constitute parts of almost all of the fields that possess well developed infrastructure, are located in habitable regions and employ highly qualified personnel.

- The existing tax system makes the producing companies be always concerned with compensating their incurred costs within the period that should not exceed 10 years. This fact results in the increased rates of oil production and water injection. The considerable pressure drop that occurs between the bottom-holes of the producing and of the injection wells predetermines the accelerated water breakthrough.

From the perspectives of the final ORF, it pays more to have lower oil production with water cut of 0%, than the higher production in the beginning followed by the intensive water breakthrough.

- Special attention should be paid to the cases of lenticle reservoirs[18,19]. In the example considered, sand lens of 500 mD permeability and 500 m radius is surrounded by the reservoirs containing non-commercial hydrocarbons with permeability of 1 mD (Figure 9).

Assume that in the center of the lenticle there is an exploration well. With initial reservoir pressure of 250 bar, oil saturation pressure of 150 bar, oil viscosity of 1 cP the well is alternately operated at constant bottom-hole pressure of 50 to 200 bar. The results of simulation of the oil production dynamics are presented in Figure 10.

Figure 10 demonstrates the phenomenon which is as follows: it appears that under certain bottom-hole pressures (50 and 100 bar) the oil production rate, as usually, decreases at first and then it starts increasing in phenomenological manner?! This can be explained by the fact that the exploration (or producing) well operation results in reduction of the pressure at the borders of the lenticle as soon as the elastic energy of the lenticle is depleted. This inevitably results in the inflow of the non-commercial oil, insofar as the oil of low permeable reservoirs is no longer produced through the vertical well of 10 cm radius, but through a much larger well with the diameter of 500 m.

Due to the inflow of the non-commercial oil the official ORF that would cover the hydrocarbons of the lenticle could be higher that 100 % (Figure 11). ORF would have been even more attractive if the water was injected in

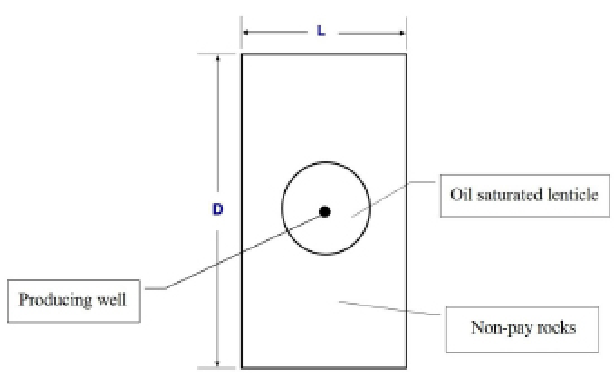

Figure 9. Schematic layout of the well location in the development of the lenticle placed in low permeability reservoir. L=10 km, D=20 km.

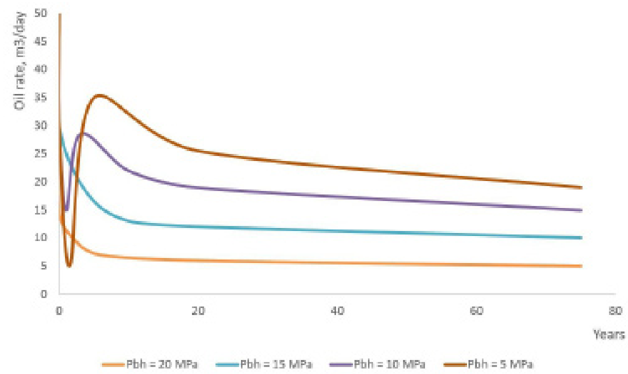

Figure 10. Dynamics of oil production rate during lenticle development under depletion drive.

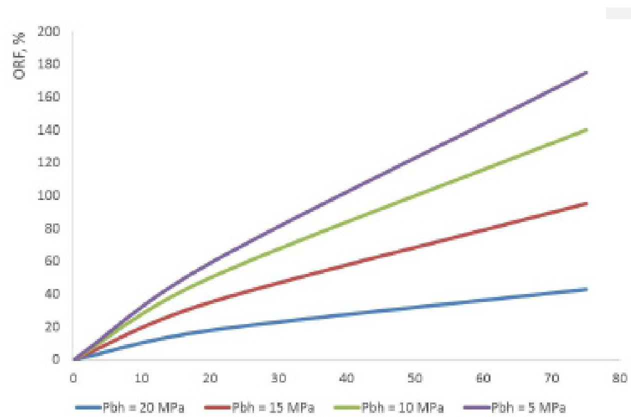

Figure 11. Dynamics of ORF.

the neighboring low permeability reservoirs trough the horizontal injection wells. Thus, it is obvious that the non-commercial hydrocarbons of the low permeability reservoirs should by no means be neglected.

Of course, the development time in the cases under consideration would be almost 2-3 times longer because of the lower production rates and as a result of the fact that the lenticle itself is not flooded with water. Therefore, this is the case of the water free development for almost all the time.

Analogous effects are observed in the development of the layered and heterogeneous formations.

- In Russia the computer revolution has been started prescriptively in 2000. The authors of this study, as experts, have discovered that the design documents for deposit developments that have been prepared assisted by computer models have been based on the pre-computer methodology of the studies adopted in the process of building 3D geological and flow simulation reservoir models[20].

Analysis and synthesis showed that the origins of the pre-computer methodology have been founded on the concept of the Absolute (non-realistic) Pore Space (APS). The fundamental model of the porous medium that applies APS principles is shown in Figure 12 a.

This negative situation was dealt with by justifying the new concept of the Effective Pore Space (EPS). Basic model of porous medium according to the concept of EPS is demonstrated in Figure 12 b. Here k_{abs} is the permeability to gas (air) of the reservoir, $m_{\hat{\imath}}$ is the total or open (interconnected) porosity, m_{eff} is the effective porosity, $m_{eff} = m_o\ (1-S_{wi})$, S_{wi} –irreducible water saturation, k_{eff} is the permeability to oil at S_{wi}[23, 24].

EPS concept introduced some adjustments to the reservoir physics and petrophysics; to the interpretation of well logging and well tests data; to underground flow theory; to the methodology of reserves estimation and of 3D geological modeling and reservoir flow simulation[21,22].

EPS concept enabled the authors of this study to create such technological solutions for field development that would have never been possible within the framework of APS concept.[21,22] For example, the technology of vertical-lateral flooding has been developed. Its analogue, the vertical-lateral cycling process, has been successfully implemented in the unique Karachaganak oil-gas-condensate field[23] (without any references made or any rewards paid to the author of the technology).

EPS concept made the authors create new technologies of well and formation testing, for example, the 3D interference test[21,22].

Among foreign authors the works by P. Ringrose should be noted. This author has come independently to the methodology of 3D geological reservoir modeling that look similar to the concept developed by the authors of this study[24].

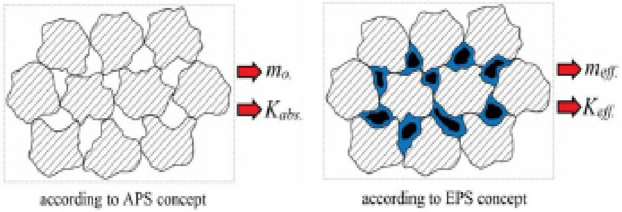

Figure 12. Schematic layout of the basic pore space structures.

- Up to now the relevant industrial ministry has been ignoring the innovative ideas and concepts of EPS. Owing to their administrative resources they have prolonged the life of the outdated ideas of APS concept. Development of any field with low permeability reservoirs, especially applying the outdated ideas will not result in anything good. One of the theorems of the authors of this study is as follows:
- Investigation and development of the non-conventional deposits by means of conventional methods will be neither rational nor efficient.
- There are an increasing number of the deposits where the developments become unprofitable due to that or another reason. According to the suggested results of the laboratory experiments, these fields should be injected with carbonized water or just with CO_2. Then, apart from improving ORF due to the agitation of the residual oil in the bed, the genesis of hydrocarbons can occur in the formation accompanied by hydrogen generation. Thus, the results of the experiments can become an extra incentive to fight for the residual oil.
- Today around the world there are a growing number of environmental projects aimed at CO_2 sequestration in different natural locations[25–31]. Here again, the depleted oil reservoirs represent quite suitable objects for such enterprises because the ecological projects, as a rule, are non-profitable and are characterized by negative cash flows. According to the experiments, CO_2 injection into the specified objects will ensure some positive cash flows as well.

Of course, all environmental and other projects need be profoundly investigated and substantiated from technical and economic perspectives. Field experiments are also of great importance.

- In order to incite interest in applying the results of the laboratory experiments to the real problematic objects the authors will refer to the large scale experiment that has been carried out by Nature itself.

Here the authors will describe the underground storage of the so-called town gas at the underground gas storage Lobodice in the Check Republic[32]. This gas storage was constructed for the purposes of storing the town gas that is generated from coal. In one of the storage cycles the analyses were performed with the incoming gas and with the gas produced for consumption. The gas that was injected in the gas storage contained 55 % of H_2, 20 % of CO_2+CO and 20 % of CH_4. After several months of storage the mixture had quite another component composition. It contained 37 % of H_2, 12 % of CO_2+CO and 40 % of CH_4. That is, in 7 months of storage the content of methane increased twice and the total content of carbon dioxide and carbon monoxide was almost two times lower. Isotopic analysis showed that in terms of isotopes a part of the produced CH_4 was different from the methane that was injected. The increase in methane content and the change of its isotopic composition were explained by the authors of those experiments by the effects produced by methane bacteria, which, from the point of view of the authors of this study, does not make a plausible explanation.

The results of the simulations described in the previous section correspond to an isolated case and are by no means absolute. Obviously, in this case a large number of cases have to be investigated; however, this was not included in the scope of this study. It is also obvious that some non-apparent effects will appear, inasmuch as in real environment the layered or zonal heterogeneity of the reservoir properties often affects negatively the economics of the oil field development. Nevertheless, the results of the investigation do prove at the qualitative level that the suggested approach to developing the oil fields with low permeability reservoirs can result in higher ORF values.

The considered approach to the development is realistic not only when applied to the oil deposits but also when applied to gas-condensate and, in some cases, to gas deposits with low permeability reservoirs. Thus, if the reservoir pressure is not maintained in the gas-condensate field then the condensate will drop-off in the reservoir becoming immovable. That is, in case of the gas-condensate deposit the pressure maintenance is meant to solve the problem of condensate recovery in the first place. In case of the depletion mode the dropped-off condensate will drastically reduce permeability to gas which will lead to lower gas recovery factor (GRF). That means that maintaining the reservoir pressure in gas-condensate deposit will help improve GRF. Maintaining the pressure in the oil deposit and in gas-condensate deposit will make it possible to postpone the period of the compressor-driven exploitation. Besides, if the pressure is maintained in these deposits the volume of the low pressure gas will decrease considerably. Thus, ideally, when the injected CO_2-based agent displaces all natural gas there will be no low pressure gas left in the Earth's interior.

5. Conclusion

The undertaken laboratory studies and numerical experiments with the simulation model prove that developing the oil deposits with low permeability reservoirs by pressure maintenance using carbonized water injection could be very efficient. Thereat, high oil recovery factors can be achieved and will be associated with in-situ generation of hydrogen and hydrocarbons in the course of disintegration of carbonized water.

6. Acknowledgement

The study has been undertaken within the framework of the applied scientific investigations with financial support from the Ministry of Education and Science of the Russian Federation (project unique identifier RFMEFI60714X0080).

7. References

1. Barenbaum AA. Scientific revolution in the problem of the origins of oil and gas. New oil and gas paradigm. Georesources; 2014: 4(59):9–15.
2. Barenbaum AA. Mechanism of formation of oil and gas deposits. Reports of the Academy of Science. 2004; 399(6):802–5.
3. Barenbaum AA. Galactocentric paradigm in geology and astronomy. Moscow, LIBROKOM; 2010.
4. Sokolov BA, Guseva AN. On the possibility of fast modern generation of oil and gas. Bulletin of Moscow State University. 1993; 3:48–56.
5. Barenbaum AA. Modern generation of oil and gas as a result of the carbon cycle in the biosphere. Georesources. 2015; 1(60):46–53.
6. Vernadsky VI. The biosphere. Leningrad, scientific and technical publishing house; 1926.
7. Vernadsky VI. Live matter. Moscow, Nauka; 1978.
8. Vernadsky VI. Essays on geochemistry and the biosphere. Translated by Olga Barash. Santa Fe, NM, Synergetic Press; 2006.
9. Molchanov VI. Experiments on synthesis of hydrocarbons with thin disintegration of mineral substances in water. Reports of the Academy of Science. 1967; 174(5):1185–7.
10. Molchanov VI, Pavlov AL, Gontsov AA. Experimental investigations of generating HC from hard organic matter. Reports of the Academy of Science. 1969; 189(2):397–9.
11. Molchanov VI, Gontsov AA. Modeling oil and gas extraction. Novosibirsk, OIGGM; 1992.

12. Cherskiy NV, Melnikov VP, Tsarev VP. Phenomenon of hydrocarbon generation from finitely oxygenized compounds of carbon and water. Reports of the Academy of Science. 1986; 288(1):201–4.
13. Cherskiy NV, Tsarev VP. Mechanisms of synthesis of hydrocarbons from nonorganic matters in the upper horizons of the Earth's crust. Reports of the Academy of Science. 1984; 279(3):730–5.
14. Barenbaum AA, Zakirov SN, Zakirov ES, Klimov DS, Serebryakov VA. Physical and chemical processes during the carbonated water flooding in the oilfields. SPE Russian Petroleum Technology Conference, 2015 Oct 26 –28, Moscow, Russia. SPE 176729-MS.
15. Zakirov SN, Zakirov ES, Barenbaum AA, Lysenko AA, Klimov DC, Oreshenkov AV. Method of developing the natural hydrocarbon deposits in low permeable horizons. RF patent No. 2590916.
16. Barenbaum AA, Zakirov SN, Zakirov ES, Serebryakov VA. Method of hydrocarbon and hydrogen production from water and carbon dioxide. Patent US. No. 20,120,315,215; 2012.
17. Khan R, Al-Nakhli AR. An overview of emerging technologies and innovations for tight gas reservoir development. Paper SPE 155442 presented at the SPE International Production and Operations Conference and Exhibition, Doha, Qatar, 2012 May14 –16 May; 2012.
18. Zakirov SN, Kontarev AA. Generation of oil in lenticle collectors. Reports of the Academy of Science. 2007; 413(1):68–70.
19. Zakirov SN, Zakirov ES, Indrupskii IM, Anikeyev DP, Baganova MN. On quotients of oil/gas/condensate recovery efficiency. Georesources. 2015; 3(62):24–30.
20. Zakirov SN, Zakirov ES, Indrupskii IM. New 3D representations in geological and hydrodynamic modeling. Oil Economy. 2006; 1:34–41.
21. Zakirov SN, Indrupskii IM, Zakirov ES, Zakirov IS. New principles and technologies of developing oil and gas reservoirs. Part II. Moscow-Izhevsk, Institute of Computerized Investigations; 2009.
22. Zakirov SN, Zakirov ES, Indrupskii IM. Innovations in oil and gas field development. Herald of RAS. 2012; 82(3):211–17.
23. Kusanov ZhK. Specific features of development of Karachaganak reservoir. Oil Economy. 2011; 6:100–3.
24. Ringrose PS. Total-property modeling: dispelling the net-to-gross myth. SPE Reservoir Evaluation & Engineering. 2008 Oct 2008; 5.
25. Kang SM, Fathi E, Ambrose RJ, Akkutlu IY, Sigal RF. Carbon Dioxide Storage Capacity of Organic-rich Shale. SPE Journal. 2013 Apr 16:842 –55.
26. Nicot JP, Duncan IJ. Common attributes of hydraulically fractured oil and gas production and CO2 geological sequestration. Greenhouse Gases Science and Technology. 2012; 2:352–68.
27. Metz B, Davidson O, de Coninck HC, Loos M, Meyer LA. IPCC special report on carbon dioxide capture and storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change; Cambridge, UK/New York, USA: Cambridge University Press; 2005.
28. Price PN, Oldenburg CM. The consequences of failure should be considered in sitting geologic carbon sequestration projects. International Journal of Greenhouse Gas Control. 2009 Sep; 3(5):658–63.
29. Captage et stockage du CO2: enjeux techniques et sociaux en France. In : Ha-Duong M, Chaabane N, editors. Collection Update Sciences and Technologies, Quae; 2010 Feb.
30. Godina OV, Maksimenko LS, Savtsova AV. Dynamic approach to strategic analysis of the innovative environment of the regional socio-economic system. Indian Journal of Science and Technology. 2016 Apr; 9(16).
31. Anisimova EL, Mingaleva ZA, Zakharova RG, Prokin VV, Rybin SV. The innovative development of the territory: Institutional aspects. Indian Journal of Science and Technology. 2016 Aug; 9(29).
32. Šmigaň P, Greksak M, Kozankova J, et al. Methanogenic bacteria as a key factor involved in changes of town gas stored in an underground reservoir. FEMS Microbiology Ecology. 1990; 73:221–4.
33. Harrison S. tNavigator – breaking reservoir simulation speed limits in Europe! The First SPE Norway Magazine. 2015 May; 5:22–7.