NAFTA-GAZ

Nafta-Gaz 2024, no. 5, pp. 293–300, DOI: 10.18668/NG.2024.05.05

The “diffusion approximation” approach for describing the oil field development process

Zastosowanie „aproksymacji dyfuzyjnej” do opisu procesu zagospodarowania złóż ropy naftowej

Aziz V. Mammadov, Arzu V. Sultanova, Ramil M. Mammadov

Azerbaijan State Oil and Industry University

ABSTRACT: Analysis of the interaction of wells in the process of oil field development is based in particular on calculating the correlation coefficient of two adjacent wells. However, due to reservoir heterogeneity, this approach fails to consider the possibility of interactions between wells located at significantly greater distances. The non-equilibrium of the system is attributed to its openness, associated with environmental impacts (flooding process and changes in the stock of existing wells). The oil field development is a complex process, subject to complex works such as well grid compaction, carrying out a wide range of geological and technical operations, etc. From this point of view, the development and exploitation of fields needs a “volumetric” approach, i.e. a diffusion approximation. A crucial aspect of oil production is the timely regulation of both current production rates and water impact on the reservoir system. The oscillatory nature of the time series of measurements of oil, water, and liquid production rates carries information about the state and behavior of the reservoir system. Analysis of the features of oscillatory processes of the technological indicators of well operation across the entire area of the deposit as a whole enables early diagnosis of changes in the state of the system. The approach of the production well stock analysis in terms of the amplitude-frequency characteristics of the dynamics of oil, water, “mobile” water, and flooding, as well as the specific ratios of produced oil to the volume of water injected into the reservoir (an indicator of the effectiveness of water stimulation) allows us to consider the development as a diffusion-like process.

Key words: approximation, frequency, oil, water, “mobile water”, fluctuations, diffusion, dependency.

STRESZCZENIE: Analiza wzajemnego oddziaływania odwiertów na etapie zagospodarowania złóż ropy naftowej opiera się w szczególności na obliczaniu współczynnika korelacji dwóch sąsiadujących ze sobą odwiertów. Jednak ze względu na niejednorodność złoża, podejście to nie uwzględnia możliwości wzajemnego oddziaływania odwiertów położonych w znacznie większych odległościach od siebie. Brak równowagi systemu wynika z jego drożności, związanej z czynnikami środowiskowymi (proces nawadniania złoża i zmiany w stanie zasobów istniejących odwiertów). Zagospodarowanie złóż ropy naftowej jest złożonym procesem, podlegającym skomplikowanym pracom, takim jak zagęszczanie siatki odwiertów, przeprowadzanie szerokiego zakresu zabiegów geologicznych i technicznych, itp. Z tego punktu widzenia zagospodarowanie i eksploatacja złóż wymagają zastosowania podejścia „wolumetrycznego”, tj. aproksymacji dyfuzyjnej. Kluczowym aspektem procesu eksploatacji ropy naftowej jest terminowa regulacja zarówno bieżącego tempa eksploatacji, jak i wpływu wody na system złożowy. Oscylacyjny charakter serii czasowych pomiarów tempa wydobycia ropy, wody i innych mediów dostarcza informacji o stanie i zachowaniu systemu złożowego. Analiza cech procesów oscylacyjnych wskaźników technologicznych funkcjonowania odwiertów na całym obszarze złoża jako całości umożliwia wczesne diagnozowanie zmian w stanie systemu. Zastosowanie analizy zasobów odwiertu wydobywczego pod względem charakterystyki amplitudowo-częstotliwościowej dynamiki ropy naftowej, wody, wody „mobilnej” i nawadniania złoża, a także określonych proporcji wydobytej ropy naftowej względem objętości wody zatłoczonej do złoża (wskaźnik skuteczności stymulacji odwiertu poprzez wtłaczanie wody) pozwala traktować zagospodarowanie złoża jako proces dyfuzyjny.

Słowa kluczowe: przybliżenie, częstotliwość, ropa naftowa, woda, „woda mobilna”, fluktuacje, dyfuzja, zależność.

Corresponding author: R.M. Mammadov, e-mail: *ramil.mammadov.mu@asoiu.edu.az*

Article contributed to the Editor: 18.07.2023. Approved for publication: 07.05.2024.

Introduction

Currently, the analysis of the interaction of wells in the process of oil field development is based in particular on the calculation of the correlation coefficient of two adjacent wells. However, due to reservoir heterogeneity, this approach fails to consider the possibility of interactions between wells located at significantly greater distances.

The proposed principle is based on the analysis of fluctuations in the main technological indicators of the development process – oil and water production rates, the dynamics of injection volumes and "mobile water" (the difference between the volume of water injected into the formation and water production), taking into account the amplitude-frequency characteristics of wells operating simultaneously across the operational object as a whole. This approach enables decision-making regarding the regulation of various processes not for individual wells, but for groups of wells that statistically cover the reservoir space in a random manner. The composition of these groups changes over time due to the transition of wells from one group to another. Thus, the proposed approach allows for the consideration of not only the heterogeneity of the system but also the effect of non-equilibrium (Mirzajanzade et al., 2004).

The non-equilibrium of the system is attributed to its openness associated with environmental impacts (flooding process and changes in the stock of existing wells).

Methodology

The oil field development is a complex process, subject to complex works such as compacting a well pattern, carrying out a wide range of geological and technical operations, etc. From this point of view, field development and operation require a "volumetric" approach – a diffusion approximation that accounts for changes in reservoir cross-sectional characteristics over time as the fields are developed.

This approach enables timely decision-making regarding the management and control of oil and gas field development by regulating the selection of well groups across the entire deposit (Mirzajanzade et al., 1997).

As a rule, information about the properties of individual elements within structured environments and the features of the interaction processes between them is either lacking or difficult to obtain. Therefore, in order to study the cooperative effects that occur during the flow of rheophysically complex fluids, it is advisable to use the concepts of the theory of self-organization, which reflects the most general properties of the behavior of complex systems.

In a non-equilibrium environment, when external parameters change, the rate of build-up of equilibrium is less than the rate of change in external parameters.

Non-equilibrium behavior can arise from inherent system properties (gas-liquid flows, oil-water emulsions, interaction of reservoir fluids with formation, etc.) and is influenced not only by the current state but also by previous parameter values (selection rate, water injection, etc.)

One of the methods of the dynamic approach is the determination of amplitude-frequency characteristics, which makes it possible to characterize the rate, acceleration, and inertia of the process. By applying this method to each well, it is possible to divide the operating time into periods, enabling further determination of oscillations in system behavior, their amplitude, and frequency. Thus, it seems possible to assess the degree of system disequilibrium for the period under review in order to make an operational decision regarding the control of technological processes.

In this context, the diffusion process should be understood as parameter dissipation, leading to a violation of the equilibrium conditions of the system. The degree of deviation in this case allows us to estimate the deviation's amplitude and its frequency. Thus, the described approach is to a certain extent related to the theory of self-organization of complex systems such as the "reservoir-well" system.

Synergetic methods, which are nothing more than methods of nonlinear physics, make it possible to describe many processes observed in systems that outwardly have nothing in common, using the same mathematical models, the number of which is relatively small.

Spectral density is a Fourier transform-based representation of time-dependent signals (both deterministic and random processes) in the form of spectra. In this approach, oil and water production indicators are considered as deterministic and stochastic signals. The Fourier transform makes it possible to convert data from the time domain to the frequency domain, decomposing it into its components.

The stochastic nature of the system's output parameters may depend on the influence of both the physical properties of the formation and fluid, and on technological indicators.

In the theory of time series, the relationship between the spectral density and the frequency of oscillations is used in the form:

$$S(f) = A^2(f) \tag{1}$$

where:

f – oscillation frequency,

A^2 – square of the oscillation amplitude.

From the analysis of this dependence, it can be seen that the initial data can be described by the following processes: as the frequency of oscillations increase (in this case, low amplitudes correspond to high frequencies), the spectral density decreases; as the oscillation frequency decreases (accompanied by high amplitudes), the spectral density increases (Mandelbroijt, 2002).

At the same time, there are differences in the average values of the amplitudes throughout the considered information array. When the average values of the amplitudes do not differ, characteristics of the series $A\omega$, $A^2\omega$, and $A\omega^2$ remain constant (Mirzajanzade, 1986; Mirzajanzade and Shahverdiyev, 1997).

The periods the change of which is accompanied by a change in the average values of the amplitudes (consequently, a change in the characteristics $A\omega$, $A^2\omega$, and $A\omega^2$) may correspond to a change in the structure of the system. An analysis of the dimensions of these characteristics shows that (Forrester, 1977; Ebeling, 1979):

$$\begin{gathered}[A] = L;\ [\omega] = T^{-1};\ [A\omega] = LT^{-1} \\ [A^2\omega] = L^2T^{-1};\ [A\omega^2] = LT^{-2}\end{gathered} \tag{2}$$

Thus, the analyzed characteristics are:
$[A\omega]$ – flow rate,
$[A^2\omega]$ – fluctuation transfer rate (area transfer), which is similar to the diffusion process,
$[A\omega^2]$ – flow acceleration (characterized by inertia forces).

Dimensional analysis forms the basis for identifying the characteristic features of the fluctuation process of the control object behavior: an increase in speed $A\omega$ leads to chaotic fluctuations; an increase in the area transfer rate $A^2\omega$ (diffusion process) leads to a change in the degree of flow fluctuations, which indicates the presence of non-equilibrium of the systems under consideration. Further, an increase in flow acceleration $A\omega^2$ indicates an intensification of fluctuation processes (Haken, 1980, 1985).

A crucial aspect of oil production is the timely regulation of both current production rates and water impact on the reservoir system (Salavatov and Mammad-zade, 2009).

The oscillatory nature of the time series of measurements of oil, water, and liquid production rates carries information about the state and behavior of the reservoir system. Analysis of the features of oscillatory processes of the technological indicators of well operation across the entire area of the deposit as a whole enables early diagnosis of changes in the state of the reservoir-well system without the use of special hydrodynamic studies and timely regulation of the operation modes of groups of wells and the waterflooding process.

This problem is solved on the basis of the analysis of fluctuations in the main technological indicators of the development process – oil and water production rates, the dynamics of injection volumes and "mobile water" (the difference between the volume of water injected into the formation and water production), as well as taking into account the amplitude-frequency characteristics of the wells operating simultaneously across the production facility as a whole. This approach will enable decision-making regarding the regulation of various processes not for individual wells, but for groups of wells (Mirzajanzade et al., 2002).

The proposed approach was tested on the information array of technological indicators of the development of the V block of the X horizon of the Neft Dashlary (Oil Rocks) field. Figures 1–6 respectively show the dynamics of average monthly oil and water production rate, water cut, "mobile" water, volumes of water injected into the formation, as well as the average monthly oil production rate per unit of injected water. The paper presents an analysis based on field data from the past development period, which will be useful in processing the information array in order to make an operational decision to regulate the development process.

It should be noted that the waterflooding process began at the end of 1962, while the operation of this block was commenced in 1957. The entire information array for the specified period was considered at certain time intervals, during which a number of wells (m_i) operated simultaneously, each with its own limits for fluctuations in extraction amplitudes A_{ij} (oil and water) – with an appropriate number of measurements (l_{ij}) for each. Thus, the analysis of the operating well stock was constantly carried out taking into account the entire area (space) and time.

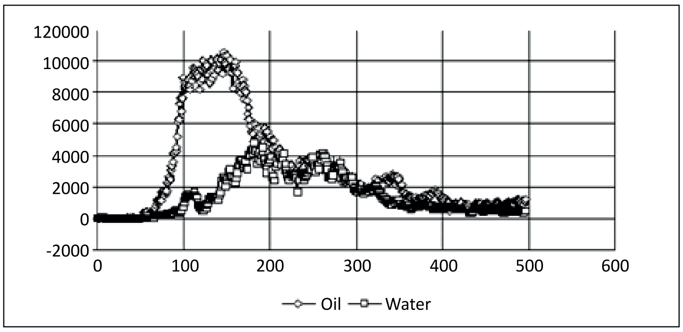


Figure 1. Dynamics of oil and water production rates

Rysunek 1. Dynamika wydobycia ropy naftowej i wody

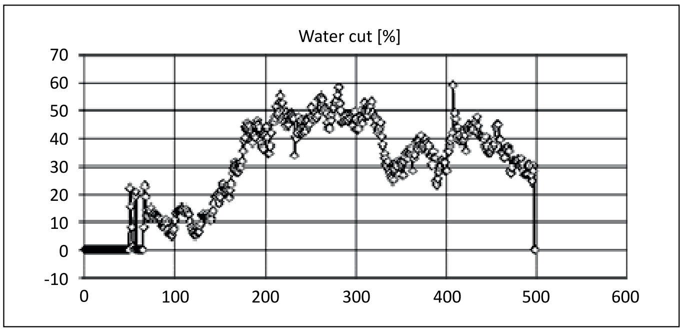


Figure 2. Dynamics of water cut

Rysunek 2. Dynamika zawodnienia

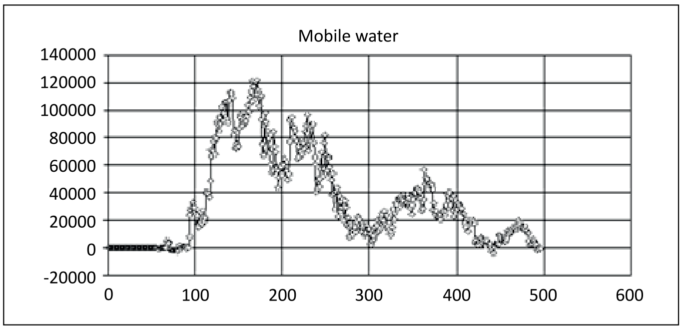


Figure 3. Dynamics of the "mobile" water
Rysunek 3. Dynamika wody "mobilnej"

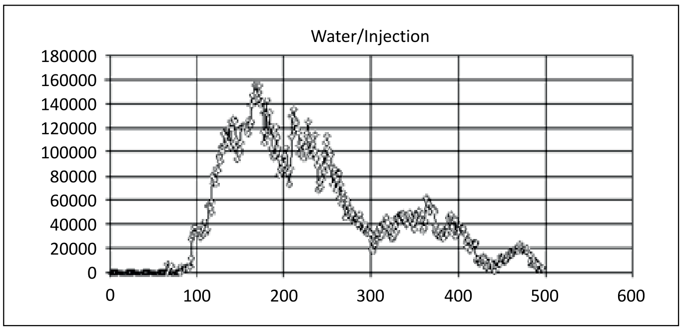


Figure 4. Dynamics of the injected water
Rysunek 4. Dynamika wody zatłaczanej

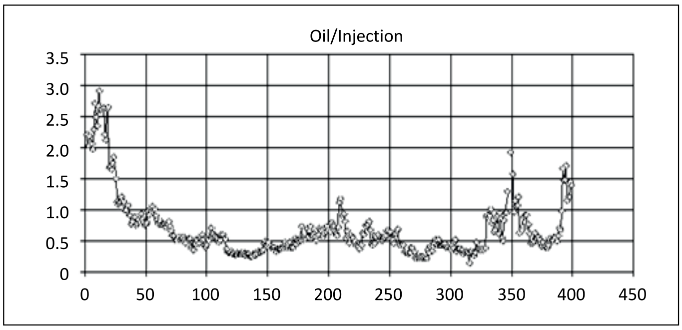


Figure 5. Dynamics of the oil production rate per unit of injected water

Rysunek 5. Dynamika wydobycia ropy naftowej na jednostkę zatłaczanej wody

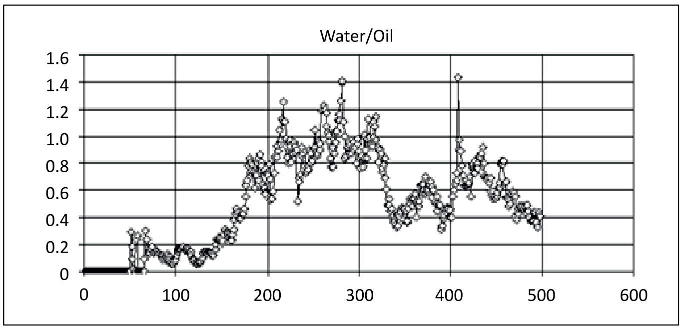


Figure 6. Dynamics of the volumes of water injected into the formation per unit of the produced oil

Rysunek 6. Dynamika objętości wody zatłaczanej do formacji na jednostkę wydobytej ropy naftowej

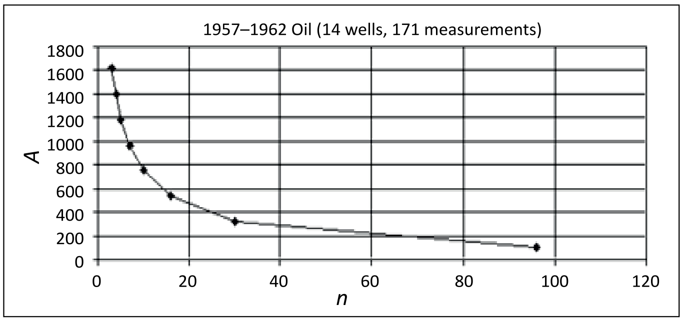


Figure 7a. Amplitude characteristics for oil
Rysunek 7a. Charakterystyka amplitudowa dla ropy naftowej

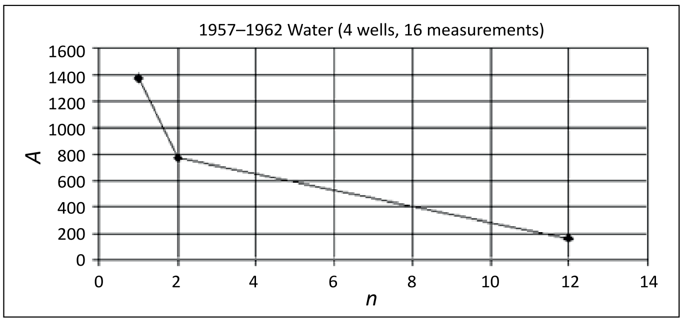


Figure 7b. Amplitude characteristics for water
Rysunek 7b. Charakterystyka amplitudowa dla wody

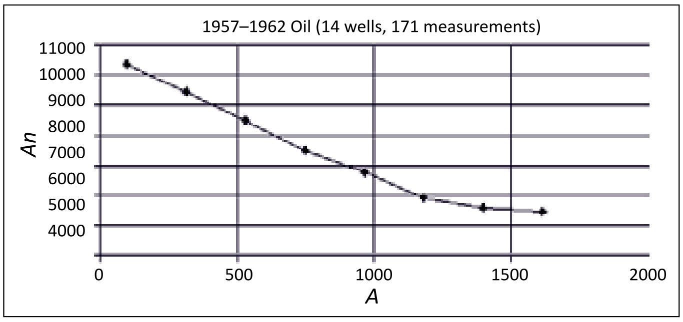


Figure 8a. Amplitude characteristics for oil

Rysunek 8a. Charakterystyka amplitudowa dla ropy naftowej

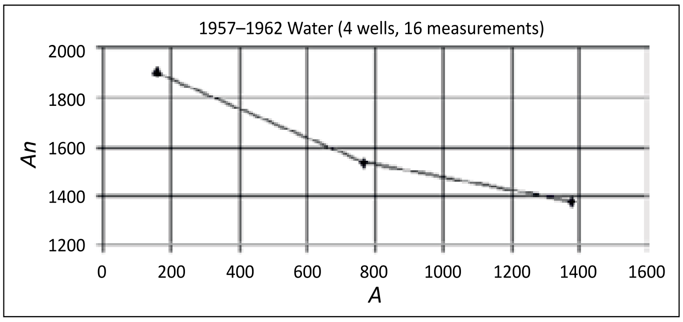


Figure 8b. Amplitude characteristics for water

Rysunek 8b. Charakterystyka amplitudowa dla wody

The entire array A_{ij} was divided, according to the Strangess procedure, into equal intervals depending on the number of measurements $N = \sum l_{ij}$, $k = 1 + 3.32 \log N$, whose step is defined

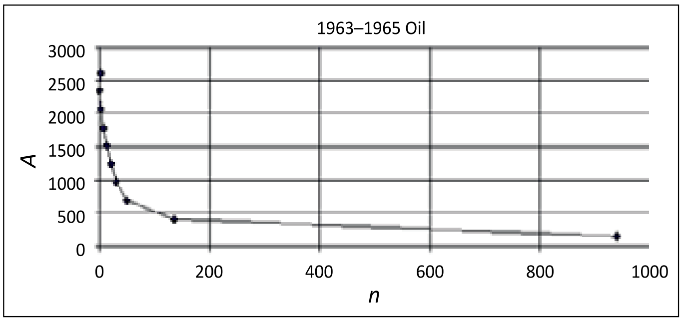


Figure 9a. Amplitude characteristics for oil
Rysunek 9a. Charakterystyka amplitudowa dla ropy naftowej

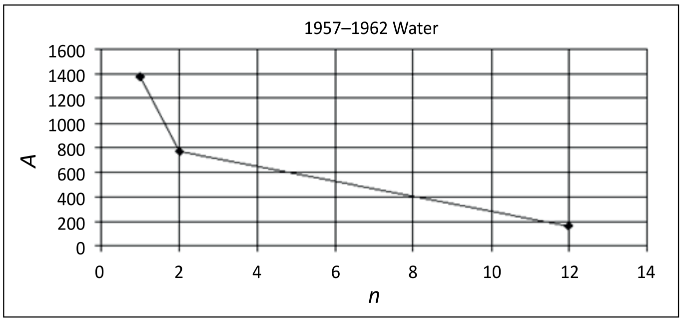


Figure 9b. Amplitude characteristics for water
Rysunek 9b. Charakterystyka amplitudowa dla wody

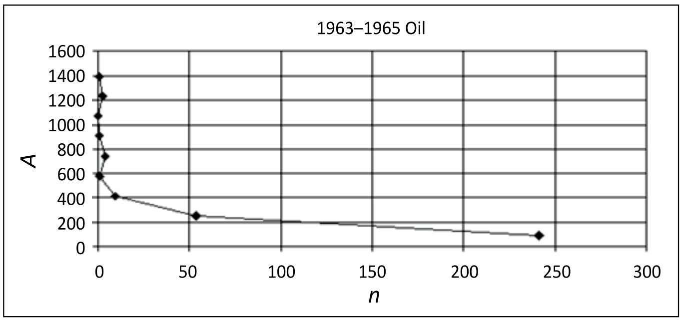


Figure 10a. Amplitude characteristics for oil
Rysunek 10a. Charakterystyka amplitudowa dla ropy naftowej

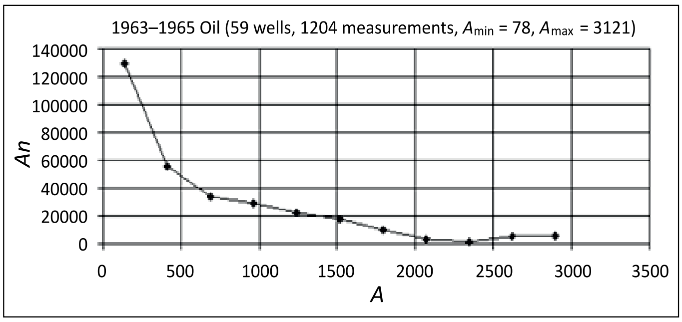


Figure 10b. Amplitude characteristics for oil
Rysunek 10b. Charakterystyka amplitudowa dla ropy naftowej

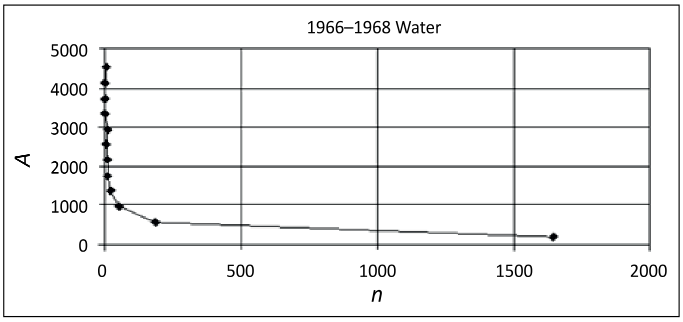


Figure 11a. Amplitude characteristics for water
Rysunek 11a. Charakterystyka amplitudowa dla wody

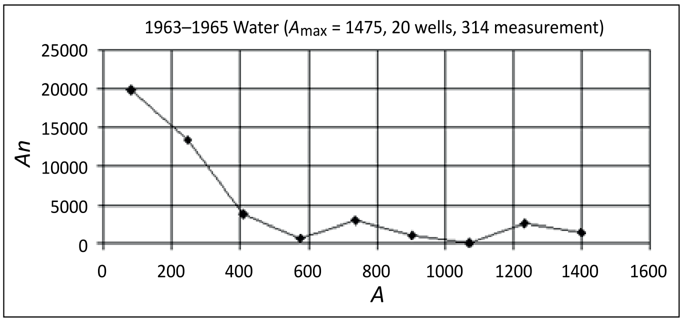


Figure 11b. Amplitude characteristics for water
Rysunek 11b. Charakterystyka amplitudowa dla wody

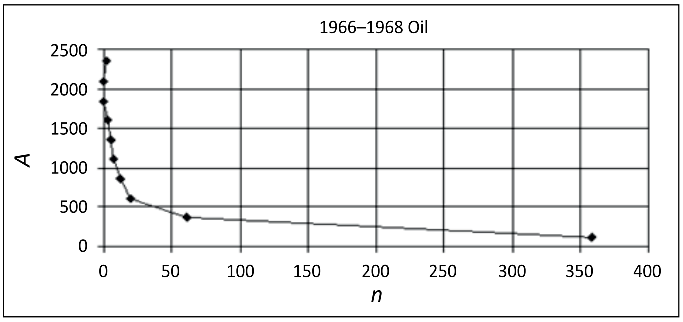


Figure 12a. Amplitude characteristics for oil
Rysunek 12a. Charakterystyka amplitudowa dla ropy naftowej

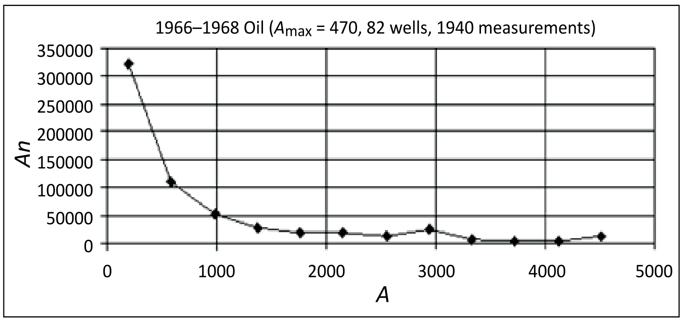


Figure 12b. Amplitude characteristics for oil
Rysunek 12b. Charakterystyka amplitudowa dla ropy naftowej

as: $d = (A_{\max} - A_{\min})/k$. Subsequently, a distribution histogram was constructed depending on the frequency of falling into one or another interval of amplitude change, thereby the process of grouping wells located randomly across the entire area was carried out (Prigojin and Glensdorf, 1973; Prigojin and Stengers, 1986).

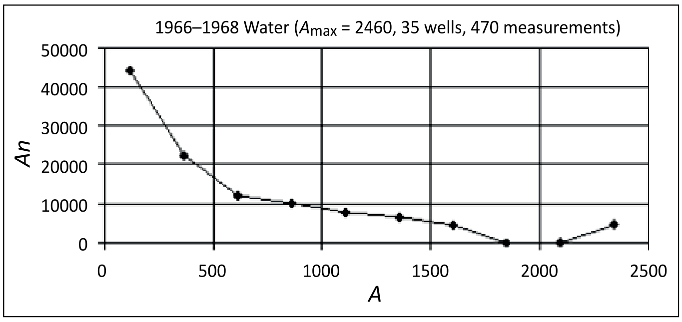


Figure 12c. Amplitude characteristics for water
Rysunek 12c. Charakterystyka amplitudowa dla wody

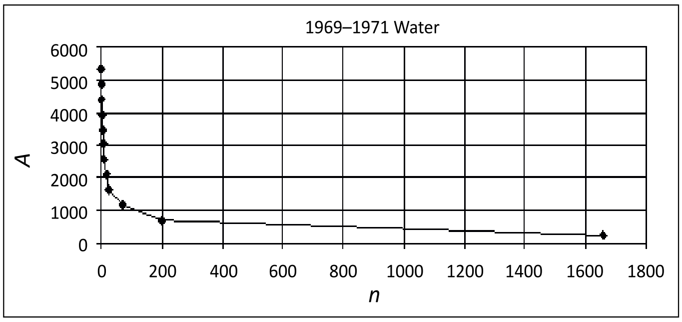


Figure 13a. Amplitude characteristics for water
Rysunek 13a. Charakterystyka amplitudowa dla wody

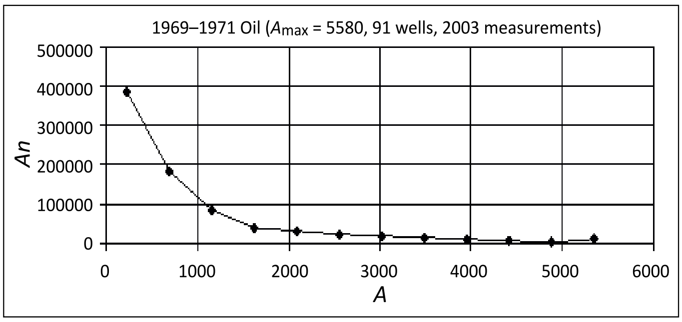


Figure 13b. Amplitude characteristics for oil
Rysunek 13b. Charakterystyka amplitudowa dla ropy naftowej

Such amplitude distribution characteristic is observed for the entire period of operation of the object under consideration (Figures 7–14). It can be observed that the dependency:

$$A\overline{\varpi} = C/A \qquad (3)$$

follows the hyperbolic law. Therefore, the diffusion coefficient $A^2\overline{\varpi}$ remains constant during the individual time intervals under consideration, i.e. $A^2\overline{\varpi} = C$. At the same time, wells that are statistically randomly distributed over the entire area are conditionally divided into three groups: "rich", "poor" and "medium".

It should be noted here that in the process of operation, a transition from one group to another takes place (Peregudov and Tarasenko, 1989).

The proposed approach to the analysis of the production well stock in terms of the amplitude-frequency characteristics of the dynamics of oil, water, "mobile" water, and flooding, as well as the specific ratios of the produced oil to the volume of water injected into the reservoir (an indicator of the effectiveness of water stimulation) allows us to consider the development as a diffusion-like process. At the same time, the diffusion coefficients for oil D_H, D_M, and "mobile" water are variable during development (Figure 15). The dynamics of these coefficients makes it possible to assess the leading role of individual components in the course of operation.

As observed in various physical processes, fluctuations in technological indicators due to the presence of both external and internal influences on the system include the pres-

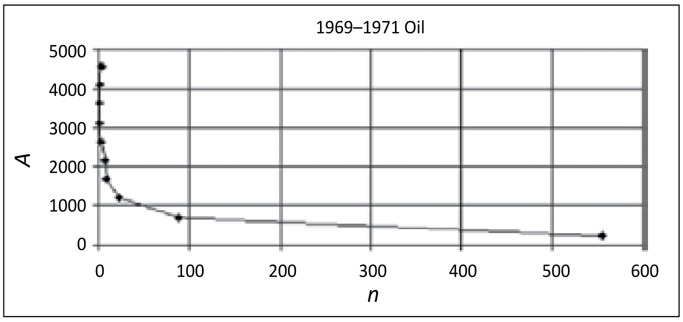


Figure 14a. Amplitude characteristics for oil
Rysunek 14a. Charakterystyka amplitudowa dla ropy naftowej

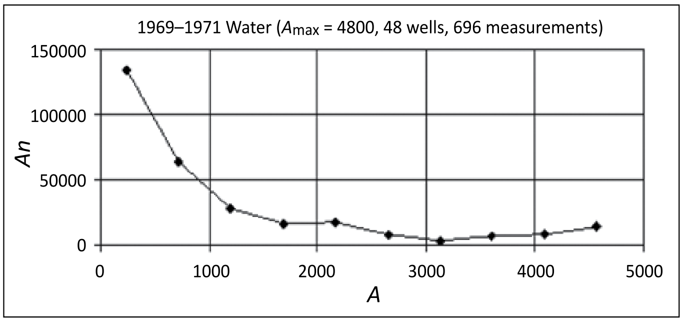


Figure 14b. Amplitude characteristics for water
Rysunek 14b. Charakterystyka amplitudowa dla wody

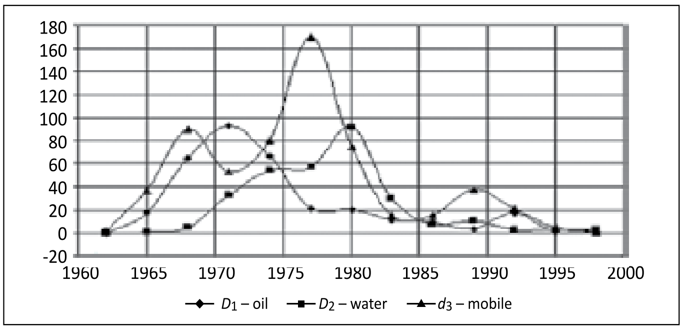


Figure 15. Diffusion coefficient dynamics for oil, water and "mobile" water

Rysunek 15. Dynamika współczynnika dyfuzji dla ropy naftowej, wody i wody „mobilnej"

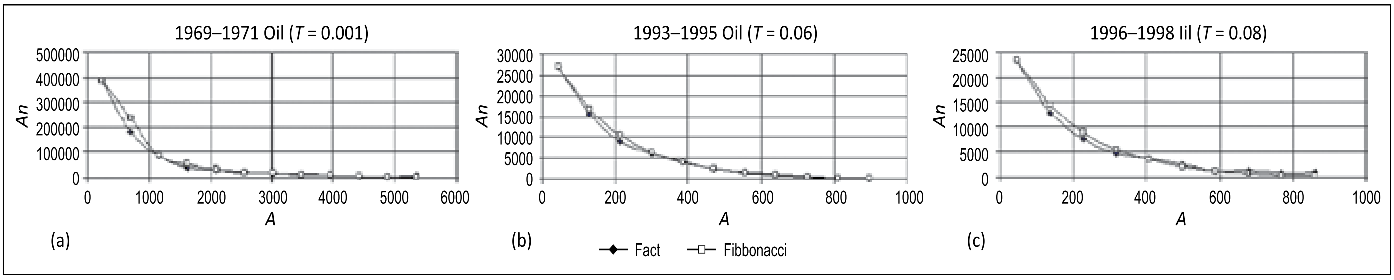


Figure 16. Fibonacci-type sequence for “Past” (a), “Current” (b), “Future” (c) members of the system

Rysunek 16. Ciąg Fibonacciego dla „Przeszłych” (a), „Bieżących” (b), „Przyszłych” (c) elementów systemu

ence of low-amplitude high-frequency oscillations – flicker noise, which serves as a precursor to global changes in the state of the systems under study. It appears that within the flicker noise, certain degrees of freedom of the system accumulate until harmonious pulsations in the “golden” ratio are imprinted on a structure that is just as perfect under given conditions.

The procedure for determining the equilibrium and non-equilibrium of the system is outlined below.

Let the time series $b_1(t)$, $b_2(t)$, $b_3(t)$, ..., $b_n(t)$, ..., describing the hyperbola, be a geometric progression with the denominator q.

Let’s try to answer the question whether a geometric progression can be a Fibonacci-type sequence. If (b_n) is a geometric progression, which is at the same time a Fibonacci-type sequence, then the identities $b_1q^2 = b_1 + b_1q$, $b_1q^3 = b_1q + b_1q^2$, ..., $b_1q^{n-1} = b_1q^{n-2} + b_1q^{n-3}$.

It is evident that each of these relations is obtained from the previous one by multiplying the right and left sides by q. Therefore, if the relation in the first line is satisfied, then all other relations are also satisfied. This means that a geometric progression can be a Fibonacci-type sequence if and only if $b_1q^2 = b_1 + b_1q$.

Let's assume that $b_1 \neq 0$. Then the right and left parts of this ratio can be divided by b_1, yielding the equation $q^2 = 1 + q$.

This means that a geometric progression is a Fibonacci-type sequence if and only if is the root of the resulting quadratic equation. Since all members of a geometric progression are positive, for an increasing progression $q_1 \approx 1.618$, and for a decreasing one $q_2 \approx 0.618$.

The property of the Fibonacci sequence, which allows determination of the next (“future”) member based on the current (“present”) and previous (“past”) members, implies that the system described by such a time series has a “memory”, i.e. is non-equilibrium (Figure 16).

A comparative analysis of all the aforementioned technological indicators enables differentiation of the entire development process into alternating stages – equilibrium and non-equilibrium.

Conclusion

The processes of self-organization as well as transitions from one structure to another, are accompanied by symmetry breaking. Self-organization processes associated with irreversible changes lead to the destruction of old and the emergence of new structures of the reservoir system during the operation of deposits.

An analysis of oil displacement showed that in terms of the rate of change in oil production rates and the proportion of water (second derivatives of cumulative production rates), the nature of the field data distribution, analyzed using the theory of complex systems with reference to a specific field, allows the following conclusion to be drawn:

Since the appearance of water in the well (the 14th month of field operation), the accelerated growth (the second derivative is positive) of the oil production rate (following a geometric progression, the Cauchy distribution) transitions to uniform growth (following an arithmetic progression, the second derivative is equal to zero, the Gaussian distribution). This means that the movement of oil slows down and shifts to uniform filtration with a constant rate, and vice versa. This must be taken into account when waterflooding an oil field.

It has been determined that when managing a deposit, it is necessary to take into account the dynamic characteristics of diffusion processes occurring in the reservoir.

References

Ebeling V., 1979. Formation of structures in irreversible processes. *Mir, Moscow*, 273.

Forrester J.B., 1977. Anti-intuitive behavior of complex systems. *Knowledge, Moscow*, 325.

Haken G., 1980. Synergetics. *Mir, Moscow*. 405.

Haken G., 1985. Synergetics. Hierarchy of instabilities in self-organizing systems and devices. *Mir, Moscow*, 420.

Mandelbroijt B., 2002. Fractal geometry of nature. *Institute of Computer Research, Moscow*, 656.

Mirzajanzade A.Kh., 1986. Decision making in oil production. Central Board of Scientific and Technical Societies Oil and Gas Industry named after Gubkin I.M. *Ministry of the Oil Industry of USSR, Moscow*, 40.

Mirzadzhanzade A.Kh., Shahverdiyev A.Kh., 1997. Dynamic Processes in Oil and Gas Production: System Analysis, Diagnosis, Forecast. *"Nauka" Publishing House, Moscow*, 254.

Mirzajanzade A.Kh., Aliyev N.A., Yusifzade H.B. et al., 1997. Fragments of the development of offshore oil and gas fields. *"Elm" ("Science") Publishing House, Baku*, 408.

Mirzajanzade A.Kh., Filippov V.P., Ametov I.M., 2002. System methods in oil production. *"Technics" Publishing House, Moscow*, 143.

Mirzajanzade A.Kh., Khasanov M.M., Bakhtizin R.N., 2004. Modeling of oil and gas production processes. *Institute of Computer Research, Moscow-Izhevsk*, 368.

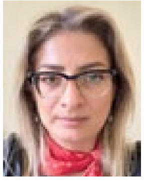
Peregudov F.I., Tarasenko F.P., 1989. Introduction to system analysis. *Higher School, Moscow*, 368.

Prigojin I., Glensdorf P., 1973, Thermodynamic theory of structures, stability and fluctuations. *Mir, Moscow*, 280.

Prigojin I., Stengers I., 1986. Order out of chaos. *Progress, Moscow*, 280.

Salavatov T.Sh., Mammad-zade R.B. et al., 2009. The New Concept of Oil Field Development Dynamics. *Azerbaijan Oil Industry, Baku, Azerbaijan*, 1: 61–65.

Aziz Vali MAMMADOV, Ph.D.
Assistant Professor at the Department of Oil and Gas Engineering
Azerbaijan State Oil and Industry University
34 Azadliq Ave., AZ1010 Baku, Azerbaijan
E-mail: *azizmamedov00@gmail.com*



Arzu Vagif SULTANOVA, M.Sc.
Scientific Researcher at the Scientific Research Institute "Geotechnological Problems of Oil, Gas & Chemistry"
Azerbaijan State Oil and Industry University
34 Azadliq Ave., Baku AZ1010, Azerbaijan
E-mail: *arzu.sultanova.va@asoiu.edu.az*

Ramil Mukhtar MAMMADOV, M.Sc.
Assistant at the Department of Oil and Gas Engineering
Azerbaijan State Oil and Industry University
34 Azadliq Ave., AZ1010 Baku, Azerbaijan
E-mail: *ramil.mammadov.mu@asoiu.edu.az*

OFERTA BADAWCZA ZAKŁADU INŻYNIERII NAFTOWEJ

- analiza przyczyn oraz badania stopnia uszkodzenia skał zbiornikowych w strefie przyotworowej,
- ocena głębokości infiltracji fazy ciekłej do skał zbiornikowych,
- ocena wpływu roztworów soli i cieczy wiertniczych na skały ilaste strefy przyotworowej,
- pomiary parametrów reologicznych cieczy i niektórych ciał stałych w zakresie temperatur od –40 do 200°C oraz ciśnień do 150 bar,
- ocena stateczności ścian otworów wiertniczych,
- symulacja eksploatacji kawernowych podziemnych magazynów gazu ziemnego wykonanych w utworach solnych, z uwzględnieniem konwergencji komór,
- zastosowanie technologii mikrobiologicznych do stymulacji odwiertów oraz usuwania osadów parafinowych w odwiertach i instalacjach napowierzchniowych,
- projektowanie zabiegów mikrobiologicznej intensyfikacji wydobycia ropy (MEOR),
- projektowanie zabiegów odcinania dopływu wód złożowych do odwiertów,
- określanie nieredukowalnego nasycenia próbek skały wodą złożową,
- testy zawadniania z użyciem wody, solanki lub CO_2,
- fotograficzne dokumentowanie rdzeni wiertniczych wraz z dowiązaniem wyników badań laboratoryjnych i innych informacji,
- określanie właściwości mechanicznych oraz sejsmoakustycznych skał w próbach okruchowych,
- oznaczenie kątów kontaktu, napięć powierzchniowych i międzyfazowych,
- badania ściśliwości przestrzeni porowej skał,
- analiza zjawisk migracji i ekshalacji gazu ziemnego oraz występowania ciśnień w przestrzeniach międzyrurowych,
- interpretacja wyników opróbowań i testów hydrodynamicznych metodami oprogramowaniem autorstwa INiG–PIB, określanie zdolności produkcyjnej odwiertów,
- opracowywanie specjalistycznego oprogramowania z zakresu inżynierii naftowej.

Kierownik: dr inż. Renata Cicha-Szot Adres: ul. Lubicz 25 A, 31-503 Kraków
Telefon: 12 617 76 65 Faks: 12 430 38 85 E-mail: renata.cicha-szot@inig.pl

INSTYTUT NAFTY I GAZU
– Państwowy Instytut Badawczy