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Статья / Article

Modeling of the Dynamics of Fractal Characteristics of Micro-Fractured Fluid-Saturated Reservoirs while their Deformation

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Моделирование динамики фрактальных характеристик микротрещиноватых флюидонасыщенных коллекторов при деформировании

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One of the primary factors that affects the effectiveness of the processing of oil and gas deposits is the natural or artificially altered movement of liquid in the formation (hydrodynamic processes). Besides, the natural flow of liquids in the productive layers can be complicated by the factors related to the methods of increasing oil recovery in the layers, such as hydraulic fracturing of layers. Typically, these actions are performed in order to enhance the production of oil and gas, as well as improve the efficiency of oil extraction. Nevertheless, due to these activities, the productive reservoirs, which are porous and permeable matters, change into different stress conditions (destructive states). These conditions are identified by the amount of fissures within a single volume (unit) of rock and the specific pattern of fluid flow within reservoir. This article is reflecting investigations on how reservoirs deform and develop a system of fractures with a fractal pattern. Additionally, a model, which explains how these cracks system are generated, considering the changes in the fractal dimension of the media.
According to the conducted researches, further phases of the process of formation of cracks have been pointed out. First, several initial cracks occur which have a chaotic disordered arrangement. Simultaneously, the fractal dimension of the system increases to a value of 1.6. During the subsequent phase, as the fractal dimension gradually rises from 1.6 to 1.73, the initial cracks start merging and creating a ruptured area. Next, the fractal dimension remains relatively stable, and once it reaches 1.75, there is a sudden break or disruption in the integrity of the medium. The reasons for possible inconsistency is in simulated crack formation, which can be attributed to the presence of multiple levels of heterogeneity and defects within real geological materials. These variations occur because of fluctuating micro- and macro stresses that are distributed among these heterogeneities.

Ключевые слова:
движение флюида в трещиноватых нефтяных коллекторах, фрактальная размерность системы трещин в горных породах, насыщенные флюидом коллекторы.

Одним из основных факторов, влияющих на эффективность разработки нефтяных и газовых месторождений, является естественное или искусственно создаваемое движение жидких сред в пласте (гидродинамические процессы). Кроме этого, естественный приток жидкостей в продуктиваных пластах усложняется воздействием факторов, связанных с методами повышения нефтеотдачи пластов, таких как гидравлический разрыв пласта. В результате внешних воздействий коллекторы, сложенные пористыми и проницаемыми породами, переходят в различные напряженные состояния (деструктивные состояния). При этом изменения свойств коллекторов определяются количеством трещин в пределах одного объема (единицы) породы и специфическим характером движения флюида внутри коллектора. В статье рассматриваются данные вопросы, в том числе процессы деформирования коллекторов с образованием системы трещин с фрактальным рисунком. Кроме того, представленная модель объясняет, как образуются трещины, учитывая изменения во фрактальной размерности среды.
Согласно проведенным исследованиям, выделены следующие фазы процесса образования трещин. Первоначально появляется несколько начальных трещин, которые имеют хаотическое неупорядоченное расположение, при этом фрактальная размерность системы увеличивается до значения 1,6. На следующем этапе, когда фрактальная размерность постепенно растет с 1,6 до 1,73, трещины начинают сливаться и образовывать область разрыва. В дальнейшем фрактальная размерность остается относительно стабильной до значений 1,75, после чего происходит нарушение целостности среды (разрыв). Причины возможного несоответствия предложенных моделей трещинообразования реальным геологическим объектам могут быть объяснены наличием множества уровней их неоднородности, что приводит к возниконвению неучтенных в моделях флюктуаций микро- и макронапряжений.

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Introduction

As is known from the practice of modern oil and gas production, even at the stage of field development design, some losses of "black gold", expressed as the indicator "recoverable reserves", are included [1–3]. That is, such total losses are equal to about 60–70 % of the initial hydrocarbon reserves.

The main cause for such losses is often the natural or artificially altered dynamics of fluid movement within the reservoir. Even in cases where the natural dynamics is favorable, they are often disrupted by technical well operations such as hydraulic fracturing and others used to enhance oil and gas production and increase the oil recovery rate [4–6]. Consequently, construction of deep penetrating hydraulic fractures in the oil reservoir can result in the formation of additional pathways for water, which in turn weakens the flow of oil through the natural fracture network. Particularly, the technique of hydraulic fracturing leads to the destruction of the natural structure of porous and permeable reservoirs containing oil and gas. These reservoirs can pass within various states of destruction, characterized by the number of fractures per unit volume of rock, also known as fractality of fracturing [7–10]. Its volume can be as large as 1 m^3 or as small as 1 cm^3 and can contain a few fractures, numerous fractures, or even be completely fractured to the point where it resembles absolutely loose sand.

In nature, the process of occurrence of cracks in reservoirs occurs because of geostatic, tectonic, etc. stresses, leading to local deformations of the environment. Moreover, the above-mentioned process of rock fracture is nonlinear and Hooke's law of deformation ($F = -k{\cdot}X$) is valid only at the initial stage of deformation. When a certain threshold value reached, the linearity of deformation is broken and stress redistribution (bond breaking) occurs [11–14]. As a result, a branched crack system (secondary cracks) appears in the rock matrix. Such deformation process is suitable for both types of deformations – tensile and shear – common in nature. Characteristic configurations of cracks in both cases have a fractal structure (Fig. 2) with a dimensionality of 1.62 – 1.64.

Research Methodology

The above-described process of fractal crack formation indicates the unpredictability of cracks growth manner, and the similarity of the fractal dimensions of crack systems under tensile and shear deformations proves the impossibility of determining the types of external load based on the orientation of cracks.

In order to identify the existence of the connection between numbers of cracks the values of the corresponding fractal dimension, it is necessary to trace the variation in the values of the fractal dimension of the system during the development of secondary cracks [15]. Since this is practically impossible to do in reality, the process, with a certain degree of reliability could be adequately modeled in the following sequence.

Let us imagine that a square area of surface $a \times a$ is divided into n elementary areas – ΔS, each of which is formed by four rods forming sides (Fig. 3). The figure shows elementary site ΔS, each side of which is a side of the neighboring site and is characterized by its ultimate strength – Pi j.

Let the force F on the line $\left(0,\ \frac{a}{2};\ a\frac{a}{2}\right)$ be applied to the centre of the square a×a linearly decreases from the value of F on the line $\left(0,\ \frac{a}{2};\ a,\ \frac{a}{2}\right)$ to 0 to the edges of the area, i.e. $F = F - \left(\frac{2}{a}\cdot i\right)\cdot F$.

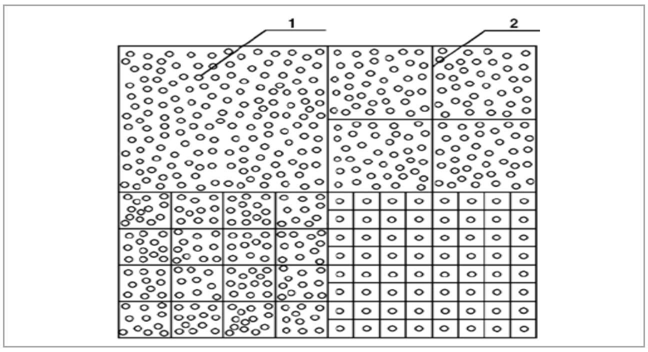
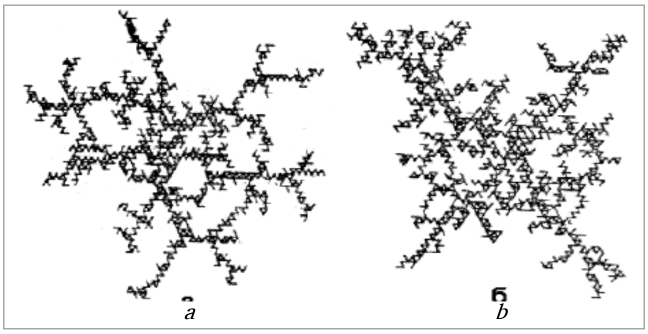


Fig. 1. Fractality of a porous reservoir



Fiq. 2. Fractality of cracks under different types of deformation: *a* – tension; *b* – shear [7]

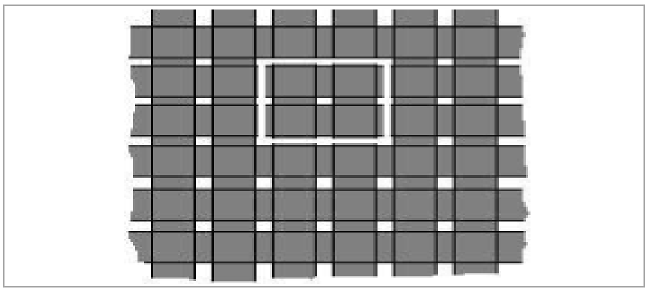
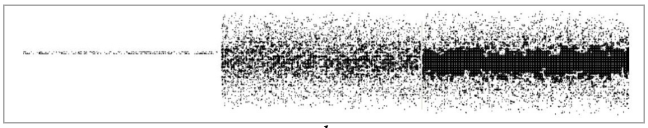


Fig. 3. Elementary areas ΔS [15]



a *b* *c*

Fig. 4. Evolution of the fractals cracks system during loading [15]

Obviously, according to the law of conservation of force, acting on the plane (Sij) by the formula ($F_i = F_{1,i} + F_{2,i} + F_{3,i} + F_{4,i}$), where F_{1i}, F_{2i}, F_{3i}, F_{4i} are the forces acting on the sides of the plane (Sij), it is reasonable to assume that $\left(F_{1i} = F_{2i} = F_{3i} = F_{4i} = \frac{F}{4}\right)$.

For calculation the site with the size 240×240 was chosen. The value of the strength limit Pij was set using a random number generator Pij < 1. Force F = 1. At condition Fij > Pij the side of the platform ΔS is destroyed.

The evolution of the system is as follows. In the first step of modelling individual cracks appear (Fig. 4, *a*). In subsequent steps they start to merge (Fig. 4, *b*) and finally a single fracture is formed (Fig. 4, *c*).

The fractal dimension of the system changes from 0 to 1.75, and the fractal dimension increases rapidly at first, a chaotic system of cracks is formed, and the fractal dimension approaches the value of 1.6. Then the cracks start to unite and form a fracture region, the fractal dimension slowly increases from 1.6 to 1.73. Once this value is reached, the fractal dimensionality of the rupture, in subsequent modelling steps, remains almost unchanged (Fig. 5). The collapses of the sides of the elementary square area are concentrated along the interaction line. Completing the formation of the rupture, its body is formed which is a fractal cluster, accompanied by a chaotic system of cracks, the fractal dimension increases slightly to 1.75. At the subsequent steps of modelling the formation of new fractures stop.

Discussion of Results

During of elastic cracking process, the total energy of the system decreases with time, so it can be argued that the more cracks grow, the more stable the system becomes; when the energy is exhausted, crack growth stops. Thus, the results of calculation of evolution and fracture zone show that fractal dimension can be used as a quantitative criterion for diagnosing the processes of self-organization of fault systems.

At the same time, real geological media most often possess a certain multilevel heterogeneity of internal structure and defectively of different hierarchical levels [16–24]. In this connection, as well as taking into account fluctuations of micro- and macro-stress distribution on these heterogeneities, obtaining specific characteristics of geometrically similar samples revealed that along with the factors confirming the law of similarity, significant deviations from this law are also observed. Since the observed deviation is a consequence of geometrical dimensions of solid deformable bodies, the causes of this deviation are related to the scale factor, and the phenomenon itself is called the scale effect [25–32]. In particular, for a continuous closed curve γ possessing the properties of homogeneity and self-similarity, the power law is valid [25–26] at constant D (Hausdorff dimension) along this curve.

$$L\eta = \lambda\eta^{1-D}, \tag{1}$$

when D above (>) 1, the curve is a fractal. Here $L\eta$ – is the length of the broken line approximating this curve, composed of segments of constant length η. The homogeneity of the curve means that all sections of the curve between adjacent vertices of the approximating broken line with links of length η create the same number of segments on the approximating broken line with links of length $\xi < \eta$, and the property of self-similarity means that the curve is similar in its part. So the number of segments of a polyline with link length ξ that fit between neighbouring vertices of a poly line with link length η depends only on the ratio η/ξ, but not on η and ξ separately.

However, the properties of homogeneity and self-similarity of a curve are not necessary for a continuous curve to be a fractal; it is sufficient to consider the essentially weaker properties of its local homogeneity and local self-similarity. This means that for any point of the curve one can specify a small neighborhoodΔ in which the curve is characterized by the following property:

– the principal term of the asymptotic representation of the number of vertices $N\xi\eta$ of an approximating poly line with link length ξ between two neighboring vertices of the poly line located in the neighborhood Δ, with link length η, depends only on the ratio η/ξ:

– when $\eta/\xi \to \infty$, i.e., when the ratio $\eta/\xi >> 1$ is fixed, there is a dependence on the ratio $\eta/\xi \to \infty$.

$$N_{\xi\eta} = f(\eta/\xi). \tag{2}$$

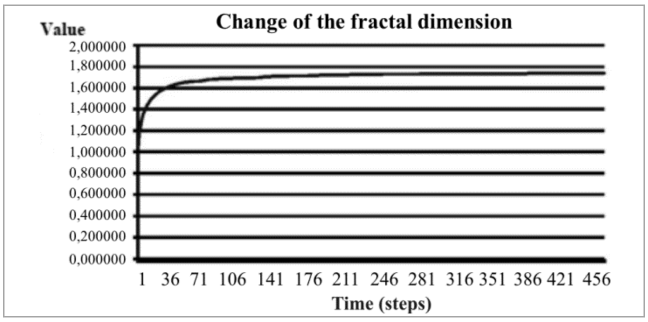


Fig. 5. Change in the fractal dimension of the system during the experiment [15]

For the lengths of approximating broken lines in the neighborhood of each point of a continuous curve having the properties of local homogeneity and local self-similarity, the steppeasymptotic relation is valid [33–38]:

$$L_{\xi} - \eta^{D}\xi^{1-D} + \ldots, \tag{3}$$

where the dots denote values small compared to the first term (this also includes the contribution from the extreme links, which may be fractional). If $D > 1$ throughout the curve, it means that the curve under consideration is fractal. The length of a broken line approximating a continuous curve between two points of the curve at a distance η depends on two-dimensional parameters: η and the length of a link of the line ξ.

From the analysis of dimensions we obtain

$$L_{\eta} = \eta\Phi(\eta/\xi). \tag{4}$$

For a smooth (or piecewise smooth) curve $\xi \to 0$, i.e., when $\eta/\xi \to \infty$, the function Φ tends to a finite limit $\Phi(\infty)$. By definition, the value

$$L_0 = \eta\,\Phi(\infty) \tag{5}$$

is the length of the segment of the smooth curve between two points of the smooth curve, which are separated by distance η. Thus, for smooth curves when $\eta/\xi \to \infty$ there is full auto modeling in the parameter η/ξ.

For fractal curves, there is no finite limit to the function Φ ($\eta\xi$) when $\eta/\xi \to \infty$; this limit is infinity. However, it follows from the above asymptotic representation (3) for $L\xi$ that when $\eta/\xi \to \infty$ the function Φ ($\eta\xi$) has a stepped asymptotic representation

$$\Phi(\eta/\xi) = (\eta/\xi)^{D-1}, \tag{6}$$

i.e. at $\eta/\xi \to \infty$ there is incomplete auto modelling by the parameter η/ξ.

Thus, passing from geometrical images to physical objects represented by them, one can easily establish fractality and incomplete auto modelling by the parameter η/ξ.

In the framework of linear fracture mechanics, it is acceptable (see [39]) to model fractal crack propagation in brittle material based on the classical Griffiths criterion. This is possible given that the stress intensity factor depends on the load, the average crack size and its fractal dimension [39]. In this case, we proceed from the fact that the surface of a fracture or crack formed during the fracture of most brittle materials is very irregular and characterized by the presence of irregularities of various sizes – jagged, peaks, ridges, etc. Therefore, a real crack is far from that idealization of a crack with smooth sides, which is considered in linear fracture mechanics. A real crack has a "saw tooth" or "zigzag" structure of the Koch curve type, depending on the scale of consideration [40].

In the case of purely brittle fracture, forces of molecular bonding are also manifested additionally. These forces together with the forces G(s) grouped under the general name of cohesive forces. So, finally must be taken into account following additional dimensional indexes: such as the crack head size d, which is determined by the load and material structure, and the characteristic value of the cohesive forces G_0.

Numerous observations show that the following hypotheses are valid for a large class of practically important cases of brittle and quasi-brittle fracture [41–46]:

1) Insignificant dimensions of the head compared to the crack size l ($d/L << 1$);

2) Autonomy of the head, i.e., the identity in the state of mobile equilibrium of the heads (and, consequently, of the bonding forces generated by them) for all cracks in a given material under given external conditions. The mobile equilibrium corresponds to the maximum bonding forces, so that at the slightest increase in load the crack instantly begins to propagate.

The autonomy of the crack head is explained by the fact that the characteristic value of the applied loads σ_0 is much smaller than the characteristic value of the cohesive forces G_0 ($\sigma_0/G_0 << 1$). Therefore, the theory of brittle (and quasi-brittle) fracture is intermediate-asymptotic, and it turns out that not each of the constants d and G_0 separately is significant: the only material constant, in addition to the constants of the theory of elasticity, is the cohesive (adhesion) modulus or crack resistance:

$$K = \int_0^d (G_s) d_s / \sqrt{S}; \; K \sim G_0 \sqrt{d}.$$

The modulus of adhesion, which has the dimension kgf/sm$^{3/2}$, is an independent characteristic of the strength properties of the material and characterises the resistance of the material to crack propagation.

For example, the values of the modulus of adhesion for structural steel are $K \sim 2.5 \cdot 10^4$ kgf/sm$^{3/2}$, and for duraluminium – $K \sim 10^4$ kgf/sm$^{3/2}$.

The adhesion modulus K introduced by Barenblatt in [33] should be distinguished from the material strength characteristic K_{If} introduced by Irwin [47] at about the same time and determined by the onset of catastrophic crack development. Catastrophic crack development requires instability of the initial mobile-equilibrium state. An autonomous crack head may not have time to form before crack propagation begins from the unstable state [48–50]. Hence, there is a large variation in the determination of kgf.

The appearance of one determining parameter $K \sim G_0 \sqrt{d}$ instead of two parameters d and G_0 is a typical manifestation of incomplete automodelling by the parameter G_0/σ_0 when $G_0/\sigma_0 \to \infty$. The cohesion modulus (fracture resistance) is one of the significant parameters in the formulation of the laws of similarity of brittle and quasi-brittle fracture.

Conclusion

The process of deformation of porous and permeable reservoirs with the formation of a branched fracture system with fractal structure is considered.

The model of connection between the process of fracture formation and changes in the fractal dimensionality of the system is described according to which at the initial stage of fracture formation a chaotic system of fractures appears, accompanied by the growth of the fractal dimensionality of the system up to the value of 1.6. At the next stage, with slow growth of fractal dimensionality from 1.6 to 1.73, cracks begin to unite and form a "mirror" fracture. Then the fractal dimensionality practically does not change and when the value of 1.75 is reached the continuity of the medium is ruptured.

Inevitable deviations of simulated media from the described regularity in the process of crack formation are explained by the fact that real geological media most often have a certain multilevel heterogeneity of internal structure and defectively of different hierarchical levels, which leads to fluctuations in the distribution of micro- and macro stresses on these heterogeneities.

The observed deviations are a consequence of geometrical dimensions of solid deformable bodies and are related to the scale factor.

Estimation of the scale factor is possible by comparing the calculated fractality and auto modelling indices of geometrical images and corresponding physical objects.

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