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Article

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IMPROVED METHODOLOGY DEVELOPMENT FOR ASSESSING THE RESERVOIR COLLECTOR PROPERTIES BY THE QUANTITATIVE RESERVOIR CHARACTERIZATION TOOLS

The object of research in the paper is the process of fluid transfer through the pore space of the reservoir rock. In this paper, using an expert method, the shortcomings of the Ukrainian methodology for assessing the reservoir properties of the reservoir were highlighted. In particular, the sources of uncertainty accumulation in determining the absolute values of the reservoir's filtration parameters have been identified. The existing problem is that the algorithms of actions, which are the basis of the Ukrainian method of assessing reservoir properties, introduce a significant degree of uncertainty into the assessment results.

In order to reduce uncertainty, the introduction of the concept of a representative elemental volume is considered when conducting laboratory research and the construction of a three-dimensional digital model of this elementary volume. It is suggested to improve the Ukrainian method of assessing the collector properties of the deposit based on current Western research.

It was established that the standard methods of assessing the reservoir properties of the deposit are a source of accumulation of uncertainty in the development of technological documentation for the development of the deposit. The work is aimed at the development of an improved methodology for assessing the collector properties of the deposit. It is proposed to add to the action algorithm the stage of determining the representative volume of the sample, building its three-dimensional model, and digitizing it. At the final stage, the connectivity of the pores inside the sample is determined using the Minkowski function to improve the quality of the project documentation for the development of deposits. Guidelines have been developed to improve standard methods for assessing the collector properties of the deposit. The use of an improved methodology for assessing the reservoir properties of the deposit leads to a significantly lower degree of uncertainty and helps to form a more reliable picture of the operation of the reservoir at the design stage of its development. The presented study will be useful for the engineering personnel of foreign contractor companies, as it justifies the need to collect additional core material and sets the quality criteria of the information obtained about the collector properties of the deposit.

Keywords: *fluid transfer, pore space, reservoir rock, uncertainty degree, representative elementary volume, Minkowski functions.*

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1. Introduction

A fundamental goal of most studies of porous media is to relate pore structure to hydraulic functions such as permeability, capillary pressure, and diffusivity, which are required for engineering applications [1]. It is possible to establish a direct relationship between filtration behavior and morphological indicators of various porous media [2]. The porous layering of rocks with different structure and morphology is formed by the random stacking of grains of different shapes and sizes. The relative performance of different porous media in the aforementioned applications is highly dependent on the internal pore structure of each material.

Therefore, the method of reliable determination of the size and geometry of the pores, their connectivity, and their influence on mass transfer processes is an actual problem for the full characterization of various properties of porous materials.

In the international sources of literature, the term «connectivity» is identical to the term «effective porosity». The analog of the term «connectivity» in the Ukrainian reference books is the term «open porosity», while the term «effective porosity» in the Ukrainian methodological guidelines is open porosity, except for the share of the pore space volume that is occupied by residual water.

The determination of the open and effective porosity coefficient according to the standards of Ukraine is mainly carried out in the prospecting and exploration stage with the aim of discovering an oil or gas field, determining its reserves, and designing a development project. The complex of prospecting works includes field geological, geophysical, and geochemical works with subsequent drilling of wells, which allows exploration of the deposit. As the drilled wells grow, the number of samples of the rock (core) under investigation increases. The results of the coefficients of effective porosity of the corresponding samples relative to the depth of the well are entered in the table. This makes it possible to separate porous layers from dense ones, in conjunction with log charts to determine perforation intervals, to calculate the average coefficient of effective porosity of the layer, which affects the calculation of reserves, to determine the radius of the drainage area and the flow rate of the well.

The object of research is a fluid transfer process through the pore space of the reservoir rock.

The purpose of research is the improvement of the Ukrainian method of assessing the reservoir properties of the deposit by adding to the algorithm the stages of determining the representative volume of the sample and building its three-dimensional digital model with the determination of pore connectivity using the Minkowski function.

2. Research methodology

There are methodological guidelines approved for determining open and effective porosity coefficients: Standard of the State Geological Service of Ukraine «Determination of Open and Effective Porosity Coefficients of Rocks». The methodology of the approved document provides for the following procedure: the sample is extracted in chloroform (Soxhlet apparatus), dried, and weighed, after which it is saturated with kerosene for 72 hours (PORP-3 installation), weighed again, after which the weight is hydrostatically measured (Archimedes installation).

The coefficient of open porosity (K_n) is calculated as the ratio of the volume of the void space of the rock sample to its external volume:

$$K_n = \frac{M_3 - M_1}{M_3 - M_2} \cdot 100,$$

where M_1 is the mass of the dry rock sample, g; M_2 is the mass of the liquid-saturated rock sample in the saturating liquid, g; M_3 is the mass of a liquid-saturated sample in air, g.

The volume of open pores, excluding the portion of the volume of the pore space that is occupied by residual water, in petroleum geology is called effective porosity (K_{pef}) (in hydrodynamics – dynamic porosity), which is determined according to the formula:

$$K_{pef} = K_p \cdot (1 - K_{rw}),$$

where K_p – coefficient of open porosity, %; K_{rw} – coefficient of residual water saturation (part of the volume of pore space occupied by water), which is determined according to DSTU 41-00032626-00-025-2000 on rock samples in which open porosity was determined.

The final result of the coefficient of effective porosity is the value that is used further for:

– calculation of reserves in the Geological and Economic Assessment (GEA);
– calculation of debits in the Technical and Economic Assessment (TEA);
– selection of perforation intervals at the Research and Industrial stage;
– selection of design wells.

According to the Ukrainian methodology, the sample is saturated without the influence of pressure. This can lead to a significant error in determining the coefficient of open and effective porosity, since the sample may contain counted cracks that change their volume on the surface and underground. In surface conditions, pressure does not act on the sample, so the filled crack can expand in volume when absorbing fluid. This process may not occur in the Earth's interior in the presence of high pressures [3]. Also, cracks are usually filled with a different composition of rocks, which is different from the main studied sample. The porosity of the recorded crack is not representative of the entire sample and introduces significant uncertainty if it is not visible but present in the sample.

3. Research results and discussion

Western sources [2, 4, 5] provide for scanning the sample with X-ray radiation, obtaining a high-resolution image, and subsequent reproduction in three-dimensional space. Such a model reflects all present cracks inside the sample. It allows calculating all voids, pore space, connectivity of pores, and permeability, and to take into account and reproduce the geometry of the porous sample and rock, which directly affects the filtration characteristics. It answers the question of how the fluid will flow in the pore space, and in the future, it makes it possible to directly simulate the processes of displacement, flooding, and oil and gas release.

Pore space reconstruction does overcome some of the limitations of direct imaging, but even then it does not address how to quantify filtration and mass transfer in these models. This requires some degree of simplification of the void geometry and connectivity after some important and basic definitions are introduced.

To scan the pore space, X-rays are used to construct three-dimensional images with micron resolution. The principles and methodology used to construct the image are similar to those used in computed tomography for medical examinations [4]. Next, visualization and image analysis are carried out [5–7].

X-ray scanning is useful because there is a clear contrast between the rock that absorbs X-rays strongly and fluids that are more transparent to X-rays. This makes it easy to distinguish between the solid rock and the pore space, and also, thanks to the careful design of the experiment, between the liquid phases. X-rays show both the porous media themselves and the chemical, biological, and flow processes occurring in them [8].

Statistical and process reconstruction of pore space involves two approaches to the reconstruction of pore space images. The first simulates grain packing in combination with compaction and cementation. Such modeling tries to simulate the sedimentary processes by which the rock was formed. This technique was used to reconstruct sandstones and calculate the characteristics of filtration in the pore space [9]. Theoretically, these models have infinite resolution. However, typically the resulting packing is then discretized to enable pore structure analysis and flow simulation [10, 11]. The second approach uses statistical methods to directly create a discretized image [12]. The simplest methods reproduce one- and two-point correlation functions of the pore space, determined from the analysis of reference (or training) images (where the indicator value 0 is assigned to a void and 1 to a solid body). The training image is a high-quality two-dimensional thin section from which a three-dimensional image of the pore space is constructed [13–15].

The method of determining the coefficient of average effective porosity of the formation according to the Standard of the State Geological Service of Ukraine consists in finding the average value of the coefficient of effective porosity of the entire studied sample of the core material. Sampling takes place at certain intervals of occurrence in the depth of the formation, which also introduces uncertainty regarding the value of the average effective porosity of the formation as a whole.

In the sources [2–5], at any stage of scaling, there is the concept of representative elementary volume (*REV*) – the minimum volume of the investigated rock sample, which is necessary for an averaged representative display of any characteristic of this sample, stratum, deposit, when in which the error value does not exceed 0.5 %. *REV* depends on the selected characteristic being investigated, as well as on the size of the volume of the space being investigated.

Determining the minimum volume of the sample for the studied characteristic (porosity, connectivity), under the condition of an error of no more than 0.5 %, qualitatively reduces the uncertainty of certain studied characteristic, which directly proportionally increases the accuracy of the obtained results.

For a spatially dependent variable f, determined in the pore space, the average value $F \equiv \overline{f}$ by volume V can be determined by the formula:

$$F = \frac{1}{V}\int f \mathrm{d}V,$$

where the integral can be both over a vacuum and over a solid body (where $f=0$).

For porosity $F \equiv \varphi$, $f=1$ in the pore space; for saturation phase p, $F \equiv \varphi S_p$ and $f=1$, where phase p is present in the pore space.

For the statistical descriptions of the pore space mentioned above, the size of the *REV* can be estimated from the correlation length of the local porosity or associated path length [4]. In rock samples, a volume spanning a few grains is generally sufficient to determine porosity, while a larger volume is required for saturation, as this is controlled by the dynamics of the process by which fluids are displaced. For flow properties, especially when multiple phases are present, the *REV* is even larger because it now depends on the relationship between the pore space and the fluids within it [16]. As an example, Fig. 1 illustrates the average porosity calculated by the formula *REV*.

Minkowski functionals are the basic geometric measures defined for binary structures. Hence, the image for analysis needs to be segmented into structure and background, in our case pores and solids, as detailed below. There are four such functionals for a three-dimensional object.

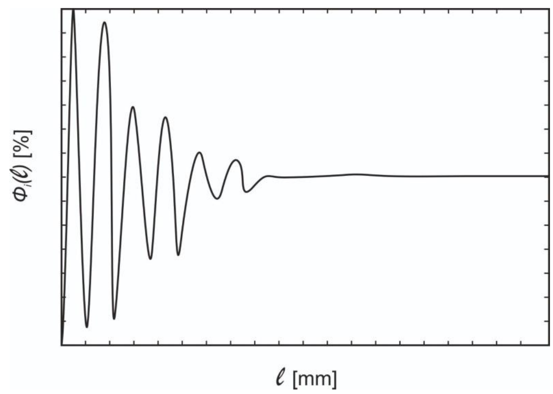

Fig. 1. Schematic representation of porosity averaged over cubes of different lengths *l* using the representative elementary volume (*REV*) equation

The zero-order Minkowski functional M_0 is the volume of the pore space. The pore size distribution defined by M_0 can be directly related to the distribution of wetting and non-wetting fluids in the pore space. The assumption that follows from this interpretation is that the interface between different fluids is spherical according to the procedure of morphological «opening» using spherical structural elements. This interpretation has already been successfully used to estimate the hydraulic properties of the rock [2, 17].

The remaining three functionals are defined on the surface between the solid and the grain. The first-order functional M_1 is the total surface area of pores. The surface density as a function of pore size, which is calculated from the M_1 functional, can potentially be used to estimate the active pore-solid interface with respect to the chemical interaction of solutes. The second Minkowski functional (M_2) is the average curvature of the boundary between a solid and a void (Fig. 2). Average curvature can be a significant measure of the mechanical properties of rocks and other porous media. The third-order Minkowski functional (M_3) is related to the Euler characteristic, χ, which is the well-known ratio between the number of edges, faces, and vertices of a polyhedron. To do this, let's generalize the relation to arbitrary shapes defining the pore space [18–20]. M_3 is a dimensionless topological measure that quantifies pattern connectivity, while M_0, M_1, and M_2 are the metric units of $[L^3]$, $[L^2]$, and $[L]$, respectively.

Establishing connectivity involves building a three-dimensional model of the pore medium, which later makes it possible to model filtration processes in the formation (flooding, displacement of fluid).

The four sublevels are analyzed separately to illustrate the spatial variability in terms of Minkowski functions.

The first graph (Fig. 3) illustrates the pore size distribution and shows a clear peak at a certain pore diameter. Sandstones mainly have this trend of pore diameter distribution.

The second graph (Fig. 4) shows how the surface density increases with a decrease in the minimum size of the considered pores. By the shape of the curve, it is possible to observe how rapidly decreases the volume of small pores, which become present when the minimum diameter decreases, as more features of the surface of the grains are revealed. The choice of the minimum pore diameter and the covered surface density in further studies will be determined by hydrodynamic characteristics (wetting angle, capillary pressure, and surface tension force). This will make it possible to model filtration processes in the investigated rock sample as accurately as possible.

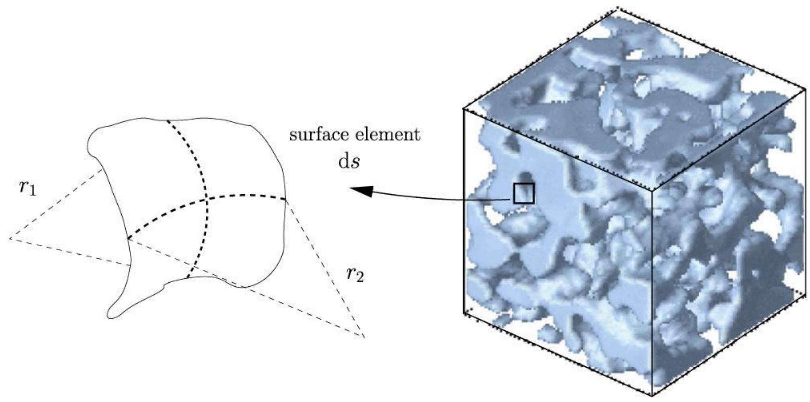

Fig. 2. An example of a three-dimensional porous structure with a pore-solid boundary and an illustration of the locally determined principal curvature radii for the second and third Minkowski functionals (M_2, M_3), where r_1 and r_2 are the principal curvature radii that determine the curvature κ [1]

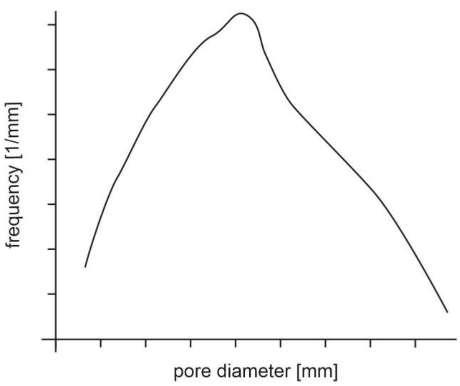

Fig. 3. Schematic representation of the meeting frequency of the pore diameter in the porous medium

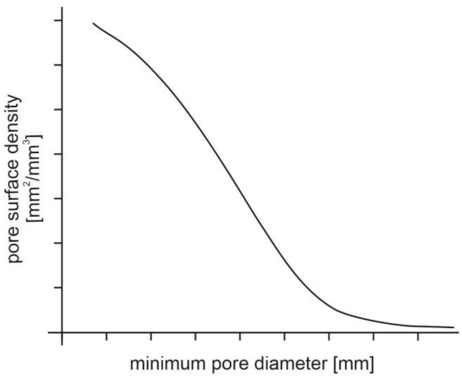

Fig. 4. Schematic representation of the Minkowski functional of the first order (M_1), the dependence of the surface density of pores on the minimum diameter of pores

The average curvature function shown in the third graph (Fig. 5) shows the general trend of pore convexity. For example, a graph of this type indicates that when considering large pores, or when reducing the considered diameter to a conventionally average size, the tendency of the convexity of the pore space increases. After a further decrease in diameter, when smaller pores are detected and smaller elements are taken into account, the tendency of convexity decreases. Thus, the average curvature becomes negative, since both small protrusions and gaps in the pore space are included.

The connectivity of the pore space is low when only large pores are considered, which is expressed by the positive Euler numbers from the fourth graph (Fig. 6). However, if smaller pores of smaller diameter are added, the pore space becomes highly connected, which is reflected in the decrease of the Euler number. For example, a graph illustrating the Euler number versus the chosen minimum pore diameter becomes negative because a smaller diameter allows more bonds to be accounted for. Thus, it can be seen from the graph that the Euler number close to zero indicates limited connectivity, since the selected minimum pore diameter is simultaneously the average pore size. If to allow only the larger pores to be considered, the connectivity of the void space is lost.

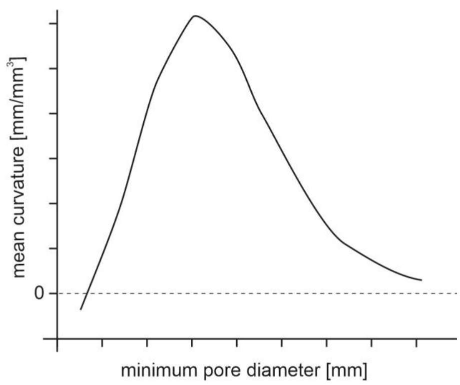

Fig. 5. Schematic representation of the Minkowski functional of the second order (M_2), the dependence of the average curvature of the porous medium on the minimum pore diameter

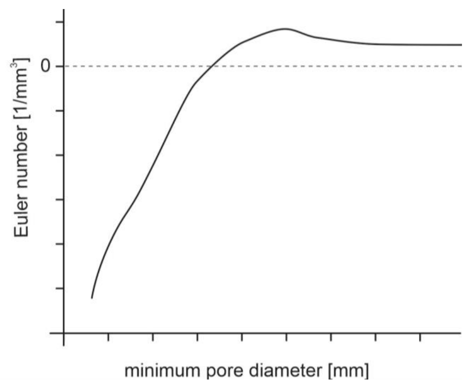

Fig. 6. Schematic representation of the dependence of the Euler number on the minimum pore diameter, including the third-order Minkowski functional (M_3)

Quantification of complex pore structures in rock based on Minkowski functions is effective and based on rigorous mathematical justification. After binary image conversion,

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which is always an important step in image analysis, the evaluation becomes simple and highly computationally efficient. The Minkowski function makes it possible to determine the connectivity of the rock, its geometry and filtration characteristics quite effectively and precisely, which in the future will allow more accurate determination of perforation intervals, deposit reserves, flow rates, radii of the drainage area, and more effective methods of field intensification and development. In turn, this will give more accurate calculations of the deposit, as well as predict the most effective extraction technology, more appropriate terms of operation. This will reduce the probability of error, increase the efficiency of production, and reduce the cases of unnecessary costs, as well as the associated risks during the search, exploration, development and operation of the deposit.

The limitation of this study is the use of the proposed method exclusively for the description of conventional and fractured oil and gas reservoirs.

A prospective direction of the development of this research is an applied comparative analysis of the traditional and updated method of assessing reservoir properties and a comparison of project solutions with the actual history of the development of the experimental deposit. This is due to the fact that the proposed innovations require careful verification before guidelines for state standards are developed based on them.

4. Conclusions

At this stage of the research, the shortcomings of the standard methods of assessing the reservoir properties of the deposit, which are a source of accumulation of uncertainty in the development of technological documentation for the development of the deposit, were revealed by the expert method.

Based on the analysis of recent sources, it was established that Minkowski functionals are suitable measures for the quantitative determination of complex structures. In combination with the tools of mathematical morphology, Minkowski functions have the potential to link the structural and functional properties of a material, which is relevant not only for natural objects, but also for materials science.

An improved methodology for assessing the reservoir properties of the deposit is proposed, which, due to the stage of determining the representative volume of the sample, will have a lower degree of uncertainty. The need to increase the volume of sampling to achieve representativeness of the sample is substantiated. The improved technique will help to create a more reliable picture of the operation of the reservoir at the design stage of its development.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other nature that could affect the research and its results presented in this study.

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