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Investigating the Influence of Reservoir Pressure on Porous Media Permeability: A Case Study of Fields in the Perm Region

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Исследование влияния пластового давления на проницаемость поровых коллекторов (на примере месторождений Пермского края)

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Keywords:
permeability, porosity, effective pressure, reservoir deformation, core, well productivity, pore pressure, deformation bands, pore reservoir, bottomhole formation zone.

Field studies of permeability changes were analyzed using the example of oil fields in the Perm Krai; laboratory studies of the effect of effective pressure on core permeability were carried out. An analysis of existing methods for assessing changes in rock permeability depending on effective pressure showed that in most cases, researchers use empirical dependencies obtained by approximating experimental data. Analysis of the results of laboratory studies showed that, regardless of the type of rock, the greatest decrease in permeability during elastic deformations was observed in highly permeable samples of limestone and sandstone and was amounted to up to 20%. It was established that the dependences of the permeability of limestone and sandstone samples under purely elastic deformations ware described with high accuracy by exponential equations. The calculated coefficients of the equations describing the change in permeability were compared based on the results of field and laboratory studies. The mechanism of deterioration in the permeability of productive formations with a decrease in reservoir pressure was revealed, on the basis of which a model is proposed that takes into account elastic and plastic deformations of porous reservoirs. It was established that highly permeable formations were most susceptible to plastic deformation with the formation of deformation bands. In layers with greater thickness, the probability of a decrease in permeability with a drop in reservoir pressure increased, which was associated with the formation of transverse deformation bands.

Ключевые слова:
проницаемость, пористость, эффективное давление, деформация коллекторов, керн, продуктивность скважин, поровое давление, деформационные полосы, поровый коллектор, призабойная зона пласта.

Выполнен анализ результатов промысловых исследований изменения проницаемости на примере нефтяных месторождений Пермского края; проведены лабораторные исследования влияния эффективного давления на проницаемость керна. Анализ существующих методов оценки изменения проницаемости горных пород в зависимости от эффективного давления показал, что в большинстве случаев исследователи используют эмпирические зависимости, полученные путем аппроксимации экспериментальных данных. Анализ результатов лабораторных исследований показал, что независимо от типа породы, наибольшее снижение проницаемости при упругих деформациях наблюдается в высокопроницаемых образцах известняков и песчаников и составляет до 20 %. Установлено, что зависимости проницаемости образцов известняка и песчаника при чисто упругих деформациях с высокой точностью описываются степенными уравнениями. Выполнено сопоставление расчетных коэффициентов уравнений, описывающих изменение проницаемости по результатам полевых и лабораторных исследований. Раскрыт механизм ухудшения проницаемости продуктивных пластов при снижении пластового давления, на основании которого предложена модель, учитывающая упругие и пластические деформации пористых коллекторов. Установлено, что высокопроницаемые пласты больше всего подвержены пластическим деформациям с образованием деформационных полос. В пластах с большей толщиной вероятность снижения проницаемости при падении пластового давления повышается, что связано с образованием поперечных деформационных полос.

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Introduction

Deformation of reservoirs during hydrocarbon production leads to a diminished performance of wells [1, 2]. This is associated with the relief of pore pressure relative to lithostatic (rock) pressure and an effective pressure boost [3–7]. The decline of formation pressure in the course of its depletion contributes to a decrease in back pressure against the weight of overlying rocks, which leads to mechanical compaction of reservoirs and closure of fractures [8–13]. A large number of scientific papers [14–18] have been devoted to studies of rock permeability depending on changes in effective pressure; most of these papers are based on laboratory studies of rock samples [19–23]. Despite the use of real core samples obtained from oil and gas wells, all researchers note that under reservoir conditions permeability is more sensitive to pressure changes than in laboratory conditions, the main reason for this is the closure of fractures when reservoir pressure decreases [24, 25]. The high sensitivity of porous reservoirs without fractures to formation pressure decline is not explained. In this connection the purpose of the paper is to analyse and reveal the causes of permeability deterioration of porous reservoirs at reservoir pressure decline on the basis of comparison of laboratory studies and field data on permeability change obtained by hydrodynamic well testing (HDWT).

The objective of the study is to assess the plastic deformation of pore reservoirs and its influence on permeability. For this purpose the following was done: the analysis of methods of predicting permeability change with effective pressure, results of field studies of permeability change on the example of oil fields of Perm Krai was performed; laboratory studies of effective pressure influence on core permeability were carried out.

The analysis of existing methods for estimating the change in rock permeability as a function of effective pressure has shown that in most cases researchers use empirical dependences obtained by approximation of experimental data [19, 25–28]. The approximation of the results is equally well suited to describe the permeability changes in both porous and fractured media [25, 29–31]. The most common equation describing the change of permeability from effective pressure is the power law.

$$\frac{k}{k_o} = A\cdot\left(\Delta P\right)^{-n}, \tag{1}$$

where k and k_o – current and initial permeability, respectively; ΔP – change of formation pressure; A – empirical coefficient; n – degree index, characterising intensity of permeability reduction from pressure change.

Laboratory methods of core studies allow obtaining the dependence of permeability change on effective pressure, and also give an opportunity to change the experimental conditions in a wide range. However, in order to understand what happens to permeability in real conditions, core studies are insufficient, a comparative evaluation of the results of field and laboratory studies is needed.

Analysis of HDWT Results

During hydrocarbon production, reservoir properties undergo various changes due to reservoir pressure decline, changes in phase permeability, colmatation, organic and inorganic deposits, etc. [32-35]. Bottomhole formation zone (BFZ) is subjected to the greatest revision. Usually the results of laboratory core tests are used to estimate permeability changes as a result of reservoir deformation. However, this method has a number of disadvantages, the main of which are incomplete reflection of formation heterogeneities and violation of the natural stress-strain state during core recovery from the well. Therefore, to obtain reliable information on changes in formation permeability, it is necessary to use the data of HDWT.

Table 1

Properties of oil-bearing formations
in the area of the investigated wells

Parameter	Formation	
	C_2b	C_1bb
Rock	Limestone	Sandstone
Permeability, $mcm^2\cdot10^{-3}$	1–34	6–564
Porosity, %	9.7–16	7.6–18
Initial formatiopressure, MPa	15.5–18.0	15.87–16.36
Formation thickness, m	8.5–15.2	9.2–20.9
Formation depth, m	1979–2167	2144–2353
A, MPa^{-1}	$\frac{0.4815 \ldots 1.0265}{0.8323}$	$\frac{0.4116 \ldots 0.843}{0.6253}$
n	0.946 … 1.138 1.138	0.619 … 2.115 1.317

The data on the C1bb and C2b formations of the Perm Krai fields were used in this work. The reservoir properties are presented in Table 1. We have analyzed well tests carried out during 23 years since 1995. We analyzed the results of well testing in the initial period of operation obtained by steady-state flow methods and methods of pressure and level recovery curves construction. For comparative assessment of the influence of reservoir pressure changes on permeability the data were normalised – permeability was given in dimensionless form: k/k_o – relative permeability, k – permeability at reduced reservoir pressure $dP_{\text{п}}$, k_o – permeability at initial reservoir pressure P_o.

Analyses of wells exploiting pore carbonate and terrigenous reservoirs with no fractures according to the results of well log interpretation were performed. In addition, to avoid the influence of relative phase permeability, the following well selection criteria were taken into account: formation pressure in the well area should not fall below the saturation pressure; well bypass should not fall below saturation pressure; water cut should not exceed 5 %. Deposition of paraffins and salts under such thermobaric conditions is unlikely, so they can be neglected. During the observation period, no stimulation or enhanced oil recovery activities should be carried out in the wells. Based on these criteria 11 wells were selected, 6 of which exploit carbonate reservoir (C2b) and 5 wells exploit terrigenous reservoir (C1bb) of one of the oil fields in Perm Krai. Dependences of permeability on formation pressure reduction ($dP_{\text{п}}$) are shown in Fig. 1. Properties of the studied reservoirs and calculated values of coefficients *A* and indicators *n* of equation (1) are shown in Table 1.

The analysis of HDWT results showed a significant impact of reservoir pressure reduction on permeability of formations: when reservoir pressure is reduced to 5 MPa, permeability decreases by more than 80 %. It was found that permeability of carbonate formation C2b is accurately described by the steppe equation (1). In the vicinity of all selected wells, the permeability of the carbonate reservoir and its sensitivity to changes in reservoir pressure are almost the same, which is due to a small difference in permeability – from $1 \cdot 10^{-3}$ to $34 \cdot 10^{-3}$ mcm^2 (see Table 1).

Analysis of the results of HDT of wells exploiting the terrigenous C1bb reservoir showed that its permeability also deteriorates according to the step dependence (1) when the reservoir pressure decreases. In the area of wells No. 1 and 5 (see Fig. 1, b) the reservoir has the highest initial permeability, its reduction is maximum and makes more than 90 %. In the area of wells No. 2, 3 and 4, the C1bb formation has lower initial permeability and sensitivity to formation pressure reduction.

Laboratory Core Tests

For comparative analysis, laboratory tests of core from wells drilled at the C1bb and C2b sites of the considered field were performed. The properties of core samples are shown in Table 2. Cleaned and dry core samples of standard size, 30 mm in diameter and 30 mm in length were filtered using nitrogen nitrate on the UltraPoroPerm-500 unit (CoreLab Instruments, USA). The procedure of filtration studies was as follows:

1. Before starting the studies the core was placed in a core holder, in which an initial lithostatic pressure – 2.76 MPa - was created by the use of a hand pump. For stress relaxation the core was kept at the initial pressure for 10 min. The results of studies showed that this time is enough for complete stabilization of deformations.

2. Determination of permeability by injection of pure nitrogen. Nitrogen was pumped through the sample at a flow rate of no more than 1 ml/s to maintain a linear flow regime.

Pore pressure change was modelled by varying the core lithostatic pressure in the core holder. During nitrogen injection the lithostatic pressure was increased stepwise from 2.76 to 13.8 MPa and then declined back to 2.76 in steps of 2.76 MPa. The chosen maximum lithostatic pressure allows us to evaluate the influence of elastic deformations only. Nitrogen was pumped at a constant flow rate to minimize the impact of slippage on the study results.

3. Data from the flowmeter and pressure sensors were recorded by the machine computer in increments of one measurement per second and instantaneous permeability values wede determined.

4. According to the results of the studies the graphs of dependency of core samples permeability on lithostatic pressure (Fig. 2).

Analysis of the results of laboratory studies showed that the permeability dependencies of limestone and sandstone samples under purely elastic deformations are described with high accuracy by power equations (1), the calculated coefficients and indicators of the equations are presented in Table 2. Regardless of the type of rock the largest decrease in permeability is observed in highly permeable samples and is 6 % and

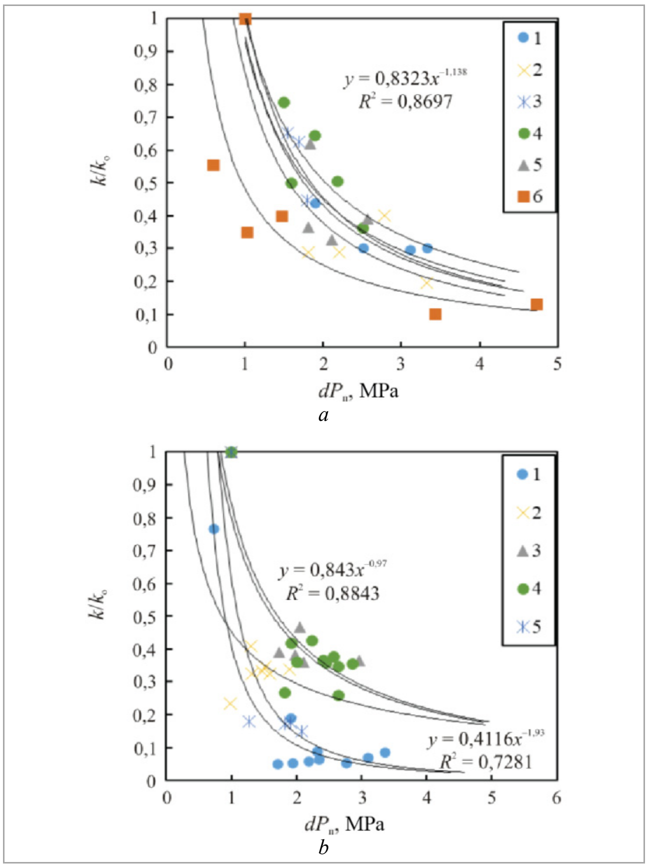

Fig. 1. Effect of formation pressure lowering ($dP_{п}$) on the permeability of carbonate (*a*) and terrigenous (*b*) reservoirs

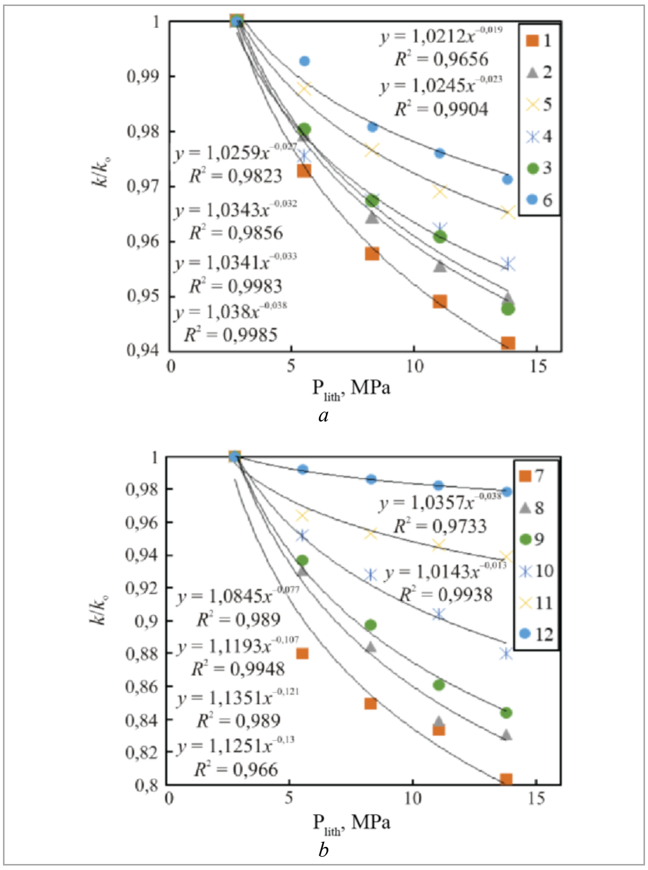

Fig. 2. Effect of lithostatic pressure on permeability of limestone (*a*) ans sandstone (*b*) samples

Table 2

Properties of core samples

Parameter	Properties of core samples						
Rock	Limestone						Average value
№ of the sample	1	2	3	4	5	6	
Absolute permeability, mcm$^2\cdot10^{-3}$	384	34	15	156	107	42	122.9
Porosity, %	14.14	14.79	10.11	14.97	13.51	15.63	13.86
A, MPa^{-1}	1.038	1.034	1.034	1.026	1.025	1.021	1.030
n	0.038	0.033	0.032	0.027	0.023	0.019	0.029
Rock	Sandstone						Average value
№ of the sample	7	8	9	10	12	11	
Absolute permeability, mcm$^2\cdot10^{-3}$	427.5	117.4	6.3	13.2	41.5	27.8	105.6
Porosity, %	15.19	15.19	11.08	11.58	9.69	7.60	11.72
A, MPa^{-1}	1.125	1.135	1.119	1.085	1.014	1.036	1.086
n	0.130	0.121	0.107	0.077	0.013	0.038	0.081

20 % for limestone and sandstone, respectively. Despite the wide range of permeability of the selected samples, the calculated values of the coefficient A of equation (1) in all samples have a low variance and are equal from 1.021 to 1.038 MPa^{-1} for limestone and from 1.014 to 1.135 MPa^{-1} for sandstones. Exponent n of the power equation (1) which characterizes the sensitivity of rocks to changes in pore pressure, averages 0.029 and varies in the range from 0.019 to 0.038 in limestones; in sandstones the value of n is from 1.014 to 1.135 with an average of 0.081. The studied sandstone samples, due to their coarse-grained structure, are characterized by a higher sensitivity of permeability to loading, than in fine-crystalline limestone with purely elastic deformations.

Discussion of Results and Modeling

In reservoir conditions elastic and plastic deformations occur when reservoir pressure declines. As a result of plastic deformations reservoirs are compacted and well productivity is irretrievably lost. Deformation of rocks and changes in porosity under the influence of external load can be described by rheological models which include elastic, plastic and creeping elements [36]. Since permeability is directly related to porosity, its change under loading can be represented as a Two-Part Hook Model (TPHM) [37], based on which we proposed a rheological model of permeability (Fig. 3) consisting of elastic and viscous elements. In the model, a heterogeneous layer consisting of n layers is represented by sequentially connected interlayers, each of which consists of parallel elastic and plastic elements (see Fig. 3). Each layer has its own filtration and mechanical properties, which are interrelated. The most permeable interlayers have greater porosity and lower strength, and vice versa. The elastic and plastic properties of rocks depend on the size of the grains, the amount of cement and their mineral compositions. Elastic element shows the change in permeability from load caused by elastic deformations of mineral grains. Elastic deformations are reversible and make an insignificant contribution to the overall change in the permeability of the interlayer. The effect of elastic strain on permeability is described by the power equation (1), and the values of coefficients and exponents for the reservoirs are determined according to the results of laboratory core studies.

The main task in monitoring the development of the deposit is to assess irreversible deformations of the reservoir. Plastic deformations occur when the reduction of reservoir pressure exceeds the yield strength of the rock, fractures are closed and porous rocks are crushed. Plastic deformations lead to irreversible reduction of permeability of interlayers. The contribution of plastic deformations to the overall reduction of permeability is significant, but in porous medium plastic deformation occurs unevenly, and first of all, crushing occurs in the most porous and productive interlayers (Fig. 4), and the general displacement of deformation is localized in narrow deformation regions, while the main part of the porous medium continues to experience only elastic deformations. Despite the fact that the filtration characteristics of the of the main parts of the porous medium remain almost unchanged, the overall permeability of the reservoir decreases due to the presence of deformation regions which act as low-permeability filtration barriers between the layers. A similar mechanism of porous media compaction is evidenced by experimental studies [38], as well as the fact that deformation bands can be observed in superficial rock outcrops all over the world.

Deformation bands are not singular and form clusters, which may vary in width from a few centimetres to tens of metres [39]. The width of deformation band clusters depends on the scale of displacements; deformation regions with larger widths are formed during tectonic shifts, and earthquakes. In productive reservoirs the reduction of reservoir pressure rarely leads to large displacement of rocks, and consequently, the width of deformation bands is insignificant. Despite the small size of these bands their

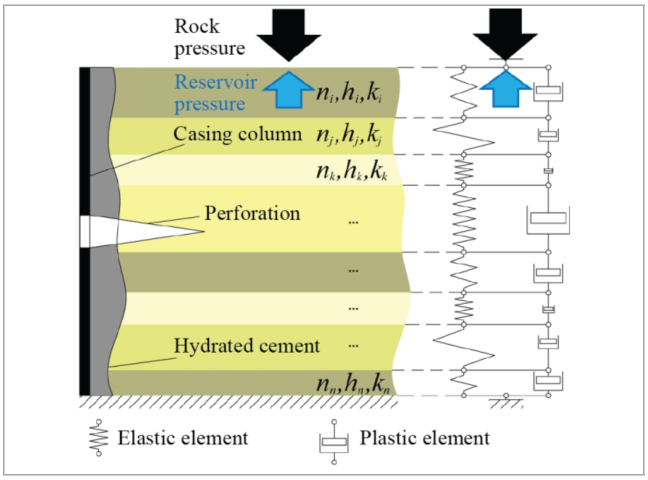

Fig. 3. Rheological model of an inhomogeneous reservoir

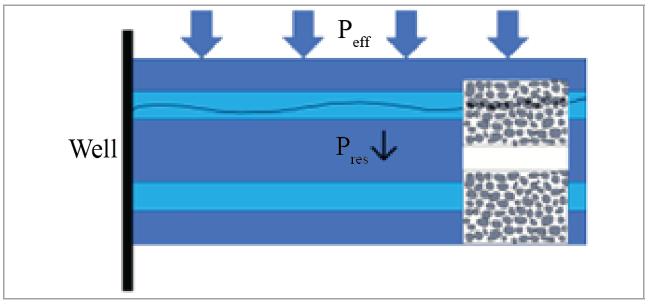

Fig. 4. Scheme of deformation bands occurrence in the bottom-hole zone of a heterogeneous reservoir at formation pressure decrease and their influence on formation fluid flows

occurrence significantly affects the filtration properties of the formation. Reservoir zones with seals are barriers to filtration, and rock cracking leads to the formation of fine clastic material, which, migrating together with fluid, forms an internal filtration crust. In contrast to deformation bands observed in surface sediments, which were formed long before the rocks came to the surface and over a long period of time have become an impermeable barrier, newly formed deformation bands do not have high strength and do not contribute to complete cessation of filtration [40].

To take into account the effect of deformation bands formation on permeability, we use the following simplification: deformation of the reservoir occurs owing to vertical loading. Localisation of deformation occurs in the middle of a homogeneous formation and reduces its effective thickness by half, which also leads to a twofold decrease in the integral permeability determined by HDWT. The formation of subsequent deformation bands will also reduce the effective thickness of the reservoir by half, so the change of reservoir effective thickness will decrease in power dependence with an indicator of degree *n* equal to 2, and in the same way the permeability determined by the HDT should change. However, as the analysis of the GDI results showed, the n exponent of the power equation (1) rarely exceeds 2 and is observed only in highly permeable sandstones (see Table 1). In reservoir conditions, a lower value of the n exponent is caused by the fact that deformation bans, although they are barriers, do not completely block filtration and has some permeability which depends on two factors:

1) compaction – reduction of pore channel cross-section. The degree of poroes media compaction depends on the amount of applied load and reduction of reservoir pressure;

2) migration of colloid particles [41, 42] – when the porous media is deformed fine clastic material is formed. It migrates with the reservoir fluid flow ans blocks the pores.

Consideration of compaction and migration of colloidal particles effect on the permeability of deformation joints is a complex task and it is difficult to be recorded in relation to the well conditions since the presence of deformation bands and their geometric dimensions are unknown, and it is possible to judge their presence only by knowing the mechanism of deformation of porous media. However, it is known [43] that permeability has power dependence on colloid migration. Thus, considering the universality of the power law [44] and the fact that the approximation of permeability dependence on the reservoir pressure change based on the results of hydraulic logging is described with high accuracy by equation (1), the rheological model of permeability can be represented in the form of the equation:

$$\frac{k}{k_o} = A \cdot (\Delta P)^{-n} \cdot B \cdot (\Delta P)^{-m} - C \cdot \Delta P, \qquad (2)$$

where k and k_o – current and initial permeability, respectively; ΔP – reservoir pressure change; *A*, *B* and C – empirical coefficients; *n* and *m* – degree indicators characterizing the intensity of permeability reduction from to pressure changes. *A* and *n* characterise elastic deformations, their values were determined by the results of laboratory core tests (see Table 2). The values of *B* and *m* show the influence of plastic deformations on the total permeability of the reservoir; by their value we can judge about the degree of formation permeability deterioration due to plastic deformations. *C* is reservoir stiffness, it characterises residual permeability at full reduction of reservoir pressure (Fig. 5).

The analysis of the calculated coefficients and indicators of the developed model (2) showed that the indicator *m*, which characterises the probability of deformation bands in the formation, is influenced by its thickness. At greater thickness the reservoir deformation causes large displacements of rocks, resulting in significant tangential stresses in the formation, which lead to the formation of transverse deformation bands (Fig. 6) having the maximum impact on the formation productivity.

Conclusion and Practical Application of the Research Results

A comparative analysis of the results of laboratory and field studies of pressure influence on permeability of terrigenous and carbonate rocks was carried out. It has been revealed the mechanism of permeability deterioration of productive reservoirs at formation pressure decrease on the basis of which a model considering elastic and plastic deformations of porous reservoirs is proposed. It was found that highly permeable reservoirs are most subject to plastic deformations with forming deformation bands. In reservoirs with greater thickness, the probability of permeability reduction at reservoir pressure drop increases which is associated with forming transverse deformation bands.

Deformation of reservoirs is an irreversible process, as a result of which its filtration characteristics are reduced. The formation of a depression funnel and a drop in reservoir pressure during hydrocarbon production is inevitable, and therefore, it is impossible to prevent deformation of the productive formation within the bottomhole zone of the reservoir. Attempts to restore the productivity of wells with deformed reservoirs by applying traditional methods, such as acid treatment, may be ineffective. During acid injection the increase in well productivity occurs due to the formation of highly conductive channels, but these channels are formed along the acid filtration path in the directions of least resistance. The presence of deformation bands prevents acid from penetrating through them and reduces formation coverage by treatment. Nevertheless, getting an idea of BFZ productivity reduction allows you to form a program for restoring well productivity. The presence of deformation processes in the formations should be taken into account during the treatment of the BFZ. Taking into account the presence of deformations and compaction zones in reservoirs, the most preferable methods of influencing the BFZ are: acid treatment with simultaneous impulse action, thermogaschemical methods of action (powder charges, binary mixtures, etc.). Before using such treatments, the reservoir pressure must be restored to values close to the initial reservoir pressure; otherwise the influence of the impulse action will lead to even greater compaction of the reservoir rocks and the reduction of well productivity.

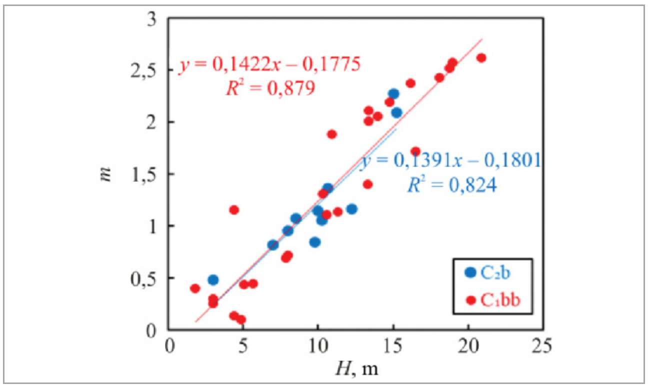

Fig. 5. Influence of reservoirs thickness on exponent *m* of the equation (2)

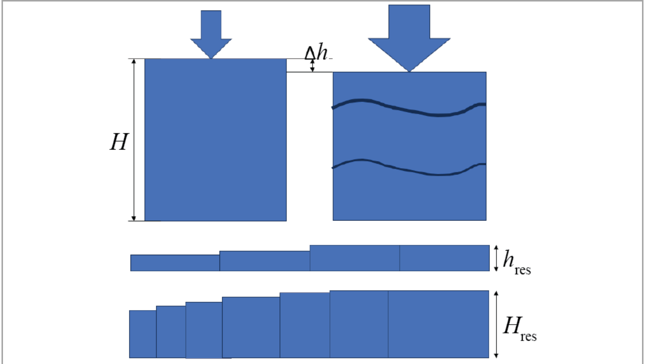

Fig. 6. Schematic representation of reservoir thickness effect on the density of vertical fractures

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