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INVESTIGATION OF FLUID DYNAMICS IN MICROFRACTURE CHANNELS

Maleyka Mammadova
PhD, Professor
Department of Industrial Machines
Azerbaijan State Oil
and Industry University
Azadlig ave., 20, Baku,
Azerbaijan, AZ 1010
E-mail: mamedova-1944@mail.ru

The object of the work is an experimental study of the features of the movement of viscous and anomalous fluids in plane-parallel and plane-radial microcracks.

In the work, the unexplored problem of hydrodynamic features of fluid motion in the considered objects – channels is solved.

It was experimentally revealed that various fluids, when moving in microcracked channels with micron-sized openings, acquire new mechanical properties, which differ from their properties in the usual condition. The effect in the "microcrack-fluid" system is the reason for changes in the mechanical properties of fluids in microcracks and equivalent ultra-low-permeable porous media. It was revealed that when a one-parameter viscous fluid moves in a crack with an opening $h<h_{cr}$, it becomes two-parameter, i.e. behaves like an anomalous fluid, and when moving with an opening $h \geq h_{cr}$, it restores one-parameter properties, and the anomalous fluid behaves like an anomalous fluid but increases the rheological constants of the model.

The results of the research require taking into consideration the crack effect in estimating the parameters of the technological processes system and technical devices "microcrack-fluid". Machines and mechanisms must additionally have nodes that would prevent this effect. This is of scientific and practical importance for various fields of the industry, machine manufacturing, instrument manufacturing, chemical technology and medicine

Keywords: non-Newtonian fluids, structural viscosity, plane-radial cracks, shear stress, plane parallel crack, shear rate

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1. Introduction

At present, in the study of the mechanical properties of fluids in pipes of various transverse sizes, it has been shown that the experimental results of hydraulic resistance in such channels are greater than those calculated using theoretical formulas, and this phenomenon is explained by various qualitative factors.

When solving numerous national economic production issues, including identifying the reasons for the low value of the oil recovery factor, gas recovery, the choice of lubricating oils to ensure the rational wear of machine parts, solving certain problems of chemical technology and medicine, they face solving the problems of fluid movement in microcracked channels. The movement of fluids in such media has other patterns, which requires starting experiments to explain the reasons for the low level of the oil recovery factor in a fractured medium. For such experiments, it is necessary to create a porous medium with ultra-low permeability and maintain the stability of fracture dimensions throughout the experiment.

Obtaining specific crack sizes on a porous medium model is difficult.

Thus, the study of the flows of Newtonian and non-Newtonian fluids in a microcrack is extremely important from both practical and fundamental points of view. This problem can be solved by knowing the patterns of fluid movement in a microfracture, which makes it possible to judge the filtration processes in the reservoir fracture system. Of particular relevance is the problem in the development of deposits with non-Newtonian oils, whose reserves are commensurate with those of Newtonian oils.

The study and development of the physical foundations of oil filtration in microfractured reservoirs are of great practical interest and important for the development of oil and gas fields, which must be taken into account when creating development technologies.

Therefore, research devoted to the study of the features of fluid movement in microfractured channels and the development of hydrodynamic foundations of the technology for extracting Newtonian and non-Newtonian oils from fractured rock deposits is relevant.

2. Literature review and problem statement

The investigations of the water flow in cracks allowed determining the boundaries of the transition from the laminar regime to the turbulent one [1]. According to the results, the critical Reynolds number equal to 600 was determined, and the influence of the crack wall roughness on the flow features was studied. Important conclusions were also made that the effect of roughness on filtering processes is manifested at an absolute roughness value of <0.065. At the same time, the obtained conclusions are not insufficient to describe the features of fluid movement in microfracture channels with an opening $h<h_{cr}$. Note that, in addition to roughness, the value of the Reynolds number is also affected by the crack opening.

The paper [2] considers steady isothermal laminar and turbulent flows of viscous non-Newtonian fluids in a gap between two cylinders with different diameters. At the same time, the study of the structure of flows and the mechanisms of their formation, the establishment of regularities and the analysis of the influence of the channel geometry, the properties of the liquid and the flow regime, in addition to the noted ones, should take into account the influence of the critical gap value on the regularity of changes in the parameters of the liquid in the "microcrack-liquid" system.

The work [3] is devoted to the study of the flow of a viscous incompressible fluid in the micro-gaps of hydraulic devices and apparatuses, taking into account an abrupt boundary change in viscosity. For the adopted model of dynamic viscosity distribution, the equations of fluid motion are integrated, on the basis of which expressions for fluid velocity along the height of the gap are obtained. Dependences for calculating the drop in the throughput of the passage section are obtained. Examples of calculating velocity distributions and throughput drop for a flat slot are given. The limits of applicability of the classical approach to calculating the flow of a viscous fluid in a microgap are estimated. However, when compiling the dependence for calculating the drop in the throughput of the flow section, in addition to the above, the influence of the value of the critical gap, which occurs in channels with micron openings, is not taken into account. The "microcrack-liquid" effect can lead to a significant influence of velocity distributions and a drop in the throughput of a flat gap.

In [4], it is proposed to describe the processes of fluid filtration in anomalous reservoirs with a deviation from Darcy's law by calculating the values of Lagrange parameters. When determining a relationship between the Lagrange parameter and the initial pressure gradient in the proposed method for describing the filtration processes of a viscoplastic fluid in low-permeability reservoirs, the critical permeability value of the equivalent openness value remained outside the calculation. However, when a liquid moves in a porous medium with permeability $K<K_{cr}$, an additional force arises in the porous medium due to the effect of the "microfractures-liquid" systems, which prevents the movement of fluid in the formation.

The paper [5] presents the results of numerical modeling for the analysis of the moment and forces exerted on an eccentrically positioned rotating inner cylinder due to the annular flow between two cylinders with parallel axes. Laminar stationary fully developed flows of Newtonian and power-law fluid flows are considered. The impact of annulus geometry, flow regime, and fluid characteristics are studied. In the numerical simulation, in order to analyze the moment and forces acting on an eccentrically located rotating inner cylinder due to the annular flow between two cylinders with parallel axes, in addition to the above factors, it is necessary to take into account the critical gap value, below which the "crack-liquid" effect appears. This effect can further enhance the occurrence of an additional force due to the effect of "microcrack-liquid" systems that impede the flow and nature of the liquid, which is important to consider when modeling.

In [6], the expression is proposed for calculating the coefficient of hydraulic resistance as a result of an experimental study in order to identify some features and patterns of turbulent flow in an annular confuser formed by cylindrical and conical surfaces, between the axes of which there is some eccentricity. In addition to the noted, the effect of crack opening on the flow of viscous incompressible fluids was not taken into account. Note that failure to take this factor into account for the flow of viscous incompressible fluids can lead to significant errors and, as a result, to a large inaccuracy in calculating the hydraulic resistance coefficient.

The study [7] considers the results of the scientific revolution that started in ago and referred to solving the problem of oil and gas genesis. The revolution led to the development of a new oil and gas paradigm. The essence of this paradigm is that oil and gas are in fact renewable natural resources that should be produced taking into account the balance of hydrocarbons (HC) generated and the possibilities for their recovery in the process of field development. Findings: These new ideas have gained the required theoretical and experimental justification within the biosphere concept of oil and gas generation (BCOG).

In this work, there are no studies on the peculiarities of the movement of liquids in low-permeability reservoirs, taking into account the opening of a microcrack, which, at $h<h_{cr}$, significantly affects the mechanical properties of liquids. It should be noted that the use of the ideas of the biosphere concept in the development of oil and gas fields with low-permeability reservoirs, taking into account the "microfracture-liquid" effect, will significantly improve the efficiency of the oil recovery method.

According to [8], a relatively high formation pressure gradient can exist in the seepage flow in low-permeable porous media with a threshold pressure gradient, and a significant error may then occur in the model computation due to neglect of the quadratic pressure gradient term in the governing equations. Based on these concerns, in consideration of the quadratic pressure gradient term, a basic moving boundary model is constructed for a one-dimensional seepage flow problem with a threshold pressure gradient. Owing to a strong nonlinearity and the existing moving boundary in the mathematical model, a corresponding numerical solution method is presented.

However, this approach doesn't give a reliable assessment of the significance of this most important mathematical model of the numerical solution method.

In low-permeability porous media, failure to account for fracture opening significantly affects the fluid filtration process, so the accuracy of the calculation of the mathematical model decreases.

The results of the study [9] devoted to the motion of a viscous fluid in cracks are not enough to explain the reasons for the abnormal hydrodynamic behavior of fluids in a microcrack. However, in the research there is no direct indicator of the influence of the crack opening size on the mechanical properties of the fluid. The rheological parameters of the fluid in the fractures are taken regardless of the crack opening. When the crack opening is below the critical value, it is necessary to take into account the "microcrack-liquid" effect, which creates additional resistance to the movement of fluids in cracks.

The work [10] is devoted to improving the efficiency of safe operation of reciprocating compressor valves operating in a gas lift system for compressing low-pressure associated petroleum gas, and therefore is relevant.

However, when developing a recommendation to improve the efficiency of safe operation of valves in terms of the tightness of the plate tongue design and operating hours for PIK-AM valves, this sealing system did not take into account the "fracture-liquid" effect. The main methods of tightness of the design of a pair of valve discs have not been studied, taking into account the choice of the critical size of the crack gap. If the gap value of the valve plate pair is lower for well production critical opening values, it will become a sealing system.

The work [11] is devoted to improving the operation of compressor stations, namely, increasing the reliability of gas-engine reciprocating compressor units installed in them. To increase the efficiency of associated petroleum gas purification from mechanical impurities, heavy hydrocarbon components and moisture, it is recommended to additionally install a horizontal gas separator of a new design on the suction line of gas-engine reciprocating compressors. Note that if the valve head clearance for hydrocarbon components and solids is below the critical opening values, then it will become a sealing system, which prevents liquid hydrocarbon components and solids from falling onto valve heads.

The influence of the crack opening size on the mechanical properties of the fluid has not been indicated in any of the above-mentioned works. The rheological parameters of the fluid in the cracks are taken regardless of the opening and the crack opening sizes are not taken into consideration in developing the fractured oil and gas fields. This is the reason for the low level of oil recovery.

As can be seen from the above-mentioned review of relevant works, there is currently no quantitative assessment of the reasons for nonlinear effects during the Newtonian fluids motion and strengthening of these effects for non-Newtonian fluids in plane and plane-radial microcracks. Therefore, clarification of the hydrodynamic process mechanism as well as the quantitative assessment of the microcrack effect in fluid and gas mechanics when used in oil production technology will allow creating the bases for the effective development of fractured rock fields.

Despite the fact that a very rich experimental and theoretical experience has been accumulated in the field of fluid motion research, a number of problems have not been sufficiently studied. This refers to the investigation of fluid motion in the "microcrack-fluid" system. New problems also occur in the fractured reservoirs development, which requires both studying the features of fluid motion in a crack with a micron-sized opening and assessing the influence of crack opening on the hydrodynamic features of fluid motion.

There is no concept of the microcrack effect existence for a homogeneous fluid being the Jamin effect analog.

Up to now, the rheological parameters of reservoir fluids determined in laboratory conditions and completely characterizing the real rheological fluid behavior in reservoir conditions have been used in solving various problems of the oil and gas fractured reservoirs development. Special attention should be paid to reliable information about the rheological parameters of filtration systems for designing and rational development of fractured reservoir fields. Unexplored rheological constants in microcrack conditions and the analysis of existing laboratory methods for determining the rheological constants of filtration systems allowed developing new methods for estimating the rheological constants of fluids in microcrack and crack opening directly on the basis of the drill hole surveying.

This effect should be taken into consideration in the calculations of oil recovery factors.

Therefore, new defined parameters arise on the basis of experimental investigations of fluid motion in microcracks. Without considering them, it is impossible to completely solve the differential equation of fluid motion in microcracked channels with manifestations of the effect in the "microcrack-fluid" system.

A review of these works shows that they are insufficient, and the authors cannot use their results to solve the proposed approaches.

An experimental study of the influence of crack opening on the features of the movement of viscous and anomalous fluids in a plane-parallel and plane-radial crack will allow us to study the causes of nonlinear effects during the movement of viscous and amplification of anomalous fluids in a plane-radial microcrack. The study of the influence of the above factors made it possible to describe the mechanism of the filtration process and give a quantitative assessment of this phenomenon in real fractured formations, as well, scientifically substantiate and develop oil production technology. Preliminary determination of the critical fracture opening makes it possible to increase the effectiveness of the impact on the bottomhole zone, as well as to avoid unreasonable measures.

The solution of this problem is promising for using the results in various industries such as: oil industry – where it is possible to achieve the maximum increase in oil recovery (average oil recovery factor around the world is about 30 %) by attracting oil from low-permeability reservoir zones into development; mechanical engineering and technology – to develop a new approach to the design of lubrication systems for machines, mechanisms and oils; in the field of medicine – to develop a new approach to the processes of formation and purification of blood clots in the vascular system.

3. The aim and objectives of the study

The aim of the study is to identify some regularities in the movement of viscous and anomalous fluids in microcrack channels by experimentally studying the hydromechanical features of the movement of water and various fluids, choosing a model and a differential equation in general, their mechanical behavior and solution. This will make it possible to create new approaches to the development of fractured and low-permeable rocks.

To achieve this aim, the following objectives are accomplished:

– to determine the effect of crack opening on the rheological properties of fluids;

– to determine critical opening values for water, viscous and anomalous fluids when moving in plane-parallel and plane-radial microcracks;

– to identify the cause of non-linear "microcrack-fluid" effects in plane-parallel and plane-radial microcracks and their quantitative assessment;

– to develop a technique for using known differential equations of motion of various fluids in microcrack channels with a demonstration of the effect in the "microcrack-fluid" system;

– to obtain dependencies for the transition from plane-parallel and plane-radial fracture models to a real porous medium with the steady motion of a viscous and anomalous fluid.

4. Materials and methods

To confirm the manifestation of the "microcrack-fluid" effect depending on the opening size of microcrack channels, the results of experimental studies of the movement of viscous and anomalous fluids in plane-parallel and plane-radial cracks with micron openings are presented below [12–15].

The structure of plane-parallel and plane-radial cracked channels and the experimental technique are given in [13, 14].

Cracks of a given thickness are created by layerings located between the plates. The pressure distribution in the crack was controlled by holes located along the radius. During the experimental investigation, the readings of pressure gauges installed in all holes were controlled, which confirmed the absence of flow discontinuity.

The experimental setup with elements was created in a way that it could provide the flow continuity in the slot and control the presence or the absence of flow continuity in the slot during the experiment.

In order to ensure crack non-deformability, the plates were made of 40X steel, which had a surface hardness of 40–50 Rockwell units after HFC (high-frequency current) heat treatment. The indicating gauge mounted on the upper plate of the model was used to control the crack deformation.

The experiments were carried out in microcracks with an opening of 10÷240 μm with water, kerosene, viscous and anomalous oil.

Experimental investigations were carried out under steady-state conditions in isothermal conditions, the temperature was maintained constant by an ultra-thermostat.

The saturation of the crack with the studied fluid was carried out under low pressure with simultaneous vacuum evaporation.

The features of the water and abnormal oil flow in microcracks of various openings were investigated on the developed experimental facility. The experiments were carried out as follows: different pressure drops were created on the fracture model, after reaching a steady-state filtration mode, the appropriate volumetric water discharges Q were measured for each pressure drop.

The mass flow rate of the liquid is determined on electronic scales with an accuracy of 0.1 mg. When determining the total relative error for the velocity gradient and ultimate shear stress with a crack opening of 10÷240 μm, it is γ=(2÷3) % and (0.2÷1.2) %, respectively.

To identify the investigated fluids in plane and plane-radial cracks, the results were processed in the $\gamma-\tau$ coordinates, where the average shear rate is $\gamma=6Q/Fh$ in the plane cracks and $\gamma=Q/4\pi h^2 r$ in the radial; shear stress is $\tau=\Delta Ph/2l$ in the plane cracks and $\tau=\Delta Ph/l$ in the radial.

Newtonian oil in the microcrack ($h<h_{cr}$) is described either by a power law model or by the Shvedov-Bingham model, and the flow in a microcrack ($h\geq h_{cr}$) is described by the parameters of fluids in bulk.

Taking into consideration the fact that engineering oilfield problems usually occur at high-velocity gradients, the Shvedov-Bingham model was used for processing experimental results, i.e. the mechanical properties of the fluid in cracks are characterized by a limit shear stress τ_{0h} and apparent viscosity μ. The limit shear stress τ_{oh} and apparent viscosities μ_h at different temperatures and crack openings were determined based on the curves $\gamma=\gamma(\tau)$ for Newtonian and non-Newtonian fluids.

So, it was experimentally determined that there is a critical opening value (h_{cr}) below which the limiting yield stress τ_{oh} and apparent viscosity μ_h are increased significantly. It was also found that during the Newtonian fluids motion in cracks, the non-Newtonian properties are manifested, and with an increase in the crack opening h the non-Newtonian properties are decreased but and at these properties disappear. But during the non-Newtonian fluids motion, the anomalous properties are increased and with increasing crack opening, they are decreased to the initial value.

A technique is developed for using known differential equations of motion of various fluids in microfracture channels showing the effect in the “microcrack-liquid” system.

According to the “Methodological guide for the development of fractured rock deposits with Newtonian and non-Newtonian oils” developed by us, dependences for the transition from a plane-parallel and plane-radial channel to a porous medium were derived [13].

For viscous fluids

$$\sqrt{k}=0.0667h-0.0180h_{cr}. \tag{1}$$

For anomalous fluids

$$\sqrt{k}=0.1637h-0.0638h_{cr}, \tag{2}$$

where h is the distance between the walls of the crack, and h_{cr} is the distance between the walls of the channel of a special viscometer.

Based on the results of micron-sized cracks h_{cr}, the equivalent layer permeability can be calculated.

Based on these dependencies, calculations were made to determine the reservoir permeability value, respectively, during the movement of a viscous and anomalous fluid.

5. Results of studying fluid motion in microcracks

5. 1. Determination of the effect of crack opening on the rheological properties of fluids

Based on the experiments, the following results were obtained: for the test fluid at different crack opening values [12–15].

Fig. 1 shows the dependences of the average velocity gradient γ on the average shear stress τ for microcracked channels with an opening $h<h_{cr}$ and $h>h_{cr}$ during viscous fluid flow in plane-parallel and plane-radial microcracks at a constant temperature.

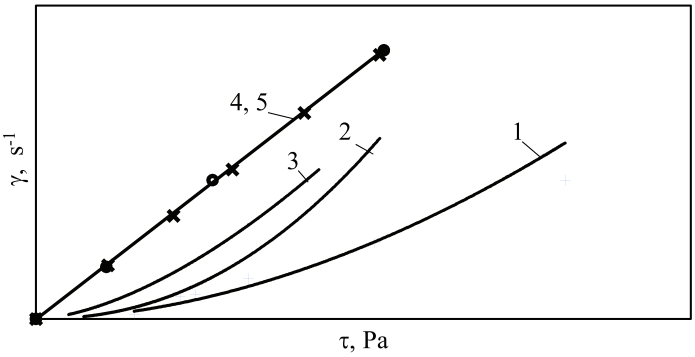

Fig. 1. Dependence $\gamma=f(\tau)$ for viscous fluids in microcracks at $h<h_{cr}$ (1–3 curves) and $h\geq h_{cr}$ (4.5 straight lines)

As seen from Fig. 1, non-Newtonian properties appear in the microcrack during viscous fluid flow (curve 1–3), which weaken with an increase in the slot opening (curve 2, 3). During viscous fluid flow in the plane-radial crack with an opening value of 30 μm, the limiting yield stress is zero but the viscosity remains constant (straight line 4). In the case of motion in the plane-parallel cracks, with an increase in the opening, the limiting yield stress and structural oil viscosity are decreased to the specified crack opening value. The limiting yield stress and structural viscosity are independent of h and remain constant at an opening value of 130 μm at a constant temperature.

Fig. 2 shows the dependences $\gamma=f(\tau)$ at different crack opening values at a constant temperature during the anomalous oil motion in plane-parallel and plane-radial microcracks. With the opening increase, the limiting yield stress and structural oil viscosity are decreased to a certain crack opening value, and the limiting yield stress and structural viscosity are independent of h and remain constant at 180 μm opening values.

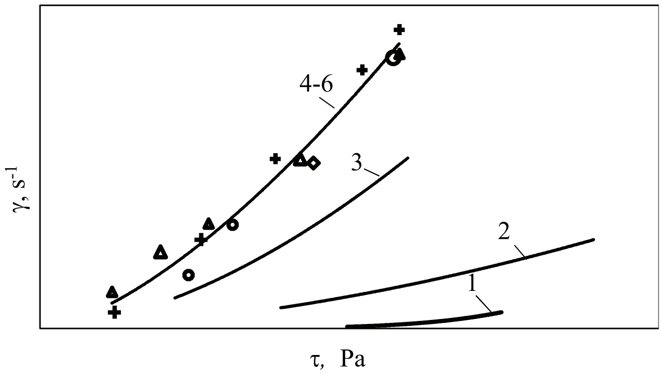

Fig. 2. Dependence $\gamma=f(\tau)$ for anomalous fluids in microcracks at $h<h_{cr}$ (1–3 curves) and $h\geq h_{cr}$ (4–6 curves)

As can be seen from these figures, both for viscous and for anomalous fluids at $h<h_{cr}$ in the $\gamma-\tau$ system, the rheological curves are different, but at $h\geq h_{cr}$ crack opening, the rheological dependences $\gamma=\gamma(\tau)$ for viscous and anomalous fluids coincide, respectively in one straight line and the curved line [12, 13].

The experimental investigations show that the flows of water and Newtonian oil in a microcrack ($h<h_{cr}$) are described either by a power law model or by the Shvedov-Bingham model, and the flow in a microcrack ($h\geq h_{cr}$) is described by the parameters of fluids in bulk.

The data on the nonlinearity of the rheological dependence for viscous and anomalous fluid are of special interest.

5. 2. Determination of the critical crack opening value for various fluids

Based on the experiments, the critical crack opening value was determined for the investigated fluid [13, 14]:

– the critical crack opening value for these fluids at 303 and 313 K temperatures is 25, 22 μm and 65, 55 μm, respectively, during water and kerosene motion in the plane-parallel cracks;

– for viscous and anomalous oil in the plane-parallel cracks, 130, 115, 100, 90 and 160, 130, 115, 105 μm were obtained at 303, 313, 323, 333 K temperatures, respectively;

– 60, 50 and 42 μm were obtained in the plane-parallel cracks for 0.3 % PAA solution at 303, 313, 323, 333 K temperatures and 90, 72, 60, 48 μm – for 0.15, 0.06 and 0.03 % PAA solution at 303 K temperature;

– the critical crack opening values of 35 and 30 μm for water in the plane-radial crack were obtained at 293 and 303 K, respectively, and for abnormal oil at 303K – 180 μm.

As seen from Fig. 1, 2, at $h\geq h_{cr}$ for different crack opening values, all points of the dependences $\gamma=f(\tau)$ for viscous (straight line 4) and anomalous fluid (curve 4), respectively, are presented on the same line. This proves the reliability of the specified critical values of the crack opening.

So, for the first time, we determined the critical opening value h_{cr} based on experimental investigations in cracks. It was found that at $h<h_{cr}$, the anomalous properties are manifested in viscous fluids and rheological parameters are increased for anomalous fluids, and at $h\geq h_{cr}$, these effects disappear. It was found that the reason for the anomalous behavior of fluids in a microcrack with the opening $h<h_{cr}$ is the effect that occurs in the "microcrack-fluid" system.

5. 3. Identification of the causes of non-linear "microcrack-liquid" effects in microcracks and their quantitative assessment

The identified effect is as follows: during viscous fluid motion in channels or equivalent porous media, the viscous fluid behaves as an anomalous fluid thereby there is a critical crack opening value h_{cr} for each fluid [12–14].

In this case, if the viscous fluid moves in the channel with an opening $h<h_{cr}$, it behaves as an anomalous fluid, but during viscous fluid motion in the channel with an opening $h>h_{cr}$, the viscous fluid restores its properties before entering the channel with an opening $h<h_{cr}$ and the anomalous fluids retain the anomalous properties, but the rheological constant models are quantitatively changed. The revealed peculiarity of fluids is manifested only in a microcrack with an opening $h\leq h_{cr}$ and is absent at the entrance to the crack with an opening $h\geq h_{cr}$.

The preservation of the fluid memory when exiting from the microcrack is shown in Table 1.

Table 1

Preservation of the fluid memory when exiting from the microcrack

Tested fluid	Memory existing	
	$h>h_{cr}$	$h<h_{cr}$
Water	yes	no
Viscous fluid	yes	no
Viscous plastic fluid	yes	no

As can be seen from Table 1, the revealed feature of fluids is shown only in a microcrack with an opening $h\leq h_{cr}$ and is absent at the entrance to the crack with an opening $h\geq h_{cr}$.

5. 4. Development of a technique for applying differential equations of fluid motion in microcrack channels with the "microcrack-fluid" effect

The development of a methodology for using known differential equations of fluid motion is required during the viscous and anomalous fluid motion in microcracked channels.

To study the viscous and anomalous fluid motion in micron-sized channels with a crack opening $h<h_{cr}$, according to Fig. 1, 2, the following rheological models were proposed:

Newton's model $\tau=\mu\gamma$; (3)

Power-law model $\tau=k\gamma^n$; (4)

Bingham model $\tau=\tau+\mu\gamma$; (5)

Shulman-Casson model $\tau^{\frac{1}{2}}=\tau_0^{\frac{1}{2}}+(\mu\gamma)^{\frac{1}{2}}$. (6)

Based on these models, the differential equations of the viscous and anomalous fluid motion obtained by [16, 17] and others in theoretical hydrodynamic mechanics are given in the technical literature. They can be used:

– if in these equations, instead of rheological parameters, we take rheological parameters taking into account a crack opening $h<h_{cr}$ determined in the universal viscometer with plane-parallel and plane-radial cracks developed by us where the rheological parameters and critical crack openings h_{cr} are determined [13, 14];

– to solve the problems, acceptable differential equations and boundary conditions are selected from the system of existing differential equations. The values of the rheological parameters taking into account the values $h<h_{cr}$ or $h>h_{cr}$ of the investigated fluids are used instead of the rheological parameters in the system of equations.

For illustration, we consider the problem of viscous and anomalous fluid motion between two parallel infinite planes (flat cracked channel). Moreover, the fluid motion is straight-line, parallel and stationary (Fig. 1, 2). The velocity profile looks as shown in Fig. 3 during viscous fluid motion in the $h>h_{cr}$ channel and as in Fig. 4 during fluid motion in the $h<h_{cr}$ channel.

We accept that the motion occurs in the direction of the Z axis. In this case, velocity projections on the X and Y axes will be $V_x=V_y=0y$.

We suggest that fluids move between two plates located at a $2h$ distance from each other, i.e. with a $2h$ opening.

To describe the mechanical behavior of a viscous fluid in the $h>h_{cr}$ channel, we use the Newton's model, i.e.

$$\tau_1=\eta_1\frac{dV_z}{dx}, \tag{7}$$

and for anomalous fluid in the $h<h_{cr}$ channel, we accept, for example, the Shvedov-Bingham model, i.e.

$$\tau_1=\eta_1\frac{dV_z}{dx}+\tau_0, \tag{8}$$

where η_1 – viscosity determined in known viscometers of a viscous fluid; η_2 – structural viscosity of an anomalous fluid; τ_0 – ultimate stress of an anomalous fluid; 1 and 2 indices determine stresses and viscosities of viscous and anomalous fluids found in the universal viscometer; τ – fluid shear stress equal to $\frac{\Delta px}{l}$; l – channel length.

The differential equation with the following boundary conditions is obtained from the system of differential equations for a viscous fluid [16].

$$-\eta_1\frac{dV_{1x}}{dx}=\frac{\Delta px}{l}, \tag{9}$$

$$\text{at } X=h;\ v_{1z}=0 \text{ and } X=0\ \ \frac{dV_{1z}}{dx}=0. \tag{10}$$

The differential equation [16] with the following boundary conditions is obtained from the differential equation system for a viscous-plastic fluid.

$$-\eta_2\frac{dV_{2z}}{dx}=\frac{\Delta px}{l}-\tau_0, \tag{11}$$

$$\text{at } x=h; V_{2z}=0 \text{ and } x_{01}=\frac{\tau_{01}\cdot l}{\Delta p_1}, \tag{12}$$

$$x=x_0,\ \ V_{2z}=V_{2z}(x_0).$$

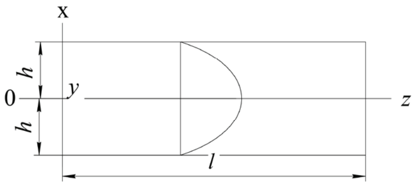

Fig. 3. Computational scheme of viscous fluid motion in the $h>h_{cr}$ channel

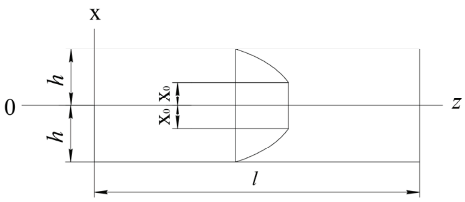

Fig. 4. Computational scheme of anomalous fluid motion in the $h<h_{cr}$ channel

We note that equations (9) and conditions (10) for viscous, as well as equation (11) and conditions (12) for viscous-plastic fluids, can be used during these fluids motion in the plane cracked channel with an opening $h>h_{cr}$, with η_1, η_2 and τ_0 rheological parameters being defined in capillary or rotary viscometers.

For the mechanical behavior of viscous and viscous-plastic fluids during their motion in the flat channel with an opening $h<h_{cr}$, equations (11) are used taking into account conditions (12). In this case, the rheological constant models (4) and (5), i.e. η_1, η_2 and τ_0, and the critical channel opening value h_{cr} should be determined in a viscometer with flat or flat-radial channels [14].

We determine the flow rate of the investigated fluids for the following cases and compare their values for error estimation:

– before scientific discovery recognition, i.e. "microcrack-fluid" effect, the fluid flow rate will be:

$$Q_1\left(h=h_{cr}\right)=\frac{2}{3}\frac{\Delta p_1h^3}{\eta_1 l}\left(1-\frac{2}{3}\bar{x}_{01}+\frac{1}{3}\bar{x}_{01}^3\right), \tag{13}$$

where $\bar{x}_{01}$ – flow core radius, η_1 – fluid viscosity found in known viscometers – after recognizing the "microcrack-fluid" effect, the flow rate will be

$$Q\left(h=h_{kp}\right)=\frac{2}{3}\frac{\Delta p_2h^3}{\eta_2 l}\left(1-\frac{3}{2}\bar{x}_{02}+\frac{1}{3}\bar{x}_{02}^3\right), \tag{14}$$

$$\bar{x}_0=x_0/h;\ \ x_{02}=\frac{\tau_{02}l}{\Delta p_2},$$

where $\bar{x}_{02}$ – flow core radius, η_2 – structural viscosity and τ_{02} – ultimate shear stress found in a viscometer with cracked channels [14, 15].

$$\frac{Q_1\left(h_{kp}\right)}{Q_2\left(h_{kp}\right)}=\frac{\Delta p_1\eta_2}{\Delta p_2\eta_1}\frac{1-\frac{3}{2}\bar{x}_{01}+\frac{1}{3}\bar{x}_{01}^3}{1-\frac{3}{2}\bar{x}_{02}+\frac{1}{3}\bar{x}_{02}^3}, \tag{15}$$

$$\alpha=\frac{\Delta p_1\eta_2}{\Delta p_2\eta_1};\ \ \frac{1-\frac{3}{2}\bar{x}_{01}+\frac{1}{3}\bar{x}_{01}^3}{1-\frac{3}{2}\bar{x}_{02}+\frac{1}{3}\bar{x}_{02}^3}=f\left(\bar{x}_0\right),$$

$$\beta = \frac{Q_1\left(h_{kp}\right)}{Q_2\left(h_{kp}\right)} = \frac{\alpha}{f\left(\bar{x}_0\right)}. \qquad (16)$$

We determine the quantitative value β using (16) at $h<h_{cr}$ and $\Delta P_1 \cong \Delta P_2$.

Using the data from known experimental investigations of water in the plane-parallel crack [13, 14], at $h=10^{-5}$ m and $T=303$ K, we have:

$h_{cr}=25\cdot10^{-6}$, $\eta_1=0.721$ Pas, $\eta_2=3.96$ Pas,

$\Delta P_1=\Delta P_2=4.3\cdot10^5$ Pa; at $h<h_{cr}$ $\tau_0=1.8$ Pa, at $h\geq h_{cr}$ $\tau_0=0$.

Substituting these values into the formula (16) for water, β is calculated, at $h<h_{cr}$.

$$\frac{Q_1\left(h_{kp}\right)}{Q_2\left(h_{kp}\right)} = \frac{\Delta p_1 \eta_2}{\Delta p_2 \eta_1} \frac{1\frac{3}{2}\bar{x}_{01}^2 + \frac{1}{3}\bar{x}_{01}^3 -}{1-\frac{3}{2}\bar{x}_{02}^2 + \frac{1}{3}\bar{x}_{02}^3} =$$

$$= \frac{4.3\cdot10^5\cdot3.960\cdot10^{-3}}{4.3\cdot10^5\cdot0.721\cdot10^{-3}} \times$$

$$\times \frac{1}{1-\frac{3}{2}\cdot0.126^2+\frac{1}{3}\cdot0.126^3} = 5.616.$$

Similar calculations are carried out for anomalous oil at a crack opening $h=115\cdot10^{-6}$ m and temperature $T=303$ K, we obtain: $h_{cr}=16\cdot10^{-5}$ m, $\eta_1=1.529$ Pas, $\eta_2=2.420$ Pas, $\Delta P_1=\Delta P_2=$ $=4.5\cdot10^5$ Pa; at $h<h_{cr}$ $\tau_0=22$ Pa, at $h\geq h_{cr}$ $\tau_0=16$ Pa.

$$\frac{Q_1\left(h_{cr}\right)}{Q_2\left(h_{cr}\right)} = \frac{\Delta p_1 \eta_2}{\Delta p_2 \eta_1} \frac{1-\frac{3}{2}\bar{x}_{01}^2 + \frac{1}{3}\bar{x}_{01}^3}{1-\frac{3}{2}\bar{x}_{02}^2 + \frac{1}{3}\bar{x}_{02}^3} =$$

$$\frac{4.5\cdot10^5\cdot1.529}{4.5\cdot10^5\cdot2.420} \frac{1-\frac{3}{2}\cdot0.093^2+\frac{1}{3}\cdot0.093^3}{1-\frac{3}{2}\cdot0.130^2+\frac{1}{3}\cdot0.130^3} = 0.640.$$

So, when determining viscous fluids flow rate, β=5.616, i.e. fluids flow rate will be 5.616 times as much, but for abnormal fluids, *β*=0.640. This fact is explained accordingly to minimize the formation of the near-wall layer. According to our experiments, this is the manifestation of the "microcrack-fluid" effect.

5. 5. Obtaining a dependence for the transition from plane-parallel and plane-radial fracture models to a real porous medium

For the transition from the model of a plane-parallel and plane-radial channel to a porous medium, based on dependences (1) and (2), calculations were carried out to determine the reservoir permeability, respectively, during the movement of viscous and anomalous fluids [13].

It should be noted that when a certain value of reservoir permeability K is less than the critical value ($K<K_{cr}$), the "microcrack-fluid" effect is manifested.

The estimation of the critical crack opening value corresponding to the equivalent effective permeability of the porous medium allows determining the presence of the "microcrack-fluid" effect on the investigated objects of oil fields.

On the basis of the crack opening estimation, it becomes possible to indirectly judge the state of the bottomhole zone, which is of great importance for increasing the success of various stimulation techniques on the formation, as well as to avoid unreasonable measures.

The equivalent layer permeability can be calculated from the results of micron-sized cracks h_{cr}. It was determined that the "microcrack-fluid" effect prevents fluid motion when $K<K_{cr}$. This effect doesn't prevent the fluid motion in the reservoir when $K>K_{cr}$. Therefore, in order to move the fluid into stagnant zones, certain reservoir fields must be transferred from the $K<K_{cr}$ state to the $K\geq K_{cr}$ state or the mechanical parameters of the fluid must be reduced, i.e. τ_{0h} and μ_h. This fact was confirmed during the impact processes of the well bottomhole zone of OGPD (Azerbaijan).

It should be noted that the "microcrack-fluid" effect manifests in all fields when a certain value of reservoir permeability K is less than the critical value ($K<K_{cr}$).

6. Discussion of the results of the study of hydrodynamic features of the movement of various fluids in microcrack channels

It is experimentally shown that the ultimate shear stress during the movement of various liquids in microcracks depends on the crack opening and the properties of liquids. It follows from Fig. 1, 2 that the flow curves of fluids in a microcrack are described by nonlinear equations, which are typical for non-Newtonian systems. These curves pass through the origin and are concave towards the shear stress axis.

We determined that during water motion in rectangular and plane-radial cracks with 10÷50 μm dimensions, the critical crack opening value at 303 K is 25 and 30 μm, respectively. It is 130 and 180 μm for Newtonian and non-Newtonian oil at a temperature of 303 K, respectively.

It was experimentally revealed that the cause of anomalous properties of viscous fluids and particularly water and the increase in these properties for anomalous fluids in cracks is a new micro-cracked effect in the "fluid-medium" system. So, we determined the critical opening value h_{cr} on the basis of experimental investigations in cracks. It was found that at $h<h_{cr}$, the anomalous properties are manifested for viscous fluids and rheological parameters are increased for anomalous fluids, and at $h\geq h_{cr}$ these effects disappear.

The manifestation of the "microcrack-liquid" effect could be explained by an analog of the Euler effect on the stability of the rod. From the models of the anomalous behavior of fluids, it follows that in a crack with small thickness, the fluid under the action of forces applied at the ends of the crack in the conditions of comparatively low average shear rates can behave like a stable compressed rod and has a certain form of equilibrium in the crack. The stable rod-shaped form of the fluid equilibrium depends on the crack thickness. If the crack thickness is small, then the forces applied at the crack ends press the fluid rod to the crack walls. Changes occur in the fluid jet properties due to changes in its structure and friction forces on the walls. With increasing crack thickness, the micro-cracked effect disappears. Between these two equilibrium states, there is a so-called critical state wherein fluid can preserve initial properties. This crack thickness is called critical.

So, it was determined that the cause of the anomalous fluids behavior in the microcrack with an opening $h<h_{cr}$ is the "microcrack-fluid" effect.

As a result of experimental investigations, it was revealed that crack opening is one of the main indices characterizing the properties of fluid flow in a fractured system. The study and assessment of the influence of the opening on the fluid properties in microcracks allow us to substantiate scientifically and develop various new technological processes.

It was found that the known differential equations of motion of viscous and anomalous fluids obtained in hydrodynamic mechanics can be used for microcrack channels, if in these equations, instead of rheological parameters, we take rheological parameters taking into account the crack opening $h<h_{cr}$ determined in the universal viscometer developed by us with plane-parallel and plane-radial cracks where rheological parameters and critical crack openings h_{cr} are determined.

For the transition from a microcrack to a porous medium, based on dependences (1) and (2), calculations were carried out to determine the reservoir permeability, respectively, during the movement of viscous and anomalous fluids. When a certain value of the reservoir permeability K is less than the critical value ($K<K_{cr}$), the "microcrack-liquid" effect appears.

The obtained critical values of the crack opening differ from the known values of the boundary layer thickness.

Estimation of the critical crack opening value, corresponding to the equivalent permeability of a porous medium, makes it possible to determine the presence of the "microcrack-liquid" effect on the studied objects of oil fields. As a result, it becomes possible to indirectly judge the state of the bottomhole zone of the well, which is of great importance for increasing the efficiency of various methods of influencing the formation, as well as avoiding unreasonable measures.

Based on experimental results, we have developed fluid and gas hydromechanics in microcracked channels, which can be used to analyze various processes of oil field development of porous, porous-fractured and fractured reservoirs, the hydromechanics of lubrication procedures of aggregate units in various branches of the industry.

The results obtained can probably be explained by the manifestation of a molecular obstacle in the fracture system, which will be specified in further studies. This requires further experimentation and perhaps an explanation for each research objective reflecting the results discussed.

The proposed solutions to the research results make it possible to close the problem area indicated by the author, with obtaining the rheological patterns of various fluids in microfracture channels, and the mechanical behavior of the fluid within the crack opening at $h<h_{cr}$ and $h>h_{cr}$.

To identify the problem of the set goal, the obtained results using the evidence base are the mechanical behavior of the fluid in the crack with an opening $h<h_{cr}$ and $h>h_{cr}$.

As noted, viscous fluids (water and oil) when moving in cracks with dimensions $h\leq h_{cr}$ acquire the character of anomalous fluids, and anomalous fluids further enhance their rheological parameters. When these fluids move in cracks with dimensions $h>h_{cr}$, their rheological parameters do not change.

The advantages of this study in comparison with those known on this topic undoubtedly lie in the fact that it defines a new direction in the mechanics of liquid, gas and plasma in channels with micron openings.

So, it is proposed to solve any problem using the known differential equations obtained by the author [16] using the rheological parameters obtained in a universal viscometer.

There are limitations to using differential equations with rheological parameters in a universal viscometer.

The disadvantage of the study is the determination of the exact mechanism of the "microcrack-liquid" effect, which requires additional experimental study.

7. Conclusions

1. Non-Newtonian properties are manifested in the crack-fluid system during viscous fluid flow into cracks with an opening $h<h_{cr}$, non-Newtonian properties are increased for anomalous fluids but these effects are absent at $h>h_{cr}$. It was found that the cause of the nonlinear effect during Newtonian fluid flow, as well as the strengthening of anomalous phenomena of non-Newtonian fluids in microcapillary cracks, is the value of crack opening.

2. For water and kerosene, the critical crack opening values h_{cr} at temperatures of 303 and 313 K are 25, 22 µm and 65, 55 µm; and for viscous and abnormal oil at temperatures of 303, 313, 323, 333 K, respectively, 130, 115, 100, 90 and 160, 130, 115, 105 µm. For a 0.3 % PAA solution at temperatures of 303, 313, 323, 333 K, respectively, 90, 72, 60, 48 µm, and for water with 0.15, 0.06 and 0.03 % PAA solutions at a temperature of 303 K, respectively, 60, 50, and 42 µm. The critical crack opening value for water in a plane-radial crack at temperatures of 293 and 303 K is 35 and 30 µm, respectively, and for anomalous oil at a temperature of 303 K – 180 µm.

3. The "microcrack-fluid" effect is a change in the mechanical properties of fluids when moving in channels having dimensions $h<h_{cr}$ and their recovery when moving in channels having dimensions $h\geq h_{cr}$. This phenomenon is explained by the change in the fluid flow properties due to changes in its structure and friction forces on the crack walls. Water has non-Newtonian properties at $h<h_{cr}$ but this effect disappears and fluid retains its original properties at $h>h_{cr}$.

4. It was suggested that the power-law, Shvedov-Bingham, Shulman-Casson rheological models are used for the motion of viscous and anomalous fluids in the micron-sized channels at a crack opening $h<h_{cr}$.

The acceptability of the known differential equations taking into consideration the rheological parameters of fluids obtained in a universal viscometer is shown for solving the problems of the anomalous fluid motion in microcracked channels at a crack opening $h<h_{cr}$.

5. It was revealed that during fluid motion in a porous medium with permeability $K<K_{cr}$, there is an additional force due to the effect of the "microcrack-fluid" systems and preventing fluid motion.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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