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Rheological peculiarities of fluids flow in microcracked channels

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1. Introduction

The fluids flow research in the microcracked channels is of great theoretical and practical interest for the various technological processes analysis in industry especially in oil production.

Starting with XIX century these considered questions in both the theoretical and the experimental plan were interested by scientists.

This issue theoretically as the basis for the fluid and gas flow with the manifestation of some peculiarities has been considered in [1-3]. Experimentally they have been considered in works [4-10].

The careful analysis of recent investigations has shown the following:

The reasons for abnormal behavior manifestation of fluids in microcrack have insufficiently investigated yet. There are different assumptions about the manifestation of abnormal hydrodynamic fluids behavior during flow on micron-sized channels [9].

Numerous works analysis has showed that the viscous fluid during flow in microcapillary cracks, in specific range of cracks sizes, behaves as non-Newtonian system [2, 3, 9 and others]. For example, it is assumed that Newtonian fluids form anomalous boundary layer, having a high viscosity and limiting shear stress during the motion in the microcapillary cracks. Boundary layers can be in solid or liquid states and their properties are changed up to the mechanical strength.

Due to numerous investigations it was determined that the boundary layers of the polar fluids, being in a medium of the surface forces action, have specific mechanical properties in comparison with these fluids properties in bulk, that is due to their different submolecular structure. The boundary layers properties of the fluids, depending on the physical-chemical properties of solid body, discovered by the English scientist W. Hardy, have high mechanical strength, able to withstand very heavy loads.

However, problems on possible values of the near-wall layer thickness of fluid with anomalous properties have not been resolved up to the present. The considerable amounts of investigations have been devoted to experimental determination of the boundary layer thickness of fluid, having anomalous properties.

The influence of the crack opening size on mechanical properties of fluid hasn't been indicated in none of these investigations. The rheological parameters of the fluid in the cracks are accepted regardless of opening in all these works. The crack opening sizes haven't been taken into consideration in all works according to the fractured oil and gas fields' development. It is the reason for the low level of oil recovery.

2. The experimental investigations results, their processing and generalization.

At present, based on the conducted numerous experimental and theoretical investigations a big factual material on study of Newtonian fluids flow in thin cracks has accumulated. However, there is no consensus on the mechanism of the anomalous behavior manifestation of Newtonian fluids and rheological properties strengthening of the non-Newtonian systems in the microcapillary cracks. Therefore, the detected quality effects aren't considered fully in the technological processes of the industry and in the practice of oil recovery from these reservoirs.

For quantitative assessment there aren't the calculated dependences and methods considering sufficiently the peculiarities of the fluid flows in microcracks, based on determination of the major indices of motion process and on prediction of the anomalous phenomena manifestations. This has a significant impact on quality of the design, control and on regulation of the processes at oil deposits confined to microcracked channels, as well as on their reserves recovery efficiency.

In earlier works, V. Hardy noted that fluid layer was independent on the nature of fluids and gases, and was equal to 4 μm. Therefore, the surface layers thicknesses of the fluids haven't been clearly determined yet.

We have determined that during water movement in the rectangular and plane radial cracks with sizes of 10-50 μm the critical values of the crack opening are 25 and 30 μm at 303 K temperature, respectively. The obtained critical values of the crack opening are different from the known values of the boundary layers thickness [8, 9].

The article object is not in revealing the considered process mechanism but in qualitative assessment of this phenomenon. In order to study the cause of nonlinear effects manifestation during the flow of Newtonian and non-Newtonian fluids in microcrack, stationary and non-stationary fluids flow in plane-parallel and plane radial cracks the experimental investigations were conducted at the unit allowing creation of the plane and radial cracks with different opening [8-10]. The slotted models design simulating the plane-parallel and plane radial fluid flow in the microcracked medium have been given in [8,10] works.

The experimental investigations of the fluids flow in the plane radial crack were conducted in two series. The fluid flow from the well to the circuit (at injection) was simulated in the first series, but in the second one – from the circuit to the well (at production). In both series, the experiments were conducted in stationary mode of the fluid flow.

During fluid flow in the microcrack (for exception of the Jamin effect influence) the crack saturation with simultaneous vacuuming were produced at low pressure by the investigated fluid.

Water, highly resinous non-Newtonian oil with 72% resin content (Oil-and-Gas Production Department (OGPD) "Shirvanneft") were used as investigated fluid.

The peculiarities of water and abnormal oil flow in microcracks of various opening have been investigated on the developed experimental facility. The experiments were carried out in the following way: different pressure drops were created on fracture model after reaching steady-state regime of filtration on each pressure drop, the appropriate volumetric water discharges-Q were measured.

The experimental results were processed in $\gamma - \tau$ coordinates for revealing investigated fluids behavior in the cracks where the average shear rate -γ and shear stress - τ on the crack walls with respect to the radial flow conditions were calculated by the formula [11]:

$$\tau_w = \frac{\Delta P h}{L}, \quad (1)$$

$$\gamma = \frac{Q}{4\pi r h^2}. \quad (2)$$

The experimental investigations show that during water flowing in microcrack ($h < h_{cr,}$), the dependence - $\tau = f(\gamma)$ has the form characteristic of abnormal fluids, i.e. they are described either by power law model or by Shvedova-Bingham model but during water flowing in microcrack ($h \geq h_{cr}$) the dependence - $\tau = f(\gamma)$ is right line, i.e. it is described by a single parameter - viscosity.

Non-Newtonian properties are increased in the case of abnormal oil flow in flat and plane radial cracks with opening of $h < h_{cr}$ in fluid-crack system but at $h > h_{cr}$ these mentioned effects are absent. Consequently the dependence- $\tau = f(\gamma)$ at $h \leq h_{cr}$ as well as at $h \geq h_{cr}$ is described by two parametric models.

Taking into consideration that the engineering oilfield problems occur usually at high velocity gradients therefore Shvedov-Bingham model has been used in this work, i.e. mechanical properties of the fluid in the cracks are characterized by limiting shear stress - τ_{0h} and apparent viscosity - μ for high gradients of shear rate.

The parameters of limiting shear stress - τ_{0h} and apparent viscosity - μ have been defined by approximation of straight-line part of curve $\tau = f(\gamma)$.

Based on graphic charts of $\gamma = \gamma(\tau)$ the yield stress of τ_{oh} and structural viscosities of μ_h at temperature of 293 and 303 K were estimated for Newtonian and non-Newtonian fluids.

There have been generalized the results of experimental investigations of the water and anomalous oil flow in the plane radial microcrack.

The results of the nondimensional values change - τ_{0h}/τ_{0max} (the ratio of limiting shear stress to the maximum value, τ_{0max} — the largest value of the limiting shear stress at h = 10 μm (micron) of crack opening, Pa) and μ_h/μ_{cr} (the ratio of the apparent viscosity to the critical value) depending on h/h_{cr} (the ratio of opening to the critical value) for water have been represented respectively in Figs. 1, 3 and 2, 4.

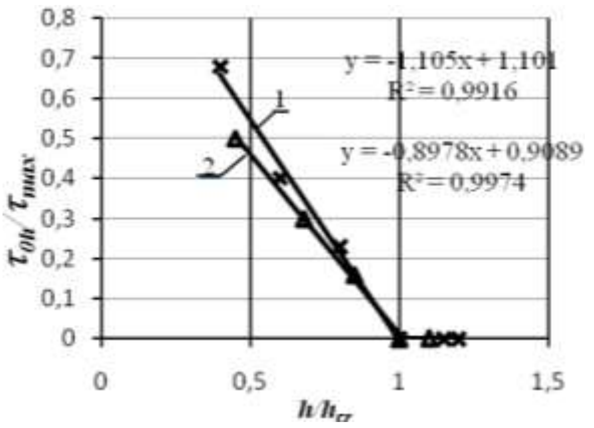

Fig. 1 Dependence of τ_{0h}/τ_{0max} from h/h_{cr} during water movement in plane parallel crack: *1, 2* — respectively at T = 303 (h_{cr}=25μm, τ_{0max}= 8 Pa) and T = 313 K (h_{cr}=22 μm, τ_{0max} = 1.7 Pa)

It should be noted that fluid practically retains its initial properties at $h \geq h_{cr}$.

Figs. 1, 2 and 3-6 correspond to the water motion in plane-parallel and plane radial cracks. It has been determined that during viscous fluid flow in thin radial crack there are manifested non-Newtonian properties that decrease with increasing crack opening. The limiting yield stress is equal to zero but apparent viscosity remains constant during water motion in plane radial crack at openness values of 30 and 35 μm, at 303 and 293 K temperatures, respectively, in both the first and second experiments series (Figs. 3-6). During water motion in the plane-parallel crack the limiting shear stress is equal to zero, and the apparent viscosity remains constant at opening values of 22 and 25 μm, at 313 and 306 K temperatures, respectively (Figs. 1 and 2). At the critical value of crack opening the viscosity (μ_{cr}) for water at 293 and 303 K temperatures is 0.0011 Pa·s and 0.0008 Pa·s, respectively. The largest limiting shear stress value (τ_{omax}) at minimum opening of the plane radial crack for water at 293 and 303 K temperatures are 3.2 and 2.4 Pa, respectively.

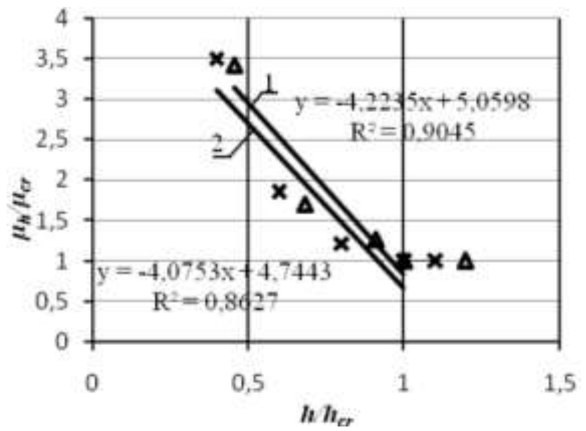

Fig. 2 Dependence of μ_h/μ_{cr} from h/h_{cr} during water movement in plane parallel crack: *1, 2* — respectively at T = 303 (h_{cr} = 25μm, μ_{cr} = 0.00072 Pa·s) and T = 13 K (h_{cr} = 22 μm, μ_{cr} = 0.00069 Pa·s)

For plane parallel and plane radial cracks, the following equations have been obtained:

$$\frac{\tau_{0h}}{\tau_{0max}} = a_1 - b_1 \frac{h}{h_{cr}} \quad (3)$$

$$\frac{\mu_h}{\mu_{cr}} = a_2 - b_2 \frac{h}{h_{cr}} . \quad (4)$$

Based on test results, the values of a_1, a_2 and b_1, b_2 coefficients have been defined for plane radial and plane parallel cracks, which have been presented in the Table.

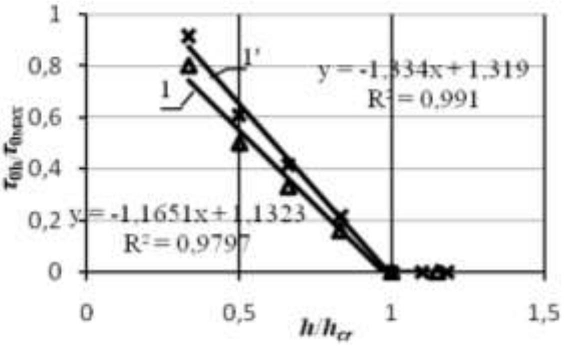

Fig. 3 Dependence of τ_{0h}/τ_{0max} from h/h_{cr} during water movement into the plane radial cracks (h_{cr} = 30 μm, τ_{0max} = 2.4 Pa) at T = 303 K: *1* and *1'* — respectively in the first and the second tests series

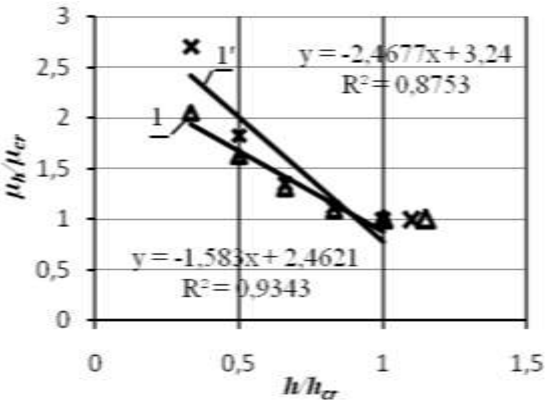

Fig. 4 Dependence of μ_h/μ_{cr} from h/h_{cr} during water movement in the plane radial cracks (h_{cr} = 30 μm, μ_{cr} = 0.0008 Pa·s) at T = 303 K: *1* and *1'* — the same as in Fig. 3

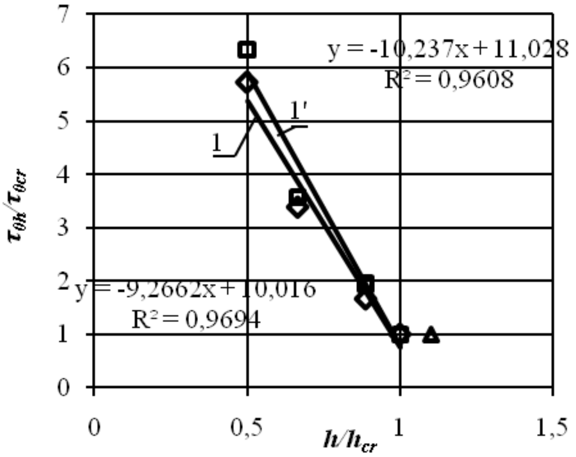

Fig. 5 Dependence of τ_{0h}/τ_{0cr} from h/h_{cr} during non-Newtonian oils motion in the microcrack (h_{cr} = 180 μm, τ_{0cr} = 65.46 Pa at the first test series and τ_{0cr} = = 77.74 Pa at the second ones) at T = 303 K: *1* and *1'*— the same as in Fig. 3

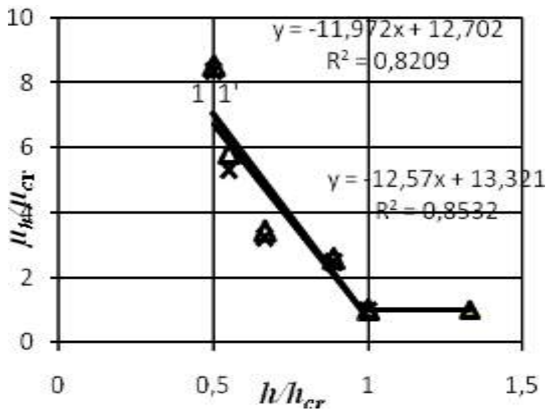

Fig. 6 Dependence of μ_{0h}/μ_{cr} from h/h_{cr} during non-Newtonian oils motion in the microcrack (h_{cr}=180μm, μ_{cr} = 79.16 Pa·s at the first tests series and μ_{cr} = = 82.59 Pa·s at the second one) at T = 303 K: *1* and *1'*— the same as in Fig. 3

It should be noted that based on experimental studies for oil samples produced from the investigated well, the μ_{cr} and h_{cr} values are determined on the slotted model and there is found this oil belonging to the non-Newtonian or Newtonian.

The results of the nondimensional values change - τ_{0h}/τ_{0cr} (the ratio of limiting shear stress to the critical value) and $\mu h/\mu_{cr}$ depending on h/h_{cr} for abnormal oil have been represented respectively in Figs. 5 and 6.

In the case of non-Newtonian oil flow in plane radial crack with increasing yield stress opening and apparent oil viscosity is decreased up to certain value of the crack opening. Both in the first and in the second test series the yield stress and apparent viscosity do not depend on h and remain constant at 303 K temperature at 180 μm opening values. The remarkable thing is that the limiting shear stress and apparent viscosity for non-Newtonian oils at $h = h_{cr}$ is τ_{0cr} = 65.46 Pa, μ_{cr} =79.16 Pa·s at first test series and τ_{0cr}= 77.74 Pa, μ_{cr} = 82.59 Pa·s at second one, respectively.

So it has been determined experimentally that there is a critical value (h_{cr}) of opening value below which limiting shear stress- τ_{0h} and apparent viscosity- μ_h are increased appreciably.

It has been defined that the critical values of crack opening at 293 and 303 K temperatures for water are 35 and 30 μm respectively; but at 303 K temperature for Non-Newtonian oil is 180 μm.

The boundary condition is the critical size of the crack opening in this work. The tested fluid (water, viscous fluid and abnormal fluid) during flow in crack at $h < h_{cr}$ size water and viscous fluid change their mechanical properties, i.e. behave as abnormal fluid but restore their initial properties in the crack – $h \geq h_{cr}$.

Non-Newtonian properties are increased during abnormal fluids flow in the crack with $h<h_{cr}$ size but at $h \geq h_{cr}$ the mentioned effects are absent, i.e. limiting shear stress and apparent viscosity remain constant.

Figs. 1-6 show that the dependence of τ_{0h}/τ_{cr} = = $f(h/h_{cr})$ and μ_h/μ_{cr} = $f(h/h_{cr})$ consists of two right lines, the first right line is characteristic of the opening value with $0 < h/h_{cr} < 1$ size where all fluids have changed their mechanical behavior. Moreover the water and all viscous fluids have become abnormal and the abnormal fluids increase Non-Newtonian properties. The second right line is characteristic of the crack opening values with sizes of $h/h_{cr} \geq 1$ thereby water and all viscous and abnormal fluids restore their mechanical behaviors, i.e. the second right line is not a continuation of the first right line so these right lines are characterized the different behaviors of the fluid. The difference of τ_{0h} and μ_h values, defined in both the first and the second test series, is explained by initiation of local resistances and flow nature during injection (one direction) and selection (opposite direction).

Table

The values of a_1, a_2 and b_1, b_2 coefficients at flow of Newtonian and non-Newtonian fluids in plane radial and plane-parallel cracks

Fluid	Determined parameters	Coefficients											
		At plane radial								At plane parallel			
		At heating				At production				At production			
		Temperature, K											
		293		303		293		303		306		313	
		a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
Water	$\frac{\tau_{0h}}{\tau_{0max}}$	1.212	1.216	1.132	1.165	1.184	1.212	1.319	1.334	1.104	1.105	0.909	0.898
	$\frac{\mu_h}{\mu_{cr}}$	3.067	2.657	2.462	1.583	2.821	2.098	3.479	2.269	5.060	4.224	4.744	4.075
Anomalous oil	$\frac{\tau_{0h}}{\tau_{0cr}}$	-	-	10.017	9.266	-	-	11.028	10.237	2.570	1.168	2.470	1.390
	$\frac{\mu_h}{\mu_{cr}}$	-	-	14.460	14.242	-	-	14.198	14.019	0.010	1.020	0.420	0.580

3. Discussion of results

In system of crack with small thickness, the Newtonian and non-Newtonian fluids under the applied forces action at the crack ends in the conditions of relatively low average velocities can behave as stable compressed core and have known form of equilibrium in the crack. The stable core-form of equilibrium depends on the crack thickness. If the thicknesses of the thin crack are small, then the forces, applied at the crack ends, press fluid core to the crack walls. There are happened changes in the fluid flow properties due to its structure changes and friction forces on the walls. The microcracked effect disappears due to increasing crack thickness. It fluid is Newtonian, then non-Newtonian properties are manifested in its but if the fluid is non-Newtonian, so non-Newtonian fluid properties are increased.

Jamin effect is origin of the additional back-pressure in the porous medium due to the fact that the pore channel presents capillaries structure of the variable radius and forms. The radii inequalities of the meniscus curvature create those additional forces that are pushing the liquid-gas mixture in the pore volume.

Between these two states of equilibrium, there is one called as critical wherein fluid can keep the original property. That kind of crack thickness is called the critical.

As a result of experimental investigation it was revealed that the cracks opening is one of the main indices characterizing the fluid filtration properties in fractured reservoirs. Study and assessment of the opening influence on the fluids properties in plane radial microcrack enable to substantiate scientifically and to develop a new oil production technology.

In order to study of the microcracked effect influence on water flow process, the experimental investigations were carried out in plane-parallel cracks with variable opening. Fluid through the first crack having $h > h_{cr}$ opening, flows to the second crack with $h < h_{cr}$ opening, then to the third with $h > h_{cr}$ opening. The experimental results were processed in $\gamma - \tau$ coordinates at $Q = const$ and had been shown in Fig. 7. As can be seen from Fig. 7, the experimental data for water don't fall on a straight line but fall on three separate lines for different values of crack opening.

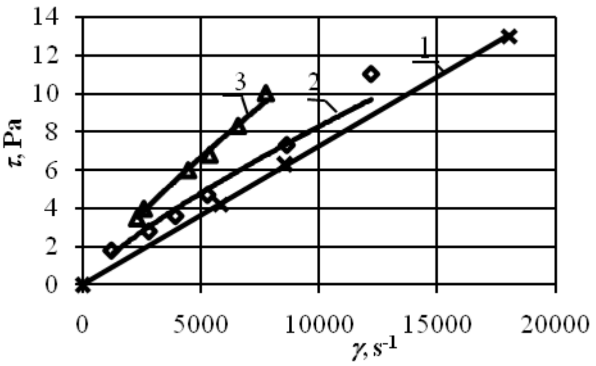

Fig. 7 Dependence of τ_h from γ during water movement in the plane parallel crack: *1* – $h = h_{cr} = 25$; *2* – $h < h_{cr} = 20$ and *3* – $h < h_{cr} = 15$ μm

This phenomenon is explained by the change in the fluid flow properties due to its structure change and friction forces on the crack walls. Water has non-Newtonian property at $h < h_{cr}$ but this effect disappears and fluid retains its original properties at $h > h_{cr}$.

First, based on the experimental data we have determined the critical opening value of h_{cr}, i.e. it has been determined that above-mentioned changes are practically disappeared at $h > h_{cr}$ in the fluids properties.

Therefore, the critical value determination of the cracks opening is one of the main indices characterizing the filtration properties of the fractured reservoirs. At values below h_{cr}, the filtration characteristics of the bottom-hole formation zone are significantly deteriorated resulting in reduction of wells production capacity. Therefore, preliminary estimation of the crack opening allows to increase the effectiveness of the carried out measures and to predict the operations success.

4. Summary

The conducted investigations' results indicate the necessity of fracture factor consideration for estimation of "fluid – crack" system parameters that is of scientific and practical importance to the design and construction of machines - mechanisms preparation with lubricant processes improvement and to the rational development of oil and gas fractured fields.

5. Conclusion

1. The bases of fluids mechanics in the cracks have been developed by experimental research and theoretical generalization of Newtonian and non-Newtonian fluids flow in the fractured channels.

2. Non-Newtonian properties are manifested in the system of crack-fluid during viscous fluids flow into cracks with $h < h_{cr}$ opening, non-Newtonian properties are increased for anomalous fluids but these effects are absent at $h > h_{cr}$.

3. These effects occur in the crack-fluid system only at $h \leq h_{cr}$.

4. It has been determined experimentally that after fluids seepage from the cracks, the above-mentioned effects are absent.

5. The obtained microcracked effect for homogeneous fluid purified from air or gas is an analog of Jamin effect and it is called as microcracked fluid effect.

6. This effect can increase still further Jamin effect at two-three phase systems of fluid flow in microcrack.

7. The empirical dependences: $\frac{\tau_{0h}}{\tau_{0max}} = f\left(\frac{h}{h_{cr}}\right)$, $\frac{\mu_h}{\mu_{cr}} = f\left(\frac{h}{h_{cr}}\right)$ and $\frac{\tau_{0h}}{\tau_{0cr}} = f\left(\frac{h}{h_{cr}}\right)$ have been obtained respectively for Newtonian and non-Newtonian fluids in plane radial crack at 293 and 306 K temperatures that can be used for prediction of the fractured reservoirs parameters, as well as for the rheological fluids parameters.

8. Based on assessment of the crack opening there occur an opportunity to estimate indirectly the bottom-hole zone state, that is of great importance for improvement of the various simultaneous methods carrying out, as well as to avoid the unreasonable measures carrying out.

9. The stimulation methods on formations as well as bottom-hole zone by powerful energy fields should contribute to increase cracks opening of the oil and gas fields of viscous and abnormal oils.

10. To ensure the increase of the crack opening size above its critical value it is reasonable to conduct formation stimulation by powerful ultrasonic, hydrodynamic, acoustic and other methods. Therefore it is necessary to use special generator- installations.

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RHEOLOGICAL PECULIARITIES OF FLUIDS FLOW IN THE MICROCRACKED CHANNELS

S u m m a r y

It has been determined that the cause of the non-linear effect manifestation during Newtonian fluids flows as well as strengthening of the anomalous phenomena of non-Newtonian fluids in microcapillary cracks is value of crack opening.

Non-Newtonian properties are manifested in the system of crack-fluid during viscous fluids flow into cracks with $h \leq h_{cr}$ opening, non-Newtonian properties are increased for anomalous fluids but these effects are absent

at $h > h_{cr}$. These effects occur in the crack-fluid system only at $h \leq h_{cr}$. It has been determined experimentally that after fluids seepage from the crack, the above-mentioned effects are absent.

The obtained microcracked effect for homogeneous fluid purified from air or gas is an analog of Jamin effect and it is called as microcracked fluid effect. This effect can increase still further Jamin effect at two-three phase systems of fluids flow in microcrack.

The critical values of the crack opening have been determined wherein the above-mentioned changes in the fluids properties are practically disappeared.

The stimulation methods and bottom-hole zone due to powerful energy fields of oil-and-gas fields with fractured rocks should promote increasing the cracks opening of the oil-and-gas fields of the viscous and anomalous oils.

Keywords: Microcrack opening, Non-Newtonian fluids, boundary layer, Jamin effect, limiting yield stress, structural viscosity.

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