Original Research Article:
full paper

(2024), «EUREKA: Physics and Engineering»
Number 1

A RHEOPHYSICAL STUDY OF THE NON-NEWTONIAN BEHAVIOR OF WATER FLOW IN THIN CHANNELS

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Abstract

The development of low-permeable hydrocarbon reservoirs is becoming an increasingly urgent task, and therefore, the study of the laws of fluid movement in subcapillary pores and microcracks is a crucial scientific and technical problem. The previous experimental studies revealed that a viscous liquid during flow in low-permeable reservoirs exhibits an anomalous non-Newtonian character, accompanied by a violation of the linearity of the filtration process, and, consequently, Darcy's law. It was also established that starting from a certain critical size of the opening of the crack, the flow of a Newtonian fluid (water, viscous oil) becomes non-Newtonian, with the manifestation of an initial pressure gradient and flow locking. In this research work, rheophysical aspects of the non-Newtonian behavior of water during flow in thin rectangular channels are considered experimentally. Using the micro-channel model, it is established that the nonlinear rheological effect in the flow of water in micro-slits is mainly caused by the value of the electrokinetic potential of the system, by reducing of which it is possible to significantly weaken the non-Newtonian nature of the fluid. To regulate the electrokinetic potential of the fluid system, an antistatic additive was used, the optimal concentration of which was established experimentally. The optimal concentration is defined to be 0.006 %. Based on the Bingham model, the rheological parameters of water flow were estimated at different micro-slit clearances changed in the range of 10÷25 micrometers, in the absence and presence of an antistatic additive. It is also established that a reduction in the electrical potential of the fluid flow leads to a significant decrease in the yield shear stress during the flow of water in the microchannel.

Keywords: antistatic additives, slit openness, electric double layer, streaming potential, microchannel.

DOI: 10.21303/2461-4262.2024.003050

1. Introduction

Microfluidics or microhydrodynamics, which studies the movement of liquids in thin and ultrathin channels, is one of the relatively new scientific and technical areas of interest in various fields, including chemistry, biology, medicine, as well as oil production [1].

Currently, the development and operation of low-permeable hydrocarbon reservoirs is becoming an increasingly urgent task, and therefore, the study of the laws of fluid movement in subcapillary pores and microcracks is an important scientific and technical problem [2]. Many scientific works have been conducted to study the rheophysical properties of water and hydrocarbon flow in low-permeable and microcrack reservoir [3].

Despite the presence of numerous works, there are some problems in this area that require further study [4]. According to the results of a number of experimental studies, a viscous liquid during flow in low-permeable reservoirs exhibits an anomalous non-Newtonian character, accompanied by a violation of the linearity of the filtration process, and, accordingly, Darcy's law [5, 6]. It was revealed that [7], with a decrease in the openness of the gap in microcracks, starting from a certain critical size, the viscous liquid (water or oil) exhibits a non-Newtonian character, with the manifestation of an initial pressure gradient and flow locking.

However, to date there is no consensus on the mechanism of these phenomena, although there are different approaches to explain the abnormal hydrodynamic behavior of viscous liquids during flow in a low-permeable porous medium and microcracks.

As is known, according to the Koehn rule [8], two substances with different permittivity in contact are charged along the contact surface. In accordance with this rule, when liquid-solid contact occurs on the boundary surface, an electric double layer (EDL) with a certain electrokinetic potential is formed. The boundary of the EDL is rather blurry and its thickness, taking into account the diffusion layer, can be on the order of several microns. The electrostatic field caused by the EDL imposes a certain effect on the character of the flow in the boundary zone. For channels (pipes) of sufficiently large transverse dimensions relative to the flow, this effect is insignificant. However, for narrow slits and tubes of small diameter, in which the transverse dimensions become commensurate with the dimensions of the electric double layer, the situation becomes principally different – the electrostatic field of the EDL becomes an additional factor of hydraulic resistance.

It has been experimentally established that [9], by regulating the electrokinetic potential of the system, it is possible to change the thermohydrodynamic characteristics of the flow in capillaries.

This article presents the results of experimental work on the study of the role of electrokinetic potential in nonlinear effects during the flow of water in microchannels.

2. Materials and methods

The experimental setup mainly consisted of a microchannel model, a high-pressure balloon, and a thermostat. Tap water was used as the working fluid. The microchannel model with a length of 30 cm and a width of 4 cm was formed by two steel plates with a thickness of 1.8 cm installed in parallel. The size of the gap between the plates in the following text will be indicated as the openness of the slit h.

Plates made of steel grade 40X, had a surface hardness of 40–50 Rockwell units (Rockwell), after heat treatment with high frequency current. The inner surface of the plates was treated and sanded with a smoothness corresponding to the 10^{th} category.

Flat microchannels of rectangular cross-section with a clearance of different openness (h) were obtained by installing the corresponding micron-thick non-wettable gaskets between the plates. The experiments were carried out at various values of h in the range of 10÷25 micrometers. To ensure the isothermality of the process, the model was placed completely in a thermobath connected to an ultrathermostat.

To determine the pressure drop, high-precision pressure gauges (with an error of 0.2–0.3 %) were installed at the inlet and outlet of the model. The mass flow rate of the liquid was determined on electronic scales with an accuracy of 0.005 mg.

3. Results and discussion

Upon reaching a steady flow regime, at different values of the clearance openness (h) flow curves for tap water were plotted – $Q = Q(\Delta P)$, dependence of the volumetric flow rate on the pressure drop, in the presence of atmospheric pressure at the outlet of the model.

To identify the hydraulic characteristics of the flow in micro-slits, on the basis of the obtained flow curves, the dependences between the shear stress and the average share rate $\gamma = \gamma(\tau)$ are revealed.

It is known that the volumetric flow rate of a liquid with a steady laminar flow between two stationary parallel plates is defined as $Q = bh^3\Delta P/12\mu L$, where, b, L and h, respectively, are the width, length and openness of a rectangular slit.

The values of γ and τ were determined as $\gamma = 6Q/bh^2$ and $\tau = \Delta Ph/2L$. The curves $\gamma = \gamma(\tau)$ were approximated by the Bingham model, on the basis of which the rheological parameters of the liquid were estimated – the yield shear stress τ_0 and the apparent viscosity μ.

In **Fig. 1** the obtained curves $\gamma = \gamma(\tau)$ for water are presented, for different values of h (15 μm, 20 μm and 25 μm), at a temperature 30 °C.

It is established that the flow curves, related to the microchannels with an openness (h) more than 25 μm, are linear and correspond to the Newtonian model. However, at values $h < h_{cr} = 25$ μm, the flow becomes nonlinear – water behaves like a non-Newtonian fluid with some yield shear stress τ_0 characteristic for Bingham model. The non-Newtonian character of the water becomes more expressive with a decrease in the openness of the slit and the effect is maximally manifested at the lowest value of h (10 μm), in the range considered.

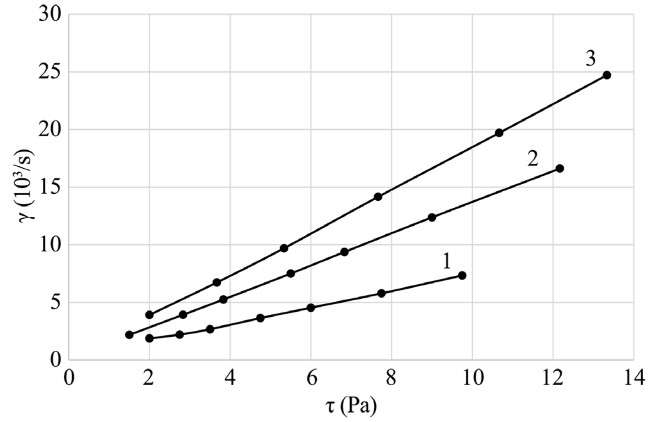

Fig. 1. $\gamma = \gamma(\tau)$ curves for water: 1 – 15 μm, 2 – 20 μm and 3 – 25 μm

The fluid viscosity was calculated with the equation of $\mu = bh^3\Delta P/12QL$. **Fig. 2** shows the dependence of the apparent viscosity of water on the value of the openness (h). As can be seen, with a decrease in h, starting from the critical value (h_{cr} = 25 μm), the value of apparent viscosity increases non-linearly, which is especially pronounced at h = 10 μm. In the higher values of openness h, the change in the value of apparent viscosity is almost insignificant. However, in lower values, as the effect becomes stronger, the apparent viscosity is significantly increased up to 3 folds.

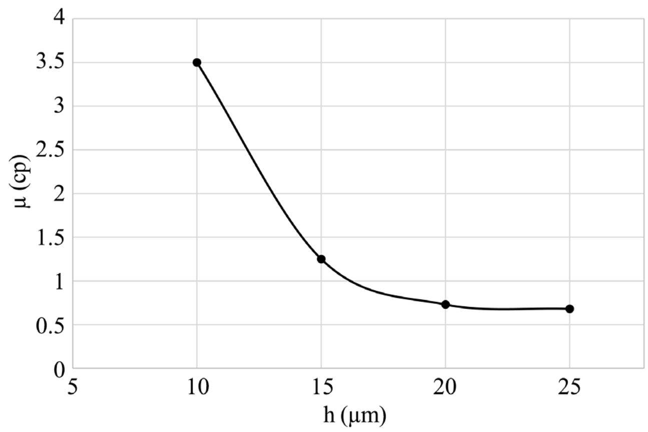

Fig. 2. The dependence of the apparent viscosity of water on the value of the openness h

In the observed transformation of a Newtonian system into a non-Newtonian one, strengthening of rheological nonlinearity, growing of hydraulic resistance in thin slits, the role of the electrokinetic factor is unconditional.

As already noted, in thin slits, the transverse geometric dimensions of the microchannel become commensurate with the dimensions of the EDL, which causes the essential manifestation of electrophysical effects. Thus, when water flows through the gap, it carries ions away from the outer diffuse part of the electric double layer at the water-metal surface boundary. As a result of which, a streaming potential – a potential difference between the ends of the microchannel is generated.

The streaming potential, in turn, causes ion transfer to reverse the flow of the liquid, which ultimately leads to the manifestation of additional resistance to movement and a corresponding increase in viscosity – a phenomenon called the electroviscosity effect [10], which is significantly reflected in the nature of the fluid flow.

In addition, it should be taken into account that tap water, in fact, is a heterophase system containing a huge number of colloidal particles with a size of up to 100 nm, as well as suspended particles of the order of several micrometers in size, which are a dispersed medium. All these particles form EDL in contact with water, and thus form a complex composition of many local ion-electrostatic microfields distributed throughout the volume of the dispersion medium. In the micro-slit, the zone of influence of these fields becomes commensurate with the openness of the slit, which causes an additional electrokinetic effect on the character of the flow.

Thus, there is a reason to believe that the hydraulic characteristics of the flow in microchannel should be dependent on the degree of electrokinetic potential of the system and by its changing the flow characteristics can be significantly settled.

To regulate the electrokinetic potential of the flow, it was decided to use antistatic additives. The ND-12 reagent was used as an antistatic agent, which is usually used as a demulsifier in oilfield conditions.

At the beginning, to determine the optimal concentration of additives, measurements of the electrode potential of water were carried out using an electrostatic cell. As a cell a stainless-steel cell with a platinum electrode installed coaxially into it was used. The second electrode was the body of the glass.

Drops of reagent were added to the water in the cell and the values of the electrode potential Δφ were taken at different concentrations.

Fig. 3 shows the dependence of the electrode potential Δφ on the concentration (%) of the antistatic reagent. The dataset was collected from experimental work. A stainless steel cell with a platinum electrode (with an error range of 0.4–0.5 %) was used in the experiment. Drops of reagent were added to the water in the cell and the values of the electrode potential Δφ were taken at different concentrations.

As can be seen, this dependence is not monotonous and the minimum potential is achieved at very small addition of the reagent. At the beginning, with an increase in concentration, the potential decreases, however, having reached a minimum, begins to increase to a certain maximum value, after which it practically remains unchanged at higher values of the additive.

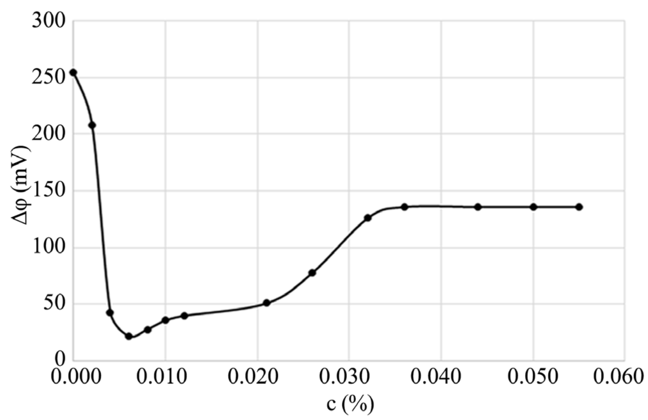

Fig. 3. The dependence of the electrode potential Δφ on the concentration (%) of the antistatic reagent

It was found that the optimal concentration value at which the minimum potential is reached is approximately 0.006 % (60 ppm). At this value of the additive, a multiple (10-fold) decrease in the potential is observed. A further addition of the antistatic is accompanied by an increase in Δφ up to the certain value, which remains almost unchanged at concentrations greater than 0.04 % (400 ppm).

In further experiments, the flow curves for water were again plotted for the same micro-slits, but with the presence of an antistatic additives.

Fig. 4 shows the $\gamma = \gamma(\tau)$ curves for water with an antistatic reagent, with an optimal concentration (60 ppm), for different values of the *h*, at temperature 30 °C.

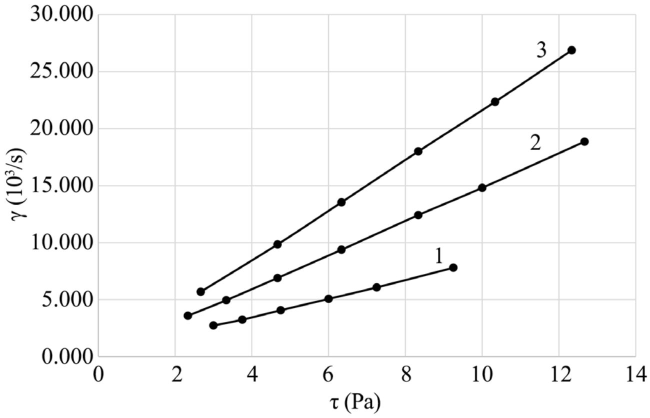

Fig. 4. γ = γ(τ) curves for water with an antistatic additive: 1 – 15 μm; 2 – 20 μm; 3 – 25 μm

The following important conclusions can be drawn from the comparison of curves represented in **Fig. 1, 4**. The non-Newtonian character, manifested for water at $h = 20$ μm, practically, disappears in the presence of an additive and the flow becomes Newtonian. For slits with an openness $h = 15$ μm, a clear weakening of the non-Newtonian behavior is observed, with a significant decrease in the yield share stress, and accordingly, in hydraulic resistance.

It should be noted that for a higher concentration (400 ppm), the effect is less pronounced.

For comparison, **Fig. 5** shows the dependences γ = γ(τ) for water in the presence and absence of additives during flow in slits with an opening of 10 μm. As can be seen, antistatic additives lead to an essential weakening of the non-Newtonian character of water and reduction in hydraulic resistance.

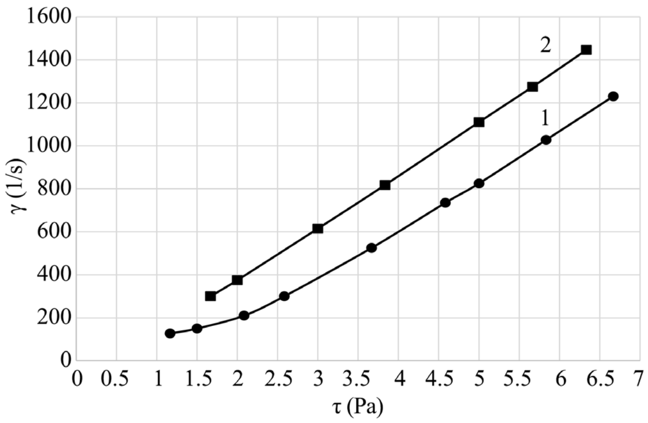

Fig. 5. γ = γ(τ) curves: 1 – water without an additive at 10 μm, 2 – water with an additive at 10 μm

The plotting of flow curves for each case was accompanied, simultaneously, by the measurement of the streaming potential Δφ. The values of Δφ, at $\Delta P = 10^5$ Pa, for various values of h, in the absence and presence of additives of two concentrations are shown in **Fig. 6**.

As can be seen, in the flow of water containing additives of optimal concentration (60 ppm) the value of the streaming potential is significantly lower. It can also be seen that the effect is less pronounced for higher concentration (400 ppm).

Fig. 7 shows the values of the yield shear stress τ_0 as a function of clearance h. In all three cases, τ_0 decreases linearly as a function of openness h. As can be seen, in the absence of additives, the flow of water in the microchannel manifests a non-Newtonian character and the value of the yield shear stress increases with a decrease in the gap, reaching a maximum value in the minimal clearance (10 μm). In the presence of additives, the critical value of the gap shifts towards smaller values of h – a non-Newtonian character, at a concentration of 60 ppm, is already observed at h less than 20 μm, increasing with a further decrease in the slit openness. Furthermore, at a concentration of 400 ppm, critical thickness sets between line 1 – water system with an additive concentration of 60 ppm and 3 – water system without an additive. This trend complements each other with the potential differences of the corresponding water systems as shown in **Fig. 6**.

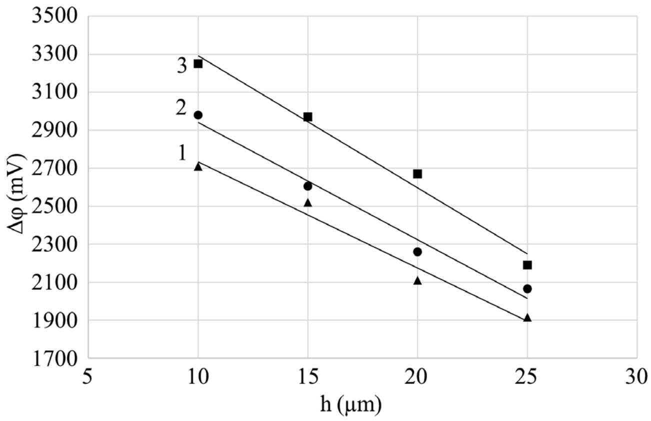

Fig. 6. The dependence of the Δφ on the value of the openness *h*: 1 – water with an additive of 60 ppm, 2 – water with an additive of 400 ppm, 3 – water without an additive

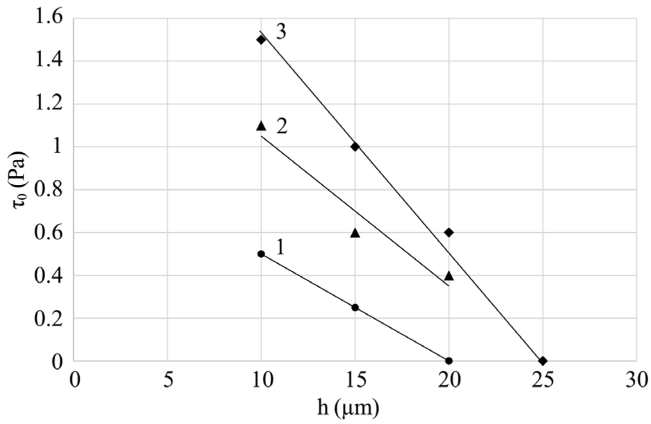

Fig. 7. The dependence of the yield shear stress τ_0 on the value of the openness *h*: 1 – water with an additive of 60 ppm, 2 – water with an additive of 400 ppm, 3 – water without an additive

The comparison shows that the presence of antistatic additives leads to a significant decrease of the yield shear stress. So, for $h = 10$ μm, there is more than a threefold decrease in value of the τ_0.

It should be noted that the presence of an antistatic additive practically does not affect the nature of the dependence of the apparent viscosity on the size of clearance $\mu = \mu(h)$, in the considered range of *h* values, and the curve presented in **Fig. 2** remains practically unchanged.

In further works, the stated idea is planned to be examined in the hydrocarbon flow through microchannels. Following to this, the methodology will be applied in low-permeable and microcrack oil fields in Azerbaijan.

4. Conclusions

The research work examined the non-Newtonian behavior of water flow through the microcrack model of a rectangular cross-section. The antistatic additive was used to regulate the electrokinetic potential of the fluid system. The rheophysical properties of the fluid flow in the presence and absence of the antistatic additive were experimentally analyzed in the microchannel.

The experimental results indicate the significant improvement in the flow parameters which shows compliance with the change of the electrokinetic potential of the system.

The dependence of the apparent viscosity on the thickness of the microcracked model $\mu = \mu(h)$ was also studied and the results show a notable increase in the fluid viscosity in the lower values of the slit clearance. However, the apparent viscosity is not affected by the presence of the antistatic additive and remained constant for both fluid systems.

It is also established that a reduction in the electrokinetic potential of the fluid flow results in a considerable decrease in the yield shear stress during the flow of water in the microchannel.

The obtained results promise a significant increase in hydrocarbon recovery factor in low-permeable and microcrack oil fields.

Conflict of Interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

Financing

The study was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Received date 06.08.2023
Accepted date 18.01.2024
Published date 31.01.2024

How to cite: *Veliyev, F., Aslanova, A. (2024). A rheophysical study of the non-newtonian behavior of water flow in thin channels. EUREKA: Physics and Engineering, 1, 11–17. doi: https://doi.org/10.21303/2461-4262.2024.003050*