INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

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OPEN ACCESS

Received: 25-10-2023

Accepted: 06-11-2023

Published: 30-12-2023

Citation: Veliyev F, Aslanova A (2023) Non-Newtonian Characteristics of Water Flow in Microchannels. Indian Journal of Science and Technology 16(47): 4605-4611. https://doi.org/10.17485/IJST/v16i47.2691

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Non-Newtonian Characteristics of Water Flow in Microchannels

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Abstract

Objectives: The rheophysical aspects of non-Newtonian behavior of water flow in thin channels are experimentally examined. The main objective of the research work is to establish the role of electrokinetic potential on the regulation of the rheophysical properties of fluid flow and by decreasing the electrokinetic potential, reducing hydraulic resistance of the system and improving the fluid flow. **Method:** Microchannel model with different openness value was used. To regulate the electrokinetic potential, antistatic additives were used, the optimal concentration of which was established experimentally. Based on Bingham model, rheological parameters of water flow were estimated at different micro-slit clearances, in the absence and presence of antistatic additive. **Findings:** It is established that nonlinear rheological effect in water flow in micro-slits is caused by the value of electrokinetic potential, by reducing of which it is possible to significantly weaken the non-Newtonian nature of the fluid. It is also determined that reduction in the electrical potential leads to a significant decrease in the yield shear stress. As a result, up to 20% increase was recorded in the fluid flow through the microcrack model by reducing the electrokinetic potential of the fluid system. **Novelty:** Previous works revealed that with a decrease in the gap openness in microcracks, starting from a critical size, the viscous liquid exhibits a non-Newtonian character, with the manifestation of an initial pressure gradient and flow locking. However, the main reason behind this phenomena was not fully supported yet. This work is the first scientific work that establish the crucial role of electrokinetic potential on the regulation of the rheophysical properties of fluid flow in microchannels. It is also the first work to determine the possibility of the reduction of the yield shear stress and flow locking in water flow through microchannels by controlling the electrokinetic potential of the system.

Keywords: Antistatic additives; Slit opennes; Electric double layer; Streaming potential; Microchannel

1 Introduction

Microfluidics or microhydrodynamics, which studies the movement of liquids in thin and ultra thin 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.

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 urgent scientific and technical problem.

Many research works have been conducted to study the rheophysical properties of the fluid flow in microchannels theoretically and experimentally. The works[1–3] examined the theories of the hydrocarbon flow through the microchannels, while the works[4,5] realized the set of the experiments to study the fluid flow peculiarities in the microchannels. Different assumptions and ideas have been stated to clarify the reason of the rheophysical phenomena of the fluid behaviour in microchannels.

In recent years, extensive researches have been conducted to study the features of the filtration process with the manifestation of the initial pressure gradient. It has been practically established that fluid filtration within the reservoirs does not always occur according to Darcy's law. The manifestation of nonlinear effects due to the rheological properties of the filtered liquid in porous media has been examined in works[6–8].

The work[2] studied the radial movement of liquids in microcracks. Empirical equations for the radial movement of water flow under laminar and turbulent regimes were obtained, considering the pressure differences through the microchannel.

In work[9], the motion of homogeneous fluid was studied in purely fractured rocks with mixed porosity. Based on the assumptions of linear dependence of formation porosity on pressure changes, equations for unsteady motion of liquid and gas in compressible porous and fractured media were obtained.

In works[2], when studying the motion of annular slit the validity of the Boussinesq approximation to determine the slit openness was examined. The target aperture values calculated using this equation practically coincided with the experimental results.

Many research papers have described the detailed study of pressure loss during the fluid flow under fully developed laminar regime in rectangular microchannels. However, the results of different papers are contradictory. Some scientists report a significant deviation from the conventional theories attributed it to an early onset of laminar to turbulent flow transition, electrokinetic forces, viscous heating effect, and microcirculation near the wall.

Despite the presence of numerous works, there are some problems in this area that require further study. 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[6,7]. It was revealed that[2], 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[9].

It has been experimentally established that[10], by regulating the electrokinetic potential of the system, it is possible to change the thermohydrodynamic characteristics of the flow in capillaries.

This research work 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 Methodology

The experimental setup mainly consisted of a microchannel model, a high-pressure balloon, and a thermostat shown in Figure 1. 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.

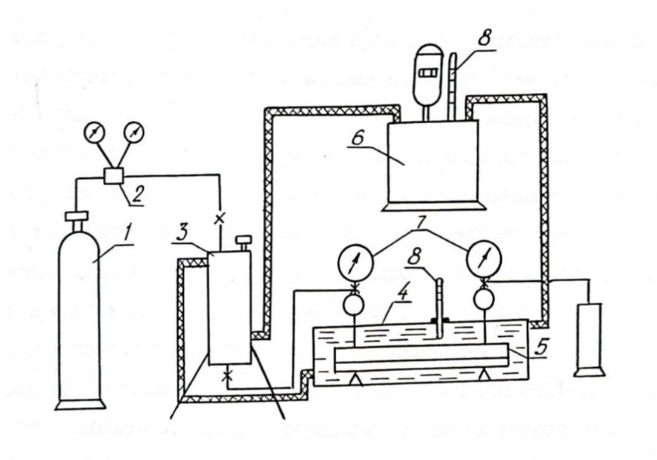

Fig 1. 1-a high-pressure cylinder, 2- A reducer for regulating the supply of compressed air, 3-a container for the test liquid, 4-a thermal bath, 5-a slot model, 6-a thermostat, 7-standart pressure gauge, 8-thermometers

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 - $Q = Q(\triangle P)$, the 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 dependence 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 Figure 2, 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.

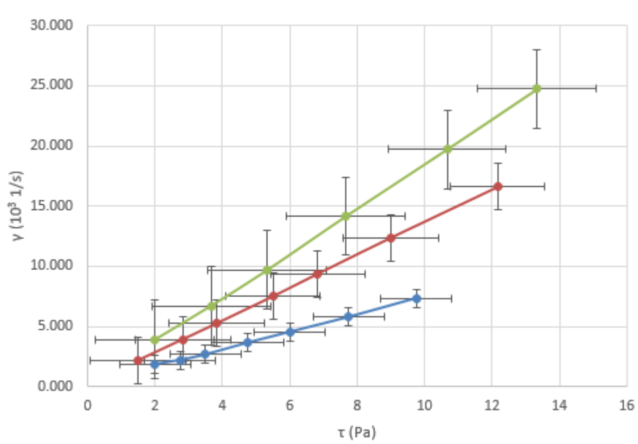

Fig 2. $\gamma=\gamma(\tau)$ curves for water. 1-15 μm, 2-20 μm and 3-25 μm

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 non-linearity in the flow is manifested – the water behaves like a non-Newtonian fluid with initial 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. The obtained results coincide with the previously conducted research works as well. Mamedova et al.[2] established the empirical methods of defining the critical openness of h in rectangular and radial microchannel models. The experimental results have been checked with those available methods and the validity has been confirmed.

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. Surface tension of the whole system changes as well. 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[11,12], which is significantly reflected in the nature of the fluid flow.

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 glass 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 $\Delta\varphi$ were taken at different concentrations.

Figure 3 shows the dependence of the electrode potential $\Delta\varphi$ on the concentration (%) of the antistatic reagent. 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.

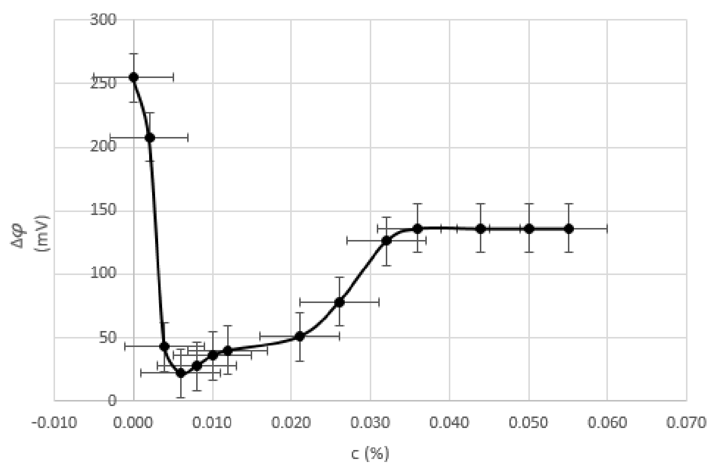

Fig 3. The dependence of the electrode potential $\Delta\varphi$ on the concentration (%) of the antistatic reagent

As shown in Figure 2, 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 from 250 mV to 24 mV. A further addition of the antistatic is accompanied by an increase in $\Delta\varphi$ 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.

Figure 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.

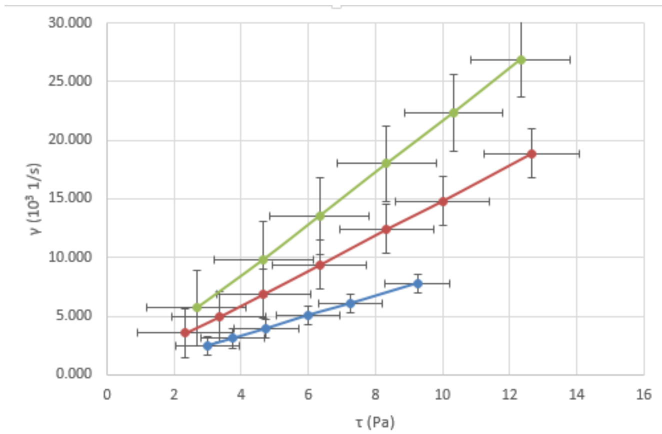

Fig 4. γ=γ (τ) **curves for water with an antistatic additive. 1-15**μ**m, 2-20**μ**m and 3-25**μ**m**

The following important conclusions can be drawn from the comparison of curves represented in Figures 3 and 2. 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.

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

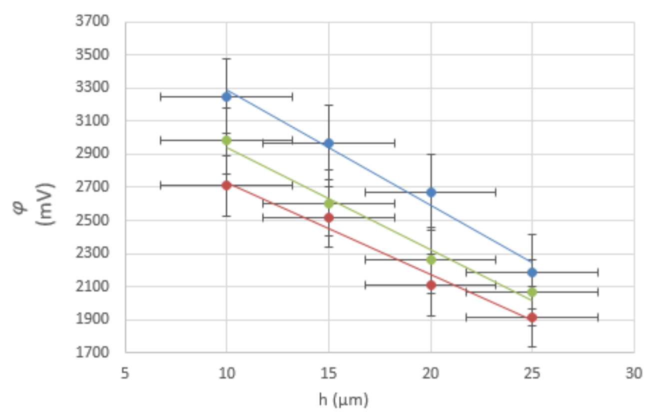

Fig 5. The dependence of the $\Delta\varphi$ **on the value of the openness h. 1-water with an additive of 60 ppm, 2-water with an additive of 400 ppm, 3-water without an additive**

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).

Veliyev in his research work (10) stated the possibility of the flow regulation by controlling the electrokinetic potential of the system. Mechanical methods have been used to regulate the system potential and analyze the effect of potential change on the manifestation of non-linear behaviour of fluid flow. However, the work did not fully examine the main reason behind the non-linearity and its control with chemical additives. In this work, the obtained results coincide with the stated idea and experimentally establish the possibility of the reduction of the yield shear stress and flow locking in water flow through microchannels by controlling the electrokinetic potential of the system.

Figure 6 shows the values of the yield shear stress τ_0 as a function of clearance 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.

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.

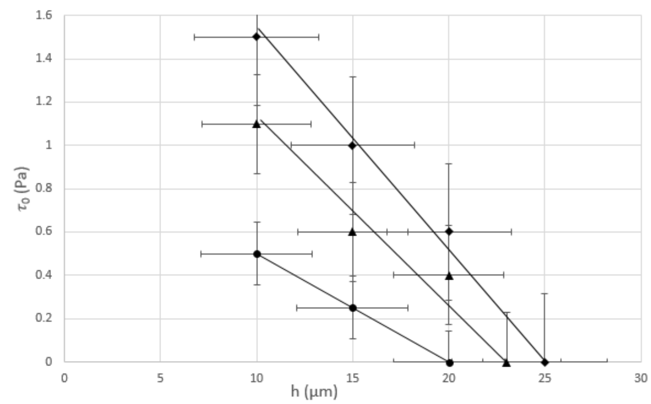

Fig 6. The dependence of the yield shear stress τ_0 on the value of the openness h. 1-water with an additive of 60 ppm, 2-water with an additive of 400 ppm, 3-water without an additive

4 Conclusion

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 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 experimentally considered. In microcrack 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, by reducing of which it is possible to significantly weaken the non-Newtonian nature of the fluid. The electrokinetic potential of water was regulated with the addition of antistatic additive the optimal concentration of which was established experimentally. Based on the Bingham model, the rheological parameters of water flow were estimated at different micro-slit clearances, 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.

The experimental results indicate significant improvement in the flow parameters which shows compliance with the change of the electrokinetic potential of the system. As an example, in the openness of h=10 μm, the system potential was declined from 3300 mV to 2700 mV and resulted with the 22% increase in flow rate.

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. As the obtained results shows, during the flow without the antistatic additive, the critical openness of h is 25 μm, while it is decreased to 20 μm with the presence of the antistatic additive.

In conclusion, the previous research works revealed that 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, the possibility of weakening the non-linearity, hence preventing the flow locking by electrokinetic regulations within the microchannels have not been established in the science yet. In this research work, it was 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. It has also determined that a reduction in the electrical potential leads to a significant decrease in the yield shear stress during the flow of water in the microchannel.

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