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Rheophysical Characteristics of Hydrocarbon Flow in Microcracks

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Abstract

The rheophysical aspects of the non-Newtonian behavior of oil-water emulsion during flow in thin channels are considered experimentally. Using the microchannel model it is established that the nonlinear rheological effect in the flow of oil-water emulsion 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, antistatic additives were used, the optimal concentration of which was established experimentally. Based on the Bingham model, rheological parameters of oil-water flow were estimated at different micro-slit clearances, in the absence and presence of an antistatic additive. It is established that a reduction in the electrical potential leads to a significant decrease in the yield shear stress during the fluid flow in the microchannel.

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. 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.

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 (Chen, Zhou, & Liu, 2000; Feng & Giaeli, 1985; Prada & Civan, 1999). It was revealed that (Mamedova & Gurbanov, 2015), 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 (Loeb, 1958), 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 (Veliyev, 1984), 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 oil-water system in microchannels.

Experimental Setup

The experimental setup mainly consisted of a microchannel model, a high-pressure balloon, and a thermostat. Oil-water emulsion with the composition of 70% and 30% respectively 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 125÷170 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.

Results

Upon reaching a steady flow regime, at different values of the clearance openness (h) flow curves for oil-water emulsion were plotted - $Q = Q(\Delta P)$, 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 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 γ=γ(τ) 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 Figure1 the obtained curves γ=γ (τ) for oil-water emulsion are presented, for different values of h (125 µm, 140 µm, 155 µm and 170 µm), at a temperature 30^0 C.

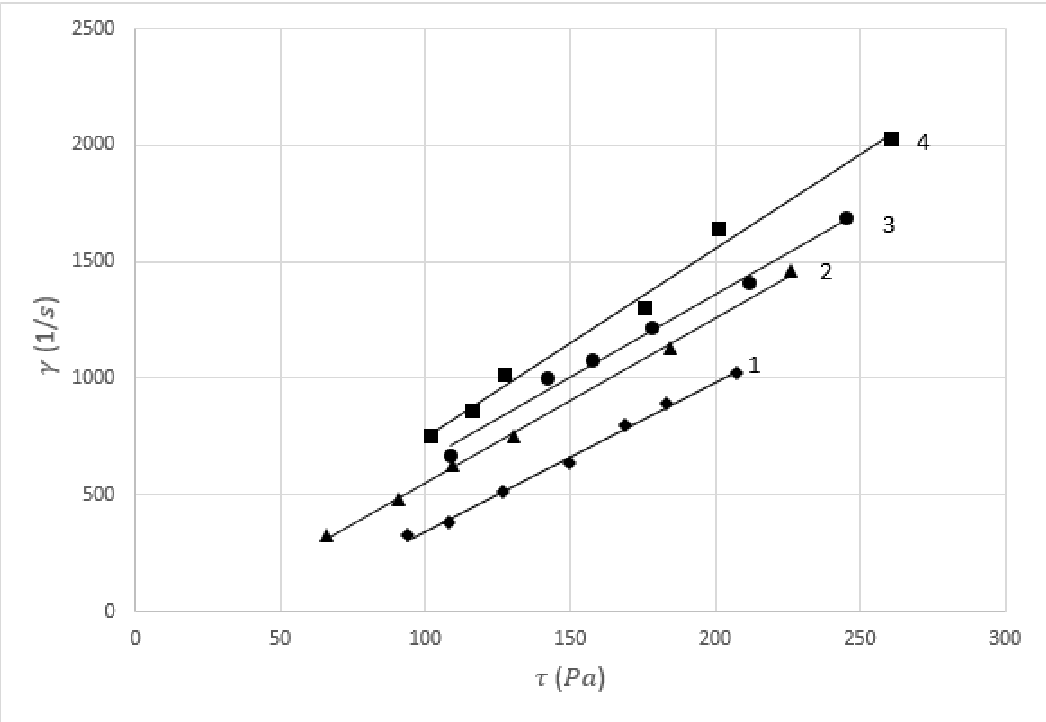

Figure 1. γ=γ (τ) curves for oil-water emulsion. 1-125 µm, 2-140 µm, 3-155 µm and 4-170 µm

It is established that regardless of the openness (h), the flow of oil-water emulsion through the microchannel is nonlinear and correspond to the Bingham model. Above the thickness of 170 µm, the degree of non-linearity is almost stabile. However, at values $h<h_{cr}$=170 µm, a degree of non-linearity becomes stronger with increased yield shear stress τ_0. The non-Newtonian character of the flow becomes more expressive with a decrease in the openness of the slit and the effect is maximally manifested at the lowest value of h (125 µm), in the range considered.

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 fluid flows through the gap, it carries ions away from the outer diffuse part of the electric double layer at the liquid-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 (Li, 2004), which is significantly reflected in the nature of the fluid flow.

In addition, it should be taken into account that oil-water emulsion, 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 liquid, 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. 5% solution of Cr salt of natural petroleum acid was used as an antistatic agent.

At the beginning, to determine the optimal concentration of additive, measurements of the electrode potential of oil-water emulsion 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 cell. Drops of reagent were added to the emulsion in the cell and the values of the electrode potential $\Delta\varphi$ were taken at different concentrations. Figure 2 shows the dependence of the electrode potential $\Delta\varphi$ on the concentration (%) of the antistatic reagent.

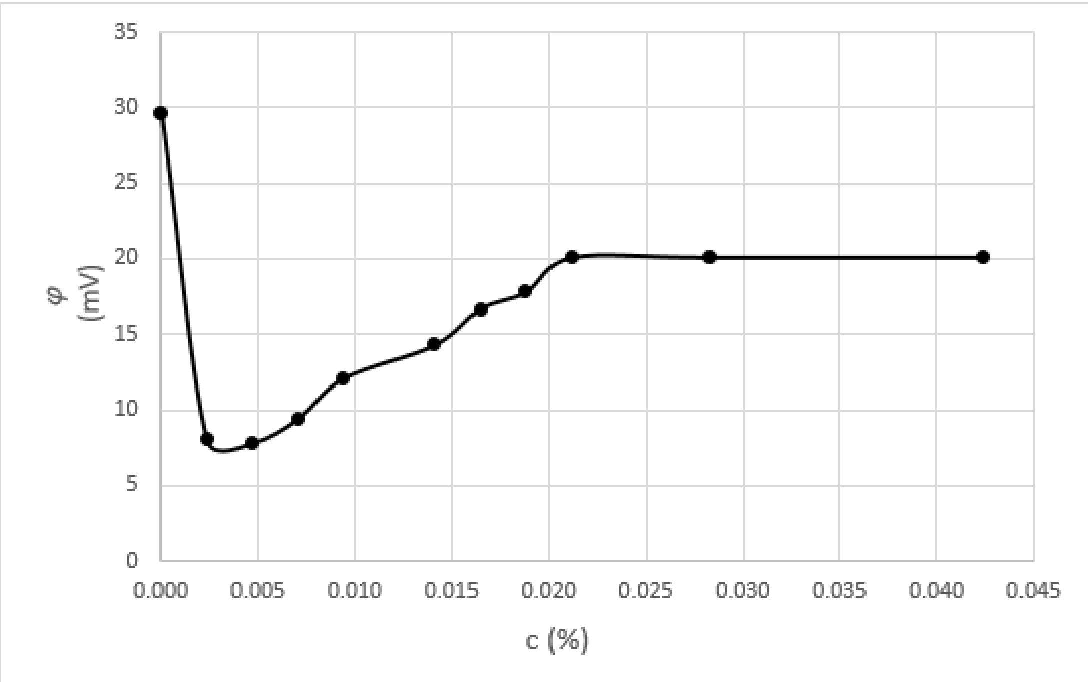

Figure 2. The dependence of the electrode potential $\Delta\varphi$ on the concentration (%) of the antistatic reagent

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.

It was found that the optimal concentration value at which the minimum potential is reached is approximately 0.003% (30 ppm). At this value of the additive, a multiple (5-fold) decrease in the potential is observed. 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 0.021% (210 ppm).

In further experiments, the flow curves for hydrocarbon emulsion were again plotted for the same micro-slits, but with the presence of an antistatic additives. Figure 3 shows the $\gamma=\gamma$ (τ) curves for oil-water emulsion with an antistatic reagent, with an optimal concentration (30 ppm), for different values of the openness (h), at temperature 30^0 C.

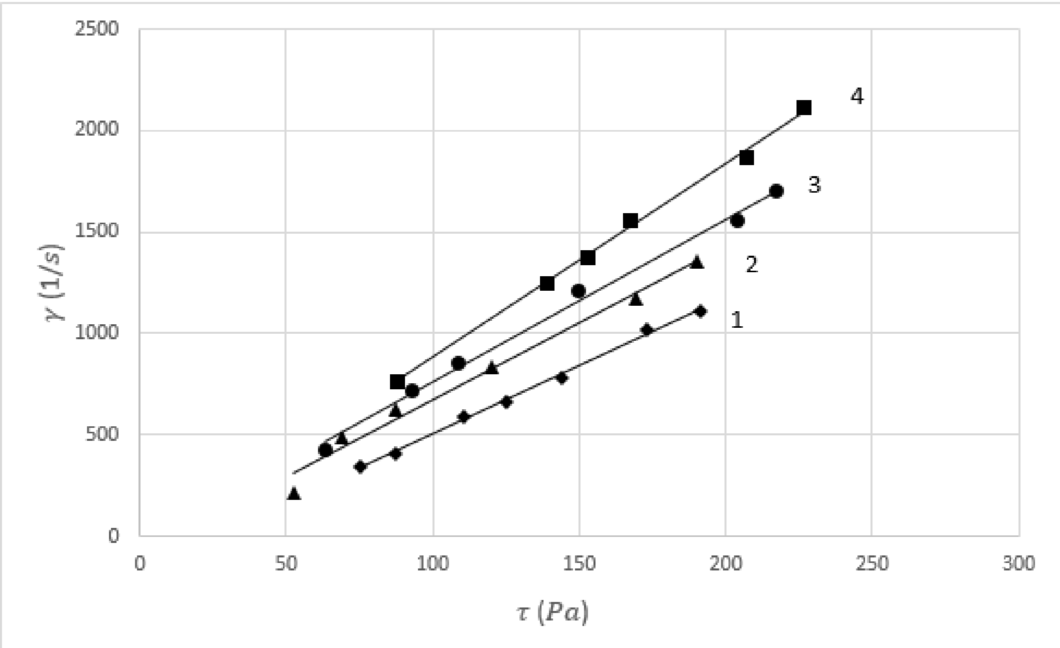

Figure 3. $\gamma=\gamma$ (τ) curves for oil-water emulsion with an antistatic additive. 1-125 µm, 2-140 µm, 3-155 µm and 4-170 µm

The following important conclusions can be drawn from the comparison of curves represented in Figure 3 and 1. The non-Newtonian character, manifested for oil-water emulsion flow at h=155 µm, practically, weakens in the presence of an additive and the flow becomes closer to the critical openness. For slits with an openness h=125 µm and 140 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.

For comparison, Figure 4 shows the dependences $\gamma=\gamma$ (τ) for oil-water emulsion in the presence and absence of additives during flow in slits with an opening of 125 µm. As can be seen, antistatic additives lead to an essential weakening of the non-Newtonian character of hydrocarbon emulsion and reduction in hydraulic resistance.

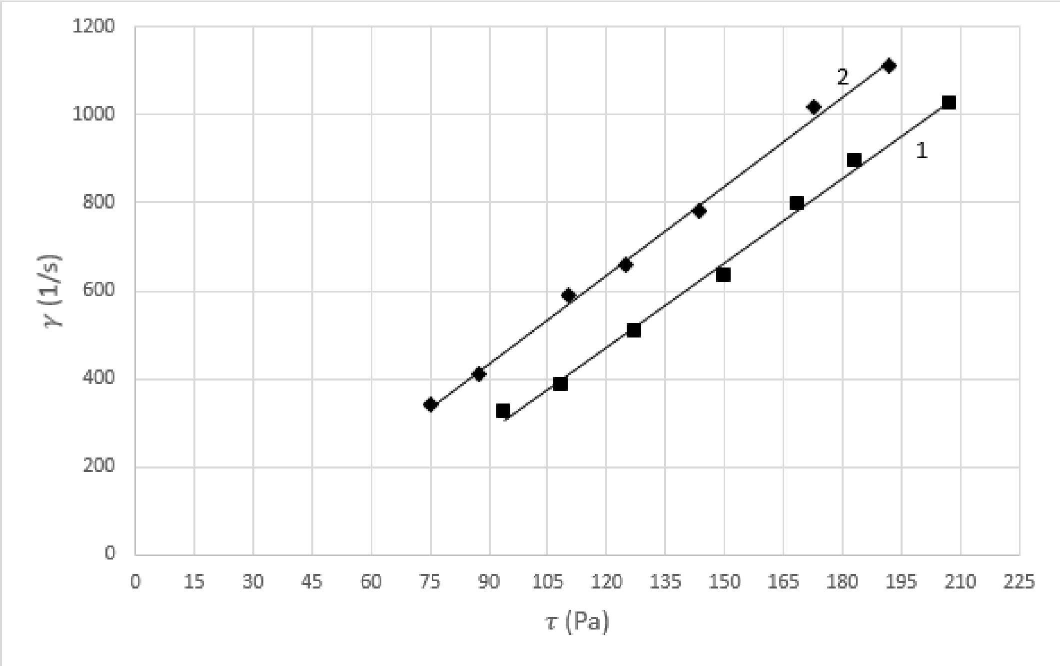

Figure 4. γ=γ (τ) curves. 1-emulsion without an additive at 125 µm, 2- emulsion with an additive at 125 µm

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 additive of optimal concentration are shown in Figure 5.

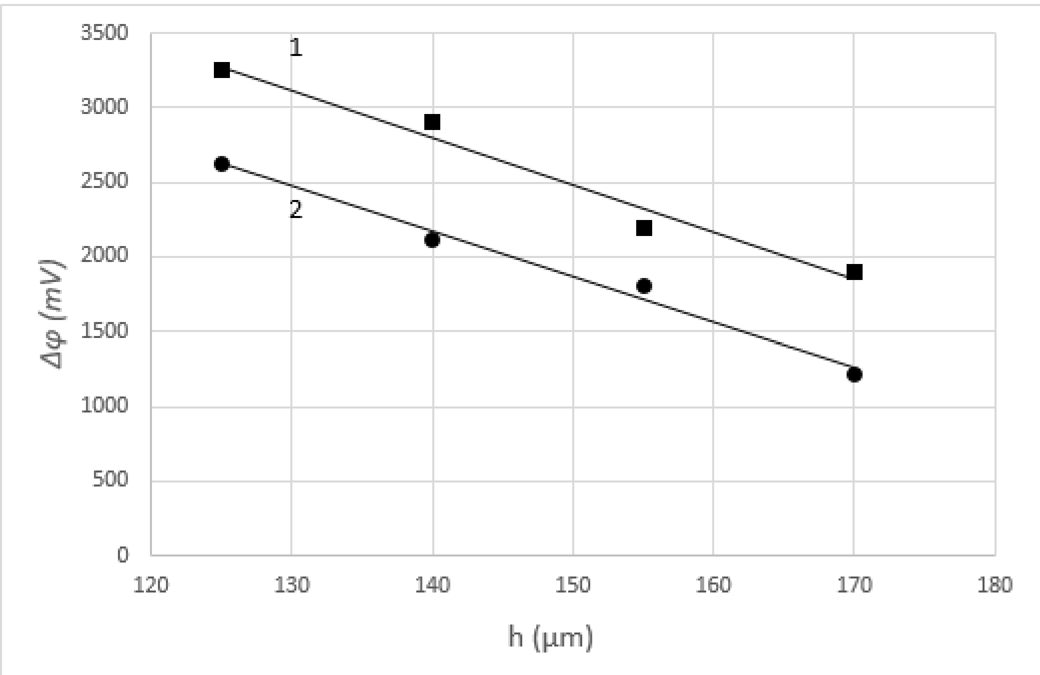

Figure 5. The dependence of the Δφ on the value of the openness h. 1-emulsion without an additive, 2- emulsion with an additive

As can be seen, in the flow of emulsion containing additives of optimal concentration (30 ppm) the value of the streaming potential is significantly lower. It can also be seen that the effect is less pronounced for higher concentration (210 ppm).

Figure 7 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 emulsion 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 (125 µm).

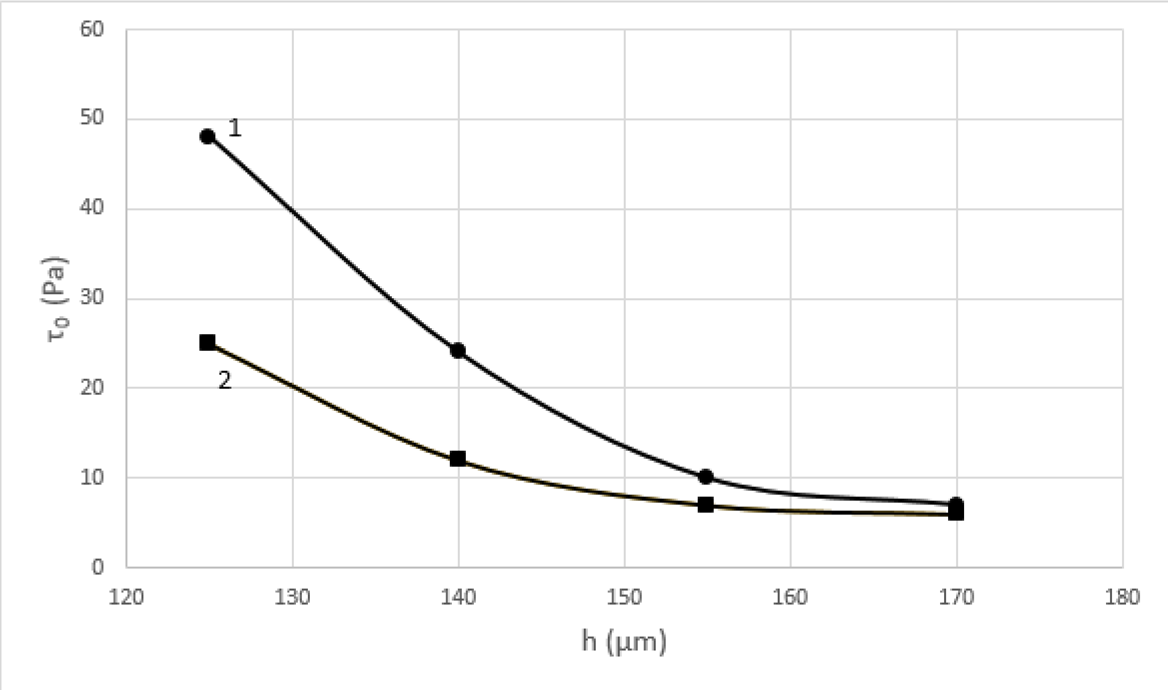

Figure 6. The dependence of the yield shear stress τ_0 on the value of the openness h. 1-emulsion without an additive, 2- emulsion with an additive

The comparison shows that the presence of antistatic additives leads to a significant decrease of the yield shear stress. So, for h=125 µm, there is almost twofold decrease in value of the τ_0.

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