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Wall effects under non-Newtonian fluid flow in a circular pipe

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Abstract. *It is the purpose of the present paper to investigate dependence of the steady-state flow rate Q and viscosity μ_∞ of the fluid from the intensity of the perturbations imposed on the thixotropic oil flow in the pipe under the near-wall effects conditions. Thixotropic effects arising under destruction and reduction of internal bonds in heterogeneous oils were experimentally investigated.*
The paper presents the experimental results in research of no-slip condition at the flow in the tubes giving rise to additional shear stresses and the relative destruction of the thixotropic structure ($\mu(\tau)$-parameter).
The effect of the disturbance impact on the parameters determining the kinetics of thixotropic structure changes and other averaged hydrodynamic characteristics was evaluated

Keywords. pulsation · fluid · fluctuation · pipe · amplitude · velocity · pressure · perturbation · flow rate

Mathematics Subject Classification (2010): 76D17

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1 Introduction

Investigations on non-Newtonian fluids flow become relevant last years in both theoretical and applied aspects in the context of the wide use of new materials and compositions with a large variety of structural, rheophysical and rheological properties (petrochemicals, plastics, polymer solutions, etc.). It merits separate attention because of structured nonlinear viscous-plastic, viscous-elastic and thixotropic systems are commonly uses in engineering processes. In pipeline transport the flow of such fluids begins after overcoming some limiting shear stress level [2, 3].

So far there is no one frame of mind on the mechanism of the flow of structured disperse systems, as witnessed by the abundance of the rheological equations [4, 5]. According to Bibik E.E. [1, 4], the structured suspension forms aggregates in the shape of doublets or chains. In the limiting case these chains form a continuous mesh.

If the particles are initially integrated into a continuous grid (frame), the system characterized by solid behavior and stationary flow begins when the shear stress τ exceeds some stress level τ_0 corresponding to breakdown of the mesh.

According to Rehbinder P.A., the effective viscosity is the result of a balance between destruction and restoration of the structure of concentrated suspensions. This equilibrium degree of destruction of the structure is determined by the correlation $(\eta(0) - \eta(\tau)) / (\eta(0) - \eta_\infty)$, where $\eta(\tau)$ - effective viscosity under given shear stress value; $\eta(0)$ - the greatest Newtonian viscosity that meets the original (undistorted) structure; η_∞- the lowest Newtonian viscosity, which is achieved with maximum destruction of the structure.

Authors [11] introduced a distinction between the destruction of the structure over time and the destruction of structure due to the change in shear rate. With plastic or pseudoplastic flow the average size of aggregates decreases as the speed increases. The deviation of the flow from the equilibrium state leads to a deviation of flow curve from the theoretical curve in the rheological equations and the hysteresis of flow curve.

Some correlations relating to the oil systems were studied in [10]. It should be noted that there is adequacy to the empirically established correlation of viscosity η dependence of heterogeneous oil and suspensions concentration for asphaltenes, resins, paraffins (ASP), naphthenic acids and other components involved in the formation of aggregates [6; 8; 13; 14].

It is important to study a periodic pressure oscillation leads to increased velocity under the flow of abnormally viscous thixotropic liquids in pipes, that highlights in [7, 13]. Formulation of thixotropic fluid model plays a key role under establishing of correlations describing the kinetics of aggregation and the relationship of the viscosity with the aggregation of the variables.

2 Objectives.

Problems subject to decision, is the determination of flow rate and effective viscosity $\eta(\tau)$ of fluid with the destructed structure structure amid signs of the sticking effect on the pipe wall.

Sticking of the boundary layer occurs under the pulsating fluid flow in the pipe caused by the periodic variation of the pressure drop. The fluctuations may be the result of variables of the perturbations imposed on the fluid flow (for example, when the reciprocating movement of the pump piston). Increasing of fluid flow after disturbances due to the effects corresponding to the conditions of sticking of the fluid layers on the walls that is the cause of the further increasing of shear stresses.

3 Experiments.

These assumptions were experimentally examined on thixotropic oil of Kursanga field (Azerbaijan) with a density of $901 kg/m^3$ and a content of the wax deposits near 9%.

A schematic of the experimental setup is shown in Fig. 1 and contain a cylindrical tube - 1 (length $l = 2.8m, diameterd = 0.01m$), valves - 2, fluid container - 3; oscillator - 4; sensors - 5; flowmeter - 6; pressure gauge7. Pressure oscillations at the inlet of the pipe created by device (4), in which the area of flow section determined by the respective number of "vortices". Two pressure sensor - (5) were installed at the inlet and at a distance from the input device. The temperature was controlled by ultrathermostat - (8).

The flow curves for water with a viscosity $\eta = 10^{-6}\ m^2/s$ under $T = 298$ were compared with the standard flow curves.

The next series of experiments was carried out on the oil samples with the above characteristics. The temperature of the pumped fluid controlled by the thermostat, holding temperature drop between the inner cavity of the pipe and the environment ($T = 298K$).

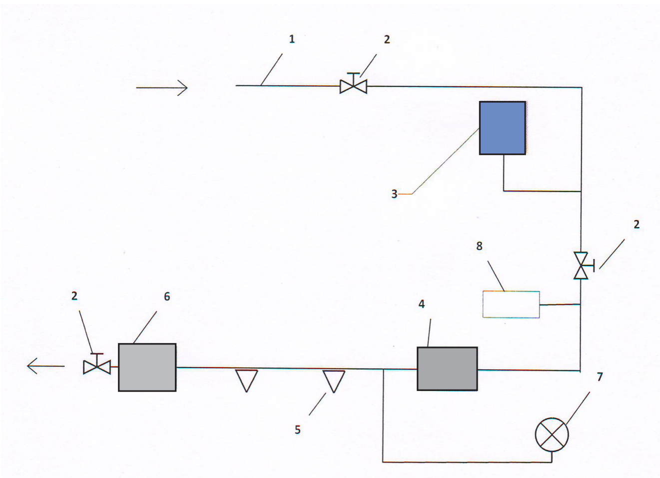

Fig. 1. Experimental setup

At the beginning of a test run the flow rate without disturbances was recorded, there was no sticking of the oil flow on the pipe's wall and dynamic viscosity was estimated ($\eta_0 = 1.8Pa's$). Here we consider the change in viscosity under oil sticking on the pipe's wall after the imposition of the disturbed motion with a vortex-causing device resulting in additional shear stresses.

These additional stresses changes both the structure of the flow and effective viscosity $\eta(\tau)$.

4 Results and discussions.

In the course of investigations perturbations of varying intensity are placed on stationary flow, using by vortex devices, and pressure measured at the inlet and outlet with help of sensors (6) (the average values by manometer (8) and the flow rate was measured by flow meter (7) and the temperature is kept constant ($T = 298K$) The impact of the number of vortices on the fluid flow was considered. The average pressure keeps at a level of $P = 0.12MPa$, average velocity was $u_0 = 0.35m/s$. Related to the experimental setup the intensity of the shear stress is contributor to the sticking effect (number of vortices) was taken as $\phi = n\pi(n = 1, ..., 6\pi$ - periods). Flow rate variation and dependence on viscosity η_∞ from the intensity of the perturbation was experimentally evaluated (Fig. 2 and 3).

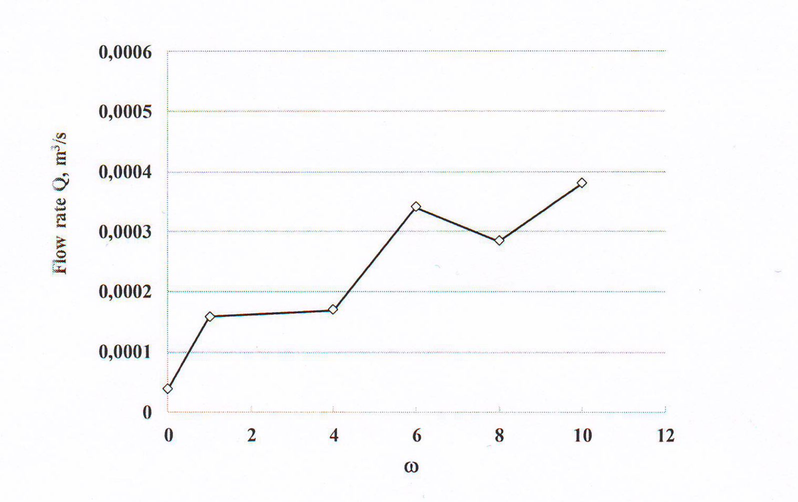

Fig. 2. Relationship plot of flow rate Q and disturbance intensity (ω)

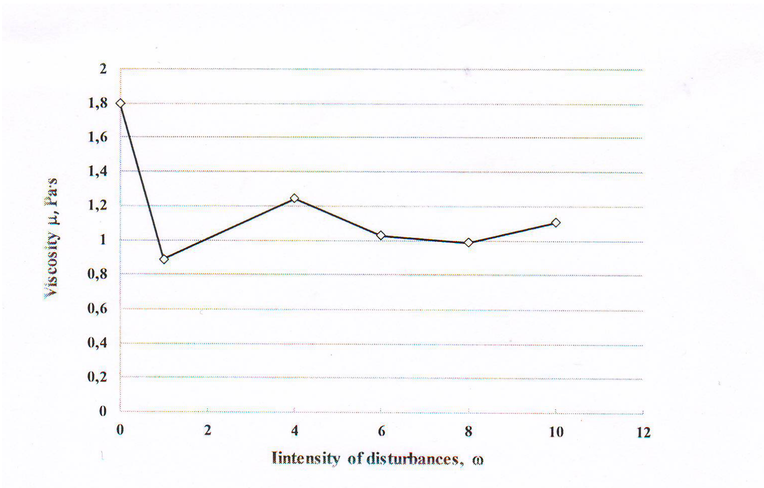

Fig. 3. Relationship plot of viscocity μ and disturbance intensity (ω)

The relative destruction of the thixotropic fluids structure $(N/N = z)(\eta(\tau)$ parameter) as a function of the non-monotonic radius increases from a minimum at $r = r_c$ to the maximum value on the wall pipe [7, 10].

The sticking effect under structured fluid flow cause to additional stress after the imposition of the disturbed motion on a plane perpendicular to the radius. These additional stress, called the "apparent" stress change the fluid structure on the laminar flow and, consequently, the effective viscosity too.

5 Theoretical result.

Let's consider this criterion after the imposition of the disturbed motion. While on the stationary flow perturbations are imposed and the ambient temperature remains constant or changed abruptly to a new constant value.

Let the hydrocarbon fluid moves through the tube of radius *R* and length $L > R$ under pressure gradient [8]

$$\frac{\partial P}{\partial x} = -P\ [1 + qf(\omega t)],\ \ |f| \ll 1 \tag{5.1}$$

where P_*, q, ω – constants, f- disturbance function, with time t and amplitude ω.

For small values of parameter $\omega R^2 \rho/\eta_0$, where ρ is the density, the inertia of the fluid can be neglected, and in a region, remote from the ends of the tube, assuming that [7]

$$1 + qf(t) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\eta\frac{\partial u}{\partial r}\right),\ \ \eta = \eta(z) \to \eta_p \tag{5.2}$$

$$1 + qf(t) = B$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\eta\frac{\partial u}{\partial r}\right) = B$$

$$\frac{\partial}{\partial r}\left(r\eta\frac{\partial u}{\partial r}\right) = Br$$

$$\int \frac{\partial}{\partial r}\left(r\eta\frac{\partial u}{\partial r}\right) dr = \int Brdr;$$

$$r\eta\frac{\partial u}{\partial r} = B\frac{r^2}{2}$$

It is required to find periodic solution on *t* of the system (5.1), (5.2) satisfying the sticking and symmetry terms:

$$u(t,1) = 0, (\partial u/\partial r)_0 = 0. \tag{5.3}$$

Subject to these terms from (5.1) are sequentially finds [11]

$$\frac{\partial u}{\partial r} = -\frac{r}{2\eta}B,\quad u = \frac{B}{2}\int_r^1 \frac{rdr}{\eta} \tag{5.4}$$

$$Q = \frac{B}{2}\int_0^1 \frac{r^3 dr}{\eta},\quad B = 1 + qf$$

Here Q - is the dimensionless flow rate; a scale for the flow rate is the value of $\pi R^2 u_*$.

For $z = \frac{N}{N_*}$, where N is the numerical concentration of all kinds of aggregates per unit of mixture volume, N^* is the maximum value of N, corresponds to the collapse of all units on a single particle with volume $\omega_0 = H/N_*$. After substituting $\partial u/\partial r$ for z results in equation, containing r as a parameter.

Here, the viscosity $\eta_1(z)$ of heterogeneous thixotropic oil between the maximum and minimum values of z over time is nonmonotonic: $\eta_\infty/(z)$ at $r \to r_c$ and reaches a maximum value at a small distance from the axis.

6 Conclusions.

As a result of conducted researches it is established that the change in the steady flow and viscosity μ_∞ the intensity of the perturbations for different values of shear stresses, caused by sticking of thixotropic oil, has a non-stationary and not ehough destructive behavior.

The effect of perturbations intensity on the process of bonds destruction in a dynamic equilibrium occurs nonmonotonically. It is found, that, under the sticking effect at the flow of thixotropic oil in a circular pipe, there is arbitrarily low stresses at the shear flow, that lead to the identical destruction behavior. This anomaly of a structured system allows to associate the coefficients of rheological equations with the characteristics of the destruction process.

Applying perturbations of different shear stresses lead to sticking phenomena on the pipe wall and will change the effective viscosity and therefore the flow rate of the heterogeneous oil. Thus, it can be assumed that there is a separate mechanism for each pattern at various disturbances intensity.

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