Investigation of the tangential discontinuities formation in the glycerol under shear load

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Abstract. The work is devoted to the study of the formation of tangential discontinuities of glycerol parameters under shear load. The studies were carried out using a modified coaxial cylinder viscometer. The experiment was inspired by the work of Ya. I. Frenkel, in which it was noted that “... liquids, being condensed media, should exhibit effects that are more characteristic of solids than gases...”, while the thermodynamic and kinetic properties should be determined by structural “variables”, traditional for both “liquid” and solid state. These studies will further help in explaining the anomalous momentum transfer regimes caused by the mechanisms of instability that are realized under the conditions of the “decay” of multiple metastable states, usually observed under intense (dynamic and shock-wave) loading in liquids and solids.

1. Introduction
In experimental and theoretical works of the authors carried out at the ICMM UB RAS inspired by the classic works of Ya.I. Frenkel [1], A.D. Sakharov [2], it was shown for the first time that the existence of shear elasticity of a “close order” in liquids presupposes the formation of mesoscopic defects, shears caused by the coordinated movement of groups of molecules, and the implementation of quasi-plastic mechanisms of momentum transfer associated with collective effects in ensembles of microshears. These effects lead to qualitatively new mechanisms of viscosity and dissipation, the values of which reach asymptotically minimum values due to the multiscale “strong” interactions characteristic of nonequilibrium “critical systems”. The possibility of implementing these mechanisms in liquids under less extreme conditions, including in turbulence processes, was first substantiated in the works [3-5].

As a rule, a hydrodynamic approximation is used to describe the flow of a liquid, for example, the Navier-Stokes equation, where the main parameter characterizing the flow is viscosity. At the same time, liquids have the properties inherent in solids - density, modulus of elasticity, heat capacity [6]. Frenkel also noticed the important property of liquids to support high-frequency shear waves of a solid.

Frenkel suggested that liquid particles vibrate for some time, similar to solids, and then diffusely move to neighboring quasi-equilibrium positions [1]. These jumps enable liquid flow and endow liquids with viscosity. He introduced $\tau$ as the average time between diffusive jumps and predicted that liquids behave like solids and hence support propagating shear modes at time shorter than $\tau$, or frequency above the Frenkel frequency $\omega_F$. 
In the work [7] devoted to the study of the flow of metal glasses from the Vitreloy-1 alloy, the formation of shear bands in a deeply supercooled liquid was established. As a result of experimental studies, the authors [7] have shown that the Newtonian flow of melts of metal glasses is realized at high temperatures and low shear rates. A non-Newtonian flow is formed at moderate temperatures and high shear rates; under these conditions, the flow becomes extremely sensitive to the shear rate and, as a consequence, is unstable, which leads to the formation of shear bands.

It is generally accepted that the so-called Newtonian fluids do not have shear strength, and their viscosity does not depend on the flow rate. However, studies of the behavior of liquid media subjected to ultra-weak shear loading show that these media have a certain shear strength.

In [8,9], using an optical technique, it was shown that polar liquids (water, acetone, ethyl alcohol, glycerol, etc.) at rest have an ordered structure, which is destroyed under weak shear deformations. It was shown in [10,11] that glycerin exhibits non-Newtonian properties in the temperature range 223-313 K: “At 313 K, glycerol is a moderately viscous liquid, explaining the moderate damping in the propagation direction. At 273 K, due to coupling with structural relaxation, the glycerol acoustic modes are very strongly damped. The asymmetric character of the wave profile with respect to the interface is linked to the finite both real and imaginary parts of the shear stiffness of the liquid. At 223 K, glycerol has very solidlike properties and low acoustic damping, explaining the lower damping”. Taking this into account, it seems important to investigate the possibility of the formation of tangential discontinuities in the parameters in liquid media, which can serve as the beginning of the process of dividing the loaded sample into fragments.

Tangential discontinuities of condensed matter parameters are divided into two types. Tangential rupture of the first degree is the formation of a zone elongated in the direction of shear deformation, where the condition $\mu_z << \mu$ is satisfied, where $\mu, \mu_z$ are the values of the structural viscosity of the medium (its definition is given in [12]) outside the zone and in the zone, respectively; the density of the medium in the zone of tangential discontinuity of the first degree and outside it is practically the same. Tangential discontinuity of the second degree is the formation of a zone elongated in the direction of shear deformation in which the conditions $\rho_z / \rho_0 \to 0, \mu_z / \mu \to 0$ are satisfied, where $\rho_z, \rho_0$ are the densities in the zone of tangential discontinuity of the second degree and an undisturbed medium, respectively [13].

2. Experimental part
The formation of tangential discontinuities of the first degree was investigated on an original viscometer with a system of coaxial cylinders (rotary rheometer) [14], which allows not only measuring the dynamic viscosity of the liquid under study but also conducting visual observations and examining liquids with solid particles immersed in them. Rotational viscometers make it possible to measure the true or absolute viscosity of both Newtonian and non-Newtonian (structured or rheological) media, the schematic diagram of the viscometer is shown in Figure 1. The space between two coaxial cylinders 1 and 2 is filled with a liquid medium 3. The stepper motor 4 drives the external cylinder with adjustable linear speed from 0.005 to 6 cm / s, the inner cylinder remains stationary. As a result of the rotation of the outer cylinder, a transition layer is formed in the medium under study, in which, at certain rates, shear deformation modes can exist, which ensure the destruction of the ordering of the structure of the medium. To register the process, the system of coaxial cylinders was placed in the light flux formed by the source 5, between two polarizers 6, after the polarizer, the light flux fell on a photo or video camera 7 recording the process under study. In addition, the inner cylinder 2 is connected to a special elastic element, the deformation of which under the action of viscous stresses in the liquid under study is measured using a high-precision laser range finder. The external view of the experimental setup is shown in Figure 2.
Figure 1. Schematic of an experimental setup for studying the formation of tangential discontinuities in fluid parameters. 1 - external movable cylinder; 2 - internal stationary cylinder; 3 - investigated liquid; 4 - electric drive of the external cylinder; 5 - light source; 6 - polarizers; 7 - photo or video camera.

Figure 2. External view of the experimental setup.

As a result of the experiments, it was found that glycerol is an optically isotropic liquid medium in the initial state (Figure 3a), which loses its optical homogeneity during the formation of shear deformations (Figure 3b, c). This means that a thin cylindrical layer with a destroyed structure is formed in the medium. It should be emphasized that the time of the destruction of glycerol in the transition layer, as well as the width of the transition layer, depends on the deformation rate. At a constant strain rate, the width of the transition layer with a permitted structure remains constant. After stopping the rotation of the outer cylinder, the structure of glycerol is restored.

3. Conclusion
Experiments have shown that the formation of tangential discontinuity in viscosity is possible in glycerol. Glycerol in the ultra-weak shear range has shear elasticity, therefore, behaves like a non-Newtonian fluid. But at high shear loads exceeding the yield point, the ordered structure is destroyed, glycerin behaves like a Newtonian fluid [13]. Based on the above, when modeling and studying slowly proceeding processes in Newtonian polar fluids, one should take into account their shear elasticity.
Figure 3. Photos of the formation of tangential discontinuities of shear viscosity in glycerol:
a) initial state; b) strain rate 0.5 cm/sec; c) strain rate 5 cm/sec.

The experiment carried out reflects the possibility of the manifestation of momentum transfer mechanisms in liquids associated with the mechanisms of plastic flow and destruction in solids. To confirm this assumption, it is of interest to compare the experimental data on the behavior of fluids under conditions of developed turbulent flow, under conditions of weak shear loads and the widespread case of unstable plastic flow, known as the Portevin-Le Chatelier effect. These studies can have broad and important areas of application, including the explanation and modeling of the effects of localized (adiabatic) shear under dynamic and shock-wave loading of a wide class of metallic materials. The possible universality of the nature of the development of the instability of condensed media (solid and liquid) under intense influences (in liquids - flows at large Reynolds numbers) is of obvious fundamental and applied interest.

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