Pulse loading of glycerol by electric explosion of wire

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Abstract. A series of experiments was carried out to investigate the relaxation properties of glycerol under shock-wave loading. The strain rates at the compression wave front were in the range of $10^5$–$10^7$ s$^{-1}$. A modified version of the wire explosion set-up was used. Free surface velocity profiles were recorded by VISAR with fiber-optic sensor. We found that the glycerol exhibits the non-Newtonian liquid behavior: viscosity is higher at the high strain rate. Strain rate at the compressive wave front is found to be dependent on the wave amplitude in power of 1.3.

1. Introduction
A power-law dependence of the strain rate at the compression wave front on the amplitude of the wave in water obtained by the authors [1] is consistent with the corresponding laws for metals and is indicative of self-similarity of the wave front profile [2]. The question arises of whether this behavior is unique only for water or it is typical for other liquids. To answer this question we have carried out an experimental study of another more viscous liquid: glycerol.

2. Physical properties of glycerol
In our experiments, we used glycerol (GOST 6824-96) with 98% purity. Glycerol is a colorless, sweet tasting, odorless viscous liquid. The melting point of glycerol is 17.9°C and boiling temperature is 290°C. Glycerol dissolves in water and organic solvents. The ignition temperature is 362°C. The refractive index and the relative density of glycerol are 1.4735 at 25°C and 1.2481 kg/m$^3$ at 20°C, respectively. Glycerol is thermally unstable and decomposes at prolonged heating at 90–130°C forming acrolein and acetone, which reduces the boiling point to 112°C. The existing standard GOST 6824-96 applies to the distilled glycerol and establishes general technical conditions for its manufacture, sale and utilization. The speed of sound in glycerol is about 1895 m/s [2].

3. The experimental setup
The dynamic response of glycerol under shock-wave loading was investigated using the electrical wire explosion set-up (EEC) equipped with the VISAR [1]. The photo of the experimental system is shown in figure 1. It consists of cylindrical chamber 1, with a conductor set at the center in the vertical position. The chamber was filled with a test liquid (glycerol). Wire is exploded less than 0.3 $\mu$s by a discharge of the capacitors placed below chamber, generating a cylindrical electric explosion wave in the surrounding glycerol. Voltage on the wire and current were recorded by two-channel oscilloscope 5.
Measurement probe [1] was designed to measure the free surface velocity of the fluid at different distances X from the explosion site. The probe with a membrane foil stretched over it was connected to the optical fiber input 6 of measuring system: a four-channel digital storage oscilloscope Tektronix DPO 7254 (8) and Martin Froeschner & Associates Optoelectronics FDVI Mark IV-3000 VISAR (9) [1]. Figure 2 shows that the probe is located at a distance X from the conductor, on its right. The distance X was set by device 7 with an accuracy of 0.1 mm. The VISAR data were processed according to procedure described in [1] using the developed software. Unlike water [1], which absorbs most of IR radiation, glycerol is transparent for radiation with wavelength close to 1550 nm, which is the reason why the received VISAR signals were distorted during the wire glow. However, at the time of arrival of the compression wave IR radiation level is decayed to low level, which allowed us to obtain a true picture of the free surface velocity profile.

After the explosion, the products of copper conductor diffused into glycerin (figure 3) due to its high viscosity and the density. The products of explosion scattered forming a “funnel” with an inhomogeneous black area that spread over the glycerol surface within 3–4 cm radius of the explosion site. In addition, the recording devices indicated the existence of the zones, where the refractive index differed from the refractive index of the original glycerol. It would be of interest to investigate the chemical composition of the substance picked up from these areas.

4. Discussion of the results

The free-surface velocity profiles obtained in this study considerably differ from the velocity profiles obtained previously in the same apparatus in distilled water [1]. Firstly, they point to a long-term existence of the spall “plate” in glycerol, which is characterized by a large number of reverberations on the velocity profile commonly observed in solids [3]. By contrast, the number of such periods for water did not exceed four [1]. Secondly, the amplitude of the spall pulse on the free surface velocity profile does not exceed the stress amplitude (figure 3), which implies the absence of cavitation observed in water [1, 3, 5, 6].

The established power-law dependence of the strain rate $\dot{\varepsilon}$ at the plastic front on the amplitude of the stress pulse $P_0$ has proved to be similar to the dependence obtained in [1, 3], (figure 5). According to the preliminary results of our work and the data of [2, 7], the exponent was close to 1.3, which suggests the existence of unique self-similar solution $\dot{\varepsilon} = A \times P_0^\beta$, combining two condensed media—solid and liquid bodies.

Also of considerable interest to the authors is the assessment of the behavior of the viscosity coefficient $\eta$ under the dynamic load $\dot{\varepsilon} = 10^5$–$10^7$ s$^{-1}$. The formula for estimating viscosity was
Figure 2. Photo of the centered copper conductor and fiber optic sensor (probe) for measuring the free surface velocity located at a distance $X$.

Figure 3. The image was obtained through the visualization window located on the side of the chamber of the EEC setup after the explosion.

Figure 4. The free surface velocity profiles obtained at a distance $X = 22$ mm from the explosion site, $\Delta t = 11 \mu s$. $\Delta t$—the time elapsed from the moment of electric explosion to the moment of velocity increase on the free surface velocity profile.

derived using the expressions from [7]:

$$
\eta \sim \frac{3SP^2}{4\rho_0C_0^2}\varepsilon^*.
$$

$S$ and $C_0$ are constants from the shock Hugoniot $D = C_0 + Su$. For the glycerol, experimental data result in $S \sim 2.2$ [8] or 1.59 [9]. The results of our work and paper [2] are shown in figure
Figure 5. The strain rate vs the compression pulse amplitude (glycerin): ♦ denotes data obtained from processing of velocity profiles presented in [2]; △ denotes data of the present work.

Figure 6. The curve of glycerol viscosity. Boxes denotes viscosity of glycerol calculated using power-law dependence of the strain rate $\dot{\varepsilon}$. The curve of glycerol viscosity plotted in logarithmic coordinates can be fitted as a power law with increase of viscosity. This observation is in agreement with work of Mineev and Zaidel [10], where shear viscosity was estimated by measuring damping of perturbation on the shock front.

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