VISCOSITY MEASUREMENT FOR SHOCK-COMPRESSED WATER

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UDC 532.13:539.89

The available experimental data on the viscosities of shock-compressed liquids have been obtained by two methods: by recording small perturbations of sinusoidal form at shock-wave fronts under geometrically similar conditions [1, 2] and from measurement of the impurity electrical conductivity [3, 4]. These methods enable one to determine η (the dynamic viscosity) only indirectly, and they can produce substantially different results. For example, the η for water at 8-24 GPa obtained in [5, 6] by the first method were about 10^4 P, whereas the second method gave about 10^{-2} P [3]. To establish the true value of η and the reasons for this large discrepancy (by six orders of magnitude), a new method was suggested [7] for determining the viscosity of a shock-compressed liquid.

One records the speed of a thin metal cylinder in a layer of material compressed by a shock wave. The cylinder speed and flow speed are recorded magnetoelectrically by the method proposed by Zavoiskii [8]. It is assumed that the force acting on the cylinder from the liquid is dependent on the viscosity as follows:

$$f = (1/2)\rho(U - V)^2 \operatorname{sign}(U - V)\psi(\mathrm{Re}), \qquad (1)$$

where $\mathrm{Re} = \rho d(U - V)/\eta$ is the Reynolds number, d is cylinder diameter, U and V are the speeds of the flow and cylinder correspondingly, and ψ(Re) is the experimental resistance function [9]. One can compare the observed dependence of the cylinder speed on time with that calculated from (1) for various values of η to determine the viscosity. In [7], the experiments were performed with copper and tungsten cylinders of diameter d = 0.36-0.5 mm at pressures of 3-8 GPa, the values of η found for water being about 10^3 P. A study of these experiments indicates certain faults in the methods, which are pointed out also in [10].

1. In the initial stages of the flow around the cylinder, the motion is determined not by the Reynolds number but by wave processes in the cylinder having the characteristic reverberation time $\tau_1 = 2d/c$, where c is the speed of sound in the cylinder material. The quasistationary flow around the cylinder is established in not less than $(5-7)\tau_1$. Under the conditions of [7], this time was 1.5-2 μsec, i.e., was comparable with the recording time.

2. The flow around the cylinder has a falling mass-velocity profile, and it therefore has variable density and pressure, so a quasistationary flow state may not be set up.

3. An equation of motion of the form of (1) does not incorporate the pulse character of the flow (Basset and adjoint-mass forces).

We have used the method of [7] subject to the above comments in new measurements on the dynamic viscosity of water shock-compressed to 6-7.5 GPa at an initial temperature of 15-18°C. The transducers were cylindrical copper and tungsten wires. To reduce the transient-response time, the main series of experiments was performed with wires of diameter 0.03-0.045 mm. With these thicknesses, the characteristic reverberation time was 0.015-0.020 μsec, and steady-state flow was established in 0.1-0.2 μsec.

Figure 1 shows the system. When the explosive charge 1 is detonated (diameter 84 mm and height 100 mm) by the plane-wave generator 2, a shock wave is excited in the layer of water 3, which is separated from the charge by an air gap of thickness 10 mm and a screen of silicate glass 4 of thickness 1.5 mm, this wave having a square mass-velocity profile. At a depth of 8-12 mm from the contact surface between the screen and the water there are the cylindrical transducer 5 and the flow speed transducer 6 made of aluminum foil of thickness 0.07 mm. The measurements were made with a field of 450 Oe between the poles of the permanent magnet 7. Figure 2 shows the velocity waveforms from these transducers, where the cylinder speed is shown at the top and the flow speed below. The frequency of the time marks is 10 MHz.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 44-48, September-October, 1984. Original article submitted July 17, 1983.

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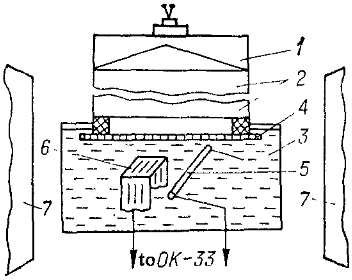

Fig. 1

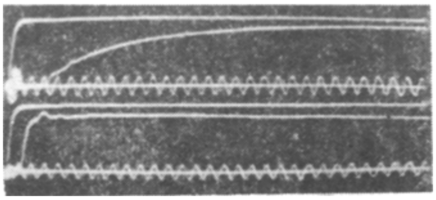

Fig. 2

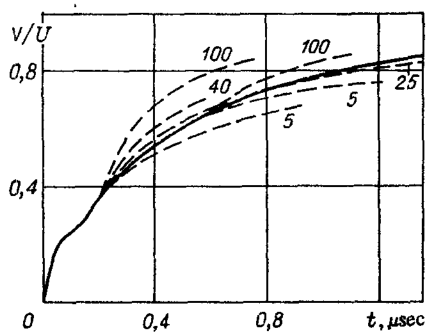

Fig. 3

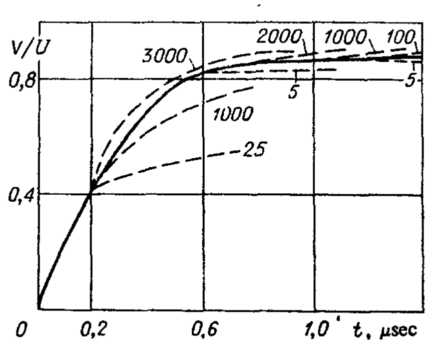

Fig. 4

With this system, a constant flow was provided for about 1.5 μsec near the transducer.

In [11], an equation was given for the nonstationary motion of a cylinder in a flow of viscous incompressible liquid for small Reynolds number (Re < 1)

$$\rho_1 \pi r^2 \frac{dV}{dt} = \pi \rho r^2 \frac{d(U-V)}{dt} + 4\sqrt{\pi\eta\rho}\, r \left[\frac{U}{\sqrt{t}} - \int_0^t \frac{dV}{d\tau} \frac{d\tau}{\sqrt{t-\tau}} \right] + f, \tag{2}$$

where ρ_1 and r are the density and radius of the cylinder in the compressed liquid, t is cylinder motion time, and τ is time ($0 \leq \tau \leq t$). The first term on the right in this equation expresses the force acting on the cylinder from the adjoint masses, while the second represents the Basset force [12] and the third the force f due to the dynamic head and viscosity. We substitute (1) into (2) to get after transformation that

$$\frac{dV}{dt} = \frac{\rho}{\pi r(\rho_1 + \rho)} (U - V)^2 \psi(\mathrm{Re}) + 4 \frac{\sqrt{\pi\eta\rho}}{\rho_1 + \rho} r \left[\frac{U}{\sqrt{t}} - \int_0^t \frac{dV}{d\tau} \frac{d\tau}{\sqrt{t-\tau}} \right]. \tag{3}$$

This expression was used to determine the dynamic viscosity by comparing the observed and calculated cylinder speeds. The initial conditions for calculating t_0 and V_0 may be chosen on the basis of the flow establishment time. For cylinders of diameter 0.03-0.045 mm, t_0 = 0.2 and 0.6 μsec, while for cylinders of diameter 0.2-0.23 mm the calculations were performed with t_0 = 0.2, 0.6, and 1 μsec. Figures 3 and 4 show the experimental velocities of the tungsten-wire transducers (diameter 0.045 mm) and the copper ones (diameter 0.2 mm), the solid lines representing the experimental values and the dashed lines the calculations in terms of dimensionless quantities. In Fig. 3, the flow speed was U = 1.49 km/sec, while in Fig. 4 U = 1.55 km/sec. The numbers on the dashed lines indicate the values of η in poise for which the calculations were performed. Agreement is obtained between the calculated and observed velocities for thin cylinders with η = 10-25 P, no matter what the choice of initial conditions. If η is reduced to 5 P or raised to 40 P, the calculated curves deviate from the experimental ones by an amount exceeding the error in the velocity measurement, which in these experiments was ±50 m/sec. Table 1 gives the results obtained with the thin transducers. In parentheses we give the range in η outside which the calculated curves deviate from the experimental ones by more than ±50 m/sec. The values found for the most likely η for water at 6.1-7.5 GPa are 20 P with limits from 5 to 40 P. These new values of η are less than those determined in [7] by two orders of magnitude.

TABLE 1

Cylinder material	Diameter, mm	U, km/sec	Pressure, GPa	η, D	Cylinder material	Diameter, mm	U, km/sec	Pressure, GPa	η, D
Copper	0,03	1,65	7,5	10(5—20)	Tungsten	0,045	1,49	6,4	25(5—40)
	0,045	1,45	6,1	20(5—40)		0,03	1,49	6,4	10(5—20)
						0,03	1,50	6,5	20(5—40)

TABLE 2

t, μsec	Calculated V_1 from (1), km/sec	Calculated V_2 from (3), km/sec	V_1-V_2, km/sec	t, μsec	Calculated V_1 from (1), km/sec	Calculated V_2 from (3), km/sec	V_1-V_2, km/sec
0,22	0,596	0,592	0,004	0,9	1,127	1,156	—0,029
0,3	0,732	0,718	0,014	1,0	1,155	1,190	—0,035
0,4	0,853	0,840	0,013	1,1	1,178	1,220	—0,042
0,5	0,939	0,934	0,05	1,2	1,199	1,245	—0,046
0,6	1,004	1,007	—0,003	1,3	1,218	1,267	—0,049
0,7	1,054	1,067	—0,013	1,4	1,234	1,286	—0,052
0,8	1,094	1,116	—0,022				

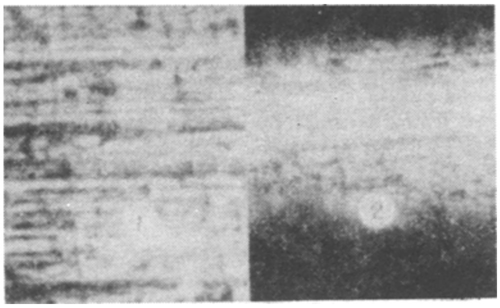

Fig. 5

We also performed experiments with transducers of diameter 0.2-0.23 mm (Fig. 4), i.e., comparable in diameter with the transducers of [7], which showed that the calculated and observed curves for the time interval from 0.2 to 0.6-0.8 μsec agree well well for $\eta \approx 3000$ P, whereas for $t > 0.8$ μsec these curves differ for such η. The calculations for $t_0 = 1.0$ μsec did not enable us to distinguish the calculated curve that most accurately describes the experimental one even for a stationary flow because the comparison region is small. We merely note that the recorded curves lie between the calculated ones for η = 100-300 P and η = 5 P, i.e., they also do not agree with those given in [7]. The experiments and calculations for cylinders of diameter 0.2-0.23 mm and above in [7] show that the value found for η by this method is very much dependent on the settling time for the quasistationary flow, namely on the choice of t_0, and also on the time for which the flow has constant parameters near the cylinder. Another possible reason for the discrepancy between our data and those of [7] lies in the calculation method. However, Table 2 gives calculations from (1) and (3) for an experiment with a tungsten cylinder of diameter 0.045 mm with η = 25 P and a flow speed of 1.49 km/sec, and the discrepancy is here not explained in terms of the forces exerted on the cylinder by the adjoint masses and the Basset force. The calculations from (1) and (3) were based on the assumption that the surface of the cylinder was smooth. The roughness k of the wires used here according to [13] was in the range 1.2-0.2 μm. On the existing roughness classification, this corresponds to finish class 8-9. Figure 5 shows enlarged pictures of a standard ground surface of class 9 finish 1 and the surface of the tungsten wire 2 of diameter 30 μm. The thicknesses δ of the boundary layers were about 14 and about 5 μm correspondingly on the assumption that $\delta \sim d/\sqrt{Re}$ for cylinders of diameter 230 and 30 μm. According to [14], the roughness has no effect on the flow for $k \ll \delta$.

Therefore, the calculations and experiments with cylinders of diameter 0.2-0.23 μm have shown that the reason for the discrepancy is the large settling time for the quasistationary state for the cylinders of [7] on account of their large diameter. The new values for the viscosity of shock-compressed water are close to the estimate made in [15]. We note that the viscosity calculated in [7] on the basis of the hole theory of liquids [16] agrees with our experimental values.

I am indebted to L. V. Al'tshuler, G. S. Doronin, and R. I. Nigmatulin for valuable advice and for discussions of the results.

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