

Relationship between the viscosity and possible phase transformations in shock-compressed water

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The viscosity of shock-compressed water at a pressure of 250 kbar is investigated. The experimental and theoretical data indicate that there is a relationship between the viscosity and phase transformations in shock-compressed water.

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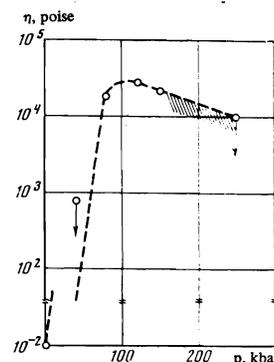
A method for investigating the viscosity of substances behind a shock-wave front (SWF) was proposed by Sakharov et al.^[1]. The method is based on the experimental study of the development of small perturbations on the SWF. Experiment^[1] and theory^[2] have shown that, when the experimental setup is geometrically similar with respect to the wavelength λ of the perturbations on the SWF, the effect of the viscosity reduces to a phase shift between the plots (perturbation amplitude versus time) of the development of perturbations with different λ . Geometric similarity in the experimental setup also ensures the absence of methodological errors. Several results of investigating the viscosity of substances behind a SWF by this method have previously been described^[1,3,4].

The present report presents experimental results of an investigation of the viscosity of water behind a SWF with a pressure $p = 250$ kbar on the front. The experimental setup and the procedure for calculating the coefficient of dynamic viscosity η of water did not differ from those in the work of Zaïdel' and one of us^[4]. The development of the perturbations on the SWF in water was investigated for $\lambda = 1$ cm and $\lambda = 2$ cm with a relative initial amplitude $a_0/\lambda = 0.1$, where a_0 is the initial amplitude of the perturbations on the SWF. The shock wave was produced in water by striking a steel detonator against a cell with water^[4]. The experimental conditions were such that there was one-dimensional and single compression of the water. The perturbations on the SWF^[1] in the water were recorded in a region free of lateral and reverse unloading. The development of perturbations on a SWF in water was investigated in two experimental devices that were geometrically similar with respect to λ , including the explosive charge and a steel detonator.

The results of the experiments have shown that the perturbations on a SWF in water at $p = 250$ kbar oscillate and are damped with time, i.e., the shock wave is stable. The law governing the development of perturbations on the SWF is independent of the wavelength of the perturbations λ with an accuracy within experimental error of $S/\lambda \leq 0.05$ (S is the phase shift between the curves of the development of perturbations with $\lambda = 1$ cm and $\lambda = 2$ cm), which corresponds^[4] under these conditions to a coefficient of dynamic viscosity of water of $\eta \leq 10^4$ P. The initial temperature and viscosity of water were, respectively, 10°C and 0.01 P. The experimental data on the dependence of the viscosity of water on the pressure on the SWF is given in the figure. The coefficients of viscosity for water at $p = 40, 80, 120,$ and 150 kbar were taken from ref. 4.

Let us note the special features of the $\eta(p)$ depend-

Dependence of the coefficient of viscosity η of water on the pressure on the shock-wave front p .



ence. When the pressure on the SWF is varied from 40 to 80 kbar, the coefficient of viscosity of the shock-compressed water increases by at least an order of magnitude. In the shock pressure range $120 < p < 250$ kbar the viscosity of water decreases.

The Rice and Walsh equation of state for water^[5], which was developed without regard to possible transformations, was used in^[4] to interpret the $\eta(p)$ dependence of water in the shock pressure range $120 < p < 250$ kbar. Schroeder and McMaster considered the possibility of the formation and subsequent melting of ice as the pressure is varied along the shock adiabat on an SWF in water^[6].

The relationship between the viscosity and changes in the phase state of shock-compressed substances has been discussed in a number of reports^[1,3,4,7]. The increase by at least an order of magnitude in the coefficient of viscosity of shock-compressed water as the pressure is varied from 40 to 80 kbar can be interpreted as the solidification of water (the formation of ice) in this pressure interval^[4].

Al'tshuler, Bakanova, and Trunin^[8], who measured the kinematic parameters of a shock wave in water and the transparency of water behind a SWF, observed a phase transition in water at $p = 115$ kbar. The investigations on the transparency of shock-compressed water at pressures ranging from 40 to 300 kbar, carried out by Zel'dovich, Kormer, Sinitsyn, and Yushko^[9], did not confirm the result of Al'tshuler et al.^[8] concerning the loss of transparency in water at $p = 115$ kbar. However, analysis of the experimental data on the dynamic compressibility of water^[6] permitted Schroeder and McMaster to conclude that shock-compressed water (with an initial temperature of 20°C) melts at a pressure of 130 kbar. According to the theories they developed^[6], the decrease in the viscosity of shock-compressed water at $p > 120$ kbar may be considered as the melting of ice behind the SWF.

We note that judging from the $\eta(p)$ dependence at $p > 120$ kbar, the melting of ice does not take place strictly at one pressure on the SWF, but occurs in the shock pressure range $120 < p \leq 250$ kbar.

In conclusion, we shall answer the critical remarks of Hamann and Linton^[10] regarding the discrepancy between their estimates of the coefficient of viscosity of water and the results of our experiments. They^[10] cited two estimates for the coefficient of viscosity of water at $p \approx 100$ kbar. The first estimate is based on extrapolation of plots of the viscosity coefficient of water against the static pressure and against the temperature at pressures to 3.5 kbar and to 833 K. This extrapolation does not take into account the possible phase transformations in shock-compressed water. According to the second estimate, the coefficient of dynamic viscosity of water is found from data on the electrical conductivity Σ of shock-compressed solutions of potassium chloride in water with the aid of Walden's relation $\Sigma \propto 1/\eta$ ^[11]. The validity of this relation at high densities and temperatures, particularly at the densities and temperatures that arise under dynamic loading conditions, has not been proved as far as we know. In addition, Walden's relation seems to be valid only for solutions whose electrical conductivity and viscosity are determined by processes that occur in one structural level. The conduction of shock-compressed water is ionic, as shown in the work of David and Hamann^[12]. The structural level which determines the viscosity of shock-compressed water is unknown. We may only state that in our case there is relative motion, with an approximate frequency^[4] 10^5 sec^{-1} , of regions of matter with a characteristic dimension on the order of the wavelength $\lambda \approx 1 \text{ cm}$ of the perturbations behind the SWF in water.

Further progress in the understanding of the nature

of the viscosity of shock-compressed water may be expected from investigations of the dependence of the coefficient of viscosity of water behind a SWF on the wavelength of the perturbations, using the procedure of ref. 1.

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