Compression of Water by Strong Shock Waves

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Submitted August 13, 1971

Zh. Eksp. Teor. Fiz. **62**, 710–712 (February, 1972)

The results are given of the determination of the relative compressibility of water at pressures ≈14 Mbar. The experimental data are compared with the calculated dependence as obtained on the basis of the quantum-statistical Thomas-Fermi model.

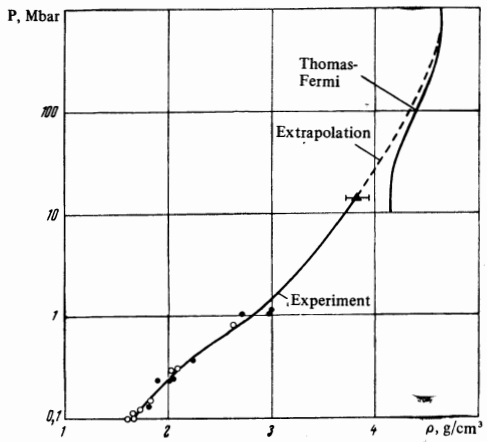
At the present time, computational methods for determining the equations of state of high-temperature and high-density media are based chiefly on models in which the statistical description of the electrons of compressed atoms is used (the Thomas-Fermi model).[1] For simple homogeneous matter (for example, metals with a large number of electrons), the statistical approach is entirely correct. At the same time, for light materials ($\rho_0 \lesssim 1$ g/cm^3), the validity of the use of such solutions is far from obvious. Furthermore, the Thomas-Fermi model is not adequate in the case of chemical compounds, in particular those consisting of atoms with strongly different properties. In particular, for water, the presence of hydrogen is taken into account by artificial procedures, for example, by the "smearing out" of its oxygen atom over the sphere or by generalization of the nuclei and electrons of hydrogen together with the electrons of oxygen into an oxygen-like atom.[2]

From the viewpoint of testing the validity of the theoretical solutions in the region of high pressures, the possibility of the direct comparison of the computed and experimental data on the dynamic compressibility of the materials is very attractive. Unfortunately, the range of detection of the shock compressibility of relatively light materials, in particular, water, by absolute methods[3,4] is limited by a number of reasons to maximum pressures in the range 1–2 Mbar. Further progress in the scale of pressures is possible at the present time only with the use of relative methods,[5-7] based on the proved interpolation of the shock adiabat of a standard substance. Aluminum can serve as such a material for water. In the coordinates of pressure (P) and relative compression ($\sigma = \rho/\rho_0$, ρ the density of the compressed material, ρ_0 the initial density), the dynamic adiabat of aluminum can be represented in the form[7]

$$P = \frac{\rho_0 C_0'^2}{(\lambda-1)^2}\sigma(\sigma-1)\left[\frac{\lambda}{\lambda-1}-\sigma\right]^{-2}$$

with the values of the constants: $\rho_0 = 2.71$ g/cm^3, $C_0' = 5.28$ km/sec, $\lambda = 1.218$. The arrangement for the current measurements consisted of the recording of the successive passage of a strong shock wave through a block of aluminum of thickness $\Delta = 160$ mm (screen) and a layer of water $\Delta = 80$ mm. The excellent symmetry of the wave permitted us to determine its velocity (D) with the necessary accuracy (the error did not exceed 1%).

The determination of the parameters of the compression of the water from the known wave velocities in the screen and in the specimen is carried out on P-U diagrams (the pressure and mass velocity of motion of matter behind the front of the shock);[3] the initial states in the aluminum screen are fixed by the intersection of the wave ray $\rho_0 \mathrm{Al} D\mathrm{Al}$ with the adiabat of aluminum (the transition from the coordinates $P - \sigma$ to $P - U$ is brought about with the use of the laws of conservation of mass and quantity of motion: $P = \rho_0 DU$ and $\sigma = D(D-U)^{-1}$), the pressure and the mass velocity in the water are determined by the point of intersection of the wave ray $\rho_{0\mathrm{H_2O}} D_{\mathrm{H_2O}}$ with the isentropic expansion of the aluminum.[1)] Inasmuch as small damping takes place in the experiment in the shock wave traveling along the investigated sample, the comparison of the wave velocities indicated above was carried out on the common boundary of separation of the aluminum and water. The transition from the mean values of the wave velocities (referred to the mean thickness of the samples) to their local values on the boundary of separation was carried out by means of the introduction of small computational corrections, which take into account the damping of the waves.



Comparison of the calculated (Thomas-Fermi) and experimental adiabats of water: ○, ●–data from [7,9], ▲–results of present research.

The initial parameters in aluminum were: $D_{\mathrm{Al\,gr}} = 36.40$ km/sec, $U_{\mathrm{Al}} = 25.55$ km/sec, $P_{\mathrm{Al}} = 25.2$ Mbar. For water we obtained the following parameters:

[1)] As estimates show, the position in the P-U plane of the isentropic expansion is practically identical (in the range of pressures and mass flows of interest to us) with the dynamic adiabatic of aluminum, as a consequence of which we have used the latter in their construction.

D = 43.95 km/sec, U = 32.42 km/sec, P = 14.25 Mbar, ρ = 3.815 g/cm^3. The error in the determination of the water density,[5] associated with the experimental inaccuracies in the recording of the wave velocities in the screen and in the sample, and also with the indeterminacy of the standard adiabat of the screen (we take $\Delta\sigma_{Al} \approx \pm 0.1$) amounts here to $\Delta\rho/\rho \approx \pm 0.03$.

The experimental data are compared with the results of[8,9] on the drawing in the coordinates pressure-density. The computed shock adiabat, obtained by the Thomas-Ferm method, is also shown. For the calculations, it was assumed that the ionized atoms of hydrogen were generalized among the electrons of the oxygen-like cell; their nuclei were taken into consideration according to Boltzmann statistics, and the electrons, as usual, according to Fermi-Dirac statistics (the same as was done in the case of the calculation of the cold compressibility of water).[2] To the generalized pressure of the electrons and hydrogen nuclei was added the thermal pressure of the nucleus of oxygen as an ideal gas. The calculated shock adiabat (see the drawing) lies somewhat to the right of the experimental data, the extrapolation of which falls in well with the calculated dependence for P $\geq$ 400 Mbar. However, taking into account the accuracy of the experiment, we can assume the calculated dependence as valid even for much lower pressures (~50–70 Mbar).

Thus, the applicability of the Thomas-Fermi model for finding the parameters of compression of light materials in the indicated superhigh pressure range is indicated by the equality of the computed and experimental dynamic adiabats.

The authors are grateful to M. P. Stadnik for the numerical calculations that have been carried out.

[1]Ya. B. Zel'dovich and Yu. P. Raĭzer, Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavlenii (The Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena) Fizmatgiz, 1963.

[2]A. Latter and R. Latter, J. Chem. Phys. **25,** 1016 (1956).

[3]L. V. Al'tshuler, K. K. Krupnikov, and M. I. Brazhnik, Zh. Eksp. Teor. Fiz. **34,** 886 (1958) [Sov. Phys.-JETP **7,** 614 (1958)].

[4]L. V. Al'tshuler, K. K. Krupnikov, B. N. Ledenev, V. I. Zhuchikhin, and M. I. Brazhnik, Zh. Eksp. Teor. Fiz. **34,** 874 (1958) [Sov. Phys.-JETP **7,** 606 (1958)].

[5]L. V. Al'tshuler, B. N. Moiseev, L. V. Popov, G. V. Simakov, and R. F. Trudin, Zh. Eksp. Teor. Fiz. **54,** 785 (1968) [Sov. Phys.-JETP **27,** 420 (1968)].

[6]R. F. Trudin, M. A. Podurets, B. N. Moiseev, G. V. Simakov, and L. V. Popov, Zh. Eksp. Teor. Fiz. **56,** 1172 (1969) [Sov. Phys.-JETP **29,** 630 (1969)].

[7]R. F. Trudin, G. V. Simakov, M. A. Podurets, B. N. Moiseev, and L. V. Popov, Izv. Akad. Nauk Az. SSR Ser. Fiz.-Tekh. Mat. Nauk **1,** 13 (1971).

[8]L. V. Al'tshuler, A. A. Bakanova, and R. F. Trudin, Dokl. Akad. Nauk SSSR **121,** 67 (1958) [Sov. Phys.-Dokl. **3,** 761 (1959)].

[9]I. C. Skidmore and E. Morris, Thermodynamics of nuclear materials, Proceeding of a Symposium, Vienna, 1962.

Translated by R. T. Beyer
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