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Abstract

Full Text

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PHASE TRANSFORMATIONS DURING THE COMPRESSION OF WATER BY STRONG SHOCK WAVES

(Presented by Academician Yu. B. Khariton, 17 I 1958)

Phase transformations of water under the action of high pressures into various crystalline modifications of ice were discovered by Bridgman (1) in investigations of the isothermal compressibility of water. With increasing temperature, the critical pressures of the first phase transition rose from 9800 atm at $t = 20°$ to 36 500 atm at $t = 175°$. Of undoubted interest is the study of phase transitions under conditions of dynamic compression of water by strong shock waves.

The first states of shock-compressed water were recorded by methods of pulsed X-ray photography in the investigations of Shal' (2) at a pressure of 190 000 atm. In 1957, Walsh and Rice (3), recording the parameters of shock waves, extended the range of investigated pressures to 420 000 atm. According to these authors, the shock adiabat of water has no breaks indicating a change in its phase state. In the same work, an attempt was made to detect phase transformations from changes in the transparency of water behind the fronts of shock waves whose amplitude did not exceed 100 000 atm. The experiments gave negative results.

Fig. 1. Experimental scheme. AA –impact surface, K –electrical-contact gauges

In the present communication data are presented on the shock compression of water in the pressure interval from 20 000 to 800 000 atm.

The research methods used, developed under the direction of one of the authors about 10 years ago, are based on the measurement of the kinematic parameters of a shock wave–its propagation velocity D and the mass velocity of the substance behind the wave front U.

Fig. 2. Pressure-velocity diagram. OA –wave straight line of the screen material, P_s –shock adiabat of the screen, 1—2 –release isentrope of the screen from state 1, OB –wave straight line of water, 2 –state of shock compression in water

Figure 2: Fig. 2. Pressure-velocity diagram. OA –wave straight line of the screen material, P_s –shock adiabat of the screen, 1—2 –release isentrope of the screen from state 1, OB –wave straight line of water, 2 –state of shock compression in water

By the laws of conservation of mass and momentum, these parameters are related to the density of shock compression

$$\rho = \rho_0 \frac{D}{D-U} \tag{1}$$

and to the pressure

$$P = \rho_0 D U, \tag{2}$$

where ρ_0 is the density of the substance before compression.

The method of investigation can be greatly simplified if the shock wave is brought to the layer of the substance under study (see Fig. 1) through screens made of a material with a known shock-compression Hugoniot $^{(4)}$. The experimentally measured quantities are the velocities of shock waves in the screen and in the water, recorded at equal distances from the impact surface.

On the pressure-velocity diagram (Fig. 2), the possible states of shock compression of the screen and of water at the recorded shock-wave velocities are represented, on the basis of (2), by two "wave straight lines" OB and OA (Fig. 2):

$$P_{\mathrm{H_2O}} = \rho_{0\mathrm{H_2O}} D_{\mathrm{H_2O}} U \quad \text{and} \quad P_{\mathrm{s}} = \rho_{0\mathrm{s}} D_{\mathrm{s}} U.$$

State 1 (Fig. 2) of shock compression of the screen is determined by the intersection of the screen wave straight line with its Hugoniot adiabat. State 2 of shock compression of water, in turn, lies at the intersection of the release isentrope of the screen material 1—2 with the wave straight line of water. The curve 1—2 is approximated with great accuracy by the mirror image of the shock adiabat of the screen with respect to the vertical passing through point 1.

Fig. 2. Pressure-velocity diagram. OA –wave straight line of the screen material, P_s –shock adiabat of the screen, 1—2 –release isentrope of the screen from state 1, OB –wave straight line of water, 2 –state of shock compression in water.

Fig. 3. A —Shock-compression adiabat of water. *a* —authors' data, *b* —data of work ([3]); 1 —beginning of the phase transition; 2 —end of the phase transition. B —dependence of the shock-wave velocity in water on the wave velocity in the aluminum screen

Figure 3: Fig. 3. A —Shock-compression adiabat of water. *a* —authors' data, *b* —data of work ([3]); 1 —beginning of the phase transition; 2 —end of the phase transition. B —dependence of the shock-wave velocity in water on the wave velocity in the aluminum screen

In most of the experiments the screen was made of aluminum, whose shock adiabat in pressure-velocity coordinates is given by the relation

$$P = \rho_{0\mathrm{Al}}(5.25 + 1.39U)U \cdot 10^4 \text{ atm} \qquad (3)$$

(U is given in km/sec.)

The wave velocities were determined by recording, on a triggered cathode oscilloscope, the moments of closing of the electrical-contact gauges K (see Fig. 1).

As the graph shows (Fig. 3), the dynamic adiabat of water breaks up into two segments, whose ends fix the region of the phase transition. This transition remained unnoticed in work ([3]) because of the insufficient number of experimental determinations.

Fig. 3. *A* —Shock-compression adiabat of water. *a* —authors' data, *b* —data of work ([3]); 1 —beginning of the phase transition; 2 —end of the phase transition. *B* —dependence of the shock-wave velocity in water on the wave velocity in the aluminum screen.

According to Bancroft and coauthors ([5]), a break in the compression curve associated with a phase transformation causes, for shock waves whose amplitude exceeds the critical pressure, the splitting of the shock front into two surfaces

discontinuity. Ahead of it a wave moves with velocity $D_1 = v_0\sqrt{\dfrac{P_1}{v_0 - v_1}}$ (see the P–V diagram, Fig. 3A). The velocity of the second discontinuity surface relative to the stationary substance is

$$D = U_1 + v_1\sqrt{\frac{P - P_1}{v_1 - v}}.$$

Restoration of a single discontinuity surface occurs at $D = D_1$ in the state $P_2 v_2$, for which

Fig. 4. Decrease in the transparency of water at a shock-compression pressure of 135,000 atm. AA—transition of the shock wave from the screen into the water

Figure 4: Fig. 4. Decrease in the transparency of water at a shock-compression pressure of 135,000 atm. AA—transition of the shock wave from the screen into the water

$$\frac{P_2 - P_1}{v_2 - v_1} = \frac{P_1}{v_0 - v_1}.$$

In the interval $P_1 < P < P_2$ the experimentally recorded velocity of the first discontinuity surface does not depend on the intensity of the applied pulse. This intensity may be characterized by the value of the wave velocity in the aluminum screen. In Fig. 3B it is compared with the velocity of the shock wave in water.

The diagram $D_{\mathrm{H_2O}}$—D_{Al} is formed by two inclined straight lines shifted relative to one another, joined, in accordance with the theory of the problem, by a horizontal segment $D_{\mathrm{H_2O}} = 5.44$ km/sec. The beginning of the phase transformation corresponds to the shock-compression pressure $P_1 = 115\,000$ atm.

Fig. 4. Decrease in the transparency of water at a shock-compression pressure of 135,000 atm. *AA*—transition of the shock wave from the screen into the water

The existence of the phase transition is also confirmed by the decrease in the transparency of water upon passage of shock waves with pressure amplitude $P > P_1$. To record the transparency, a light beam, as in (3), after passing through a layer of water, was reflected by the surface of the screen into the objective of a high-speed chronophotograph. The latter, with the aid of a rotating mirror, swept the image of the screen, diaphragmed by a narrow slit, along the film.

When a strong shock wave passed from the screen into the water, the intensity of the image decreased abruptly (Fig. 4). For shock waves with pressure amplitude $P < P_1$, no change in transparency was observed.

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