DYNAMIC TENSILE STRENGTH OF WATER

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ABSTRACT: This paper reports the results of an experimental study of the tensile strength of water under dynamic loading conditions in the absence of a free surface.

References [1, 2] present the results of investigations of the tensile strength of water under static loading conditions. The overwhelming majority of authors cite figures of the order of 10 atm, for example, [1]. The values given in [3], which were obtained in a capillary, are much higher (about 280 atm). This high value is apparently associated with the experimental method itself: the experiments were conducted in a capillary, and the effect of surface tension during formation of the interface was not taken into account.

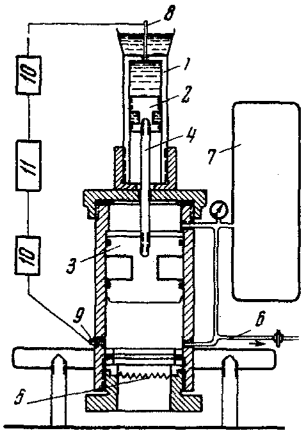

Fig. 1

It should be noted that these experimenters investigated the strength of purified degassed water. Ordinary water contains gas bubbles whose diameter is of the order of 0.01 mm [2]; under static loading conditions failure occurs at a pressure equal to the saturation vapor pressure at the experimental temperature.

Whereas numerous static loading experiments have been reported, the question of the dynamic strength of water has received little attention.

Cavitation effects are usually investigated by optical methods, discontinuities in the medium being fixed either by direct photography or from the change in refractive index. In the experiments described below the choice of method was determined by the following considerations. The effect of discontinuities on the medium and objects placed in it, as well as on the profile of a transmitted wave, is manifested, above all, in a change in pressure. In this case an important part is played by the frequency of the pressure fluctuations. If a bubble, formed when the water is placed under load, remains sufficiently small during the fluctuation period, it will have only a slight effect on the medium. However, it is rather difficult to establish this small critical diameter, although it is absolutely necessary in optical investigations.

In our experiments, to establish the presence of cavitation, we measured the pressure in the liquid. The advantages of this method are obvious: first, it does not involve the determination of the critical diameter of the bubbles, but is based on the registration of their effect on the medium; second, it permits the direct measurement of the negative pressure at which cavitation occurs and the time required to reach it.

The apparatus for investigating the tensile strength of water consisted of two vertical cylinders (Fig. 1), the upper of which is filled with water. The cylinders contained two pistons 2, 3, connected by a rod 4. The bottom of the lower cylinder is closed by a diaphragm 5. Supplying air to the header 6 results in an increase in pressure both above the diaphragm and in the space above piston 3.

At a certain pressure the diaphragm bursts, and under the action of the compressed air in the space above it, the lower piston begins to move downwards, carrying with it the upper piston which exerts a tensile force on the water in the upper cylinder. To ensure that the system moves under constant pressure, the space above the piston communicates with a vessel 7, whose volume is roughly 200 times greater than the volume of the space above the piston.

The end face of the upper cylinder is fitted with a TsTS piezoceramic transducer 8 which, with the help of an amplifier and oscillograph, registers the changes in pressure in the water. The lower part of the air cylinder contains a sensor 9 which triggers the oscillograph at the moment with the diaphragm bursts.

In this apparatus the acceleration of the piston reached 170 g.

The equation of motion of the piston has the form

$$x^{\cdot\cdot} = \frac{pS}{m} - \frac{\rho c S_0}{m} x. \qquad (1)$$

Here m is the mass of the pistons and connecting rod, p is the pressure setting the system in motion, S is the area of the lower and S_0 the area of the upper piston, ρ the density of water, and c the speed of sound in water. The force of friction is neglected.

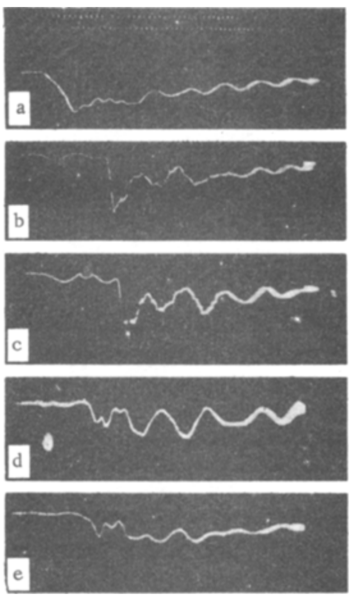

Fig. 2

The initial conditions at t = 0 are

$$x(0) = 0, \quad x^{\cdot}(0) = 0.$$

The solution of Eq. (1) under these conditions has the form

$$x = \frac{\alpha}{\beta}\left[t + \frac{1}{\beta}(e^{-\beta t} - 1)\right]$$

$$\left(\alpha = \frac{pS}{m},\quad \beta = \frac{\rho c S_0}{m}\right).$$

This motion of the piston creates a rarefaction wave moving upwards through the water. The pressure on the upper end of the cylinder, with allowance for reflection of the wave from the wall, will be described in the initial period by the equation

$$p_t = p_0 - 2\rho c \frac{\alpha}{\beta}(1 - e^{-\beta t}).$$

In view of the existing law of motion the piston cannot be a source of compression waves at any time during the interval up to impact against the stop, which in the experiments described was about $6 \cdot 10^{-2}$.

The action of the moving piston exerts a tensile force on the water, and the transducer registers the increase in negative pressure. At the moment of failure the negative stresses disappear. The transducer registers this moment as a rise in the curve on the pressure oscillogram. After failure, the changes in pressure are random in character owing to the irregular oscillation of the bubbles (Fig. 2a, b, c).

The experiments to determine the limiting negative pressure were performed with ordinary tap water free of visible bubbles. In the presence of visible bubbles the nature of the oscillogram changed sharply, the characteristic initial increase being replaced by random developing oscillations (Fig. 2d, e). The time marks represent 50 kHz.

On the oscillograms we measured the maximum negative pressure p_* (atm) and the loading time t (μsec), as which we took the interval from the beginning of the rise in pressure to the first drop.

The results of the experiments are presented in graphical form in Fig. 3 (where zero corresponds to atmospheric pressure). Here the points above the zero line, corresponding to vacuum, were obtained in the absence of visible bubbles, the points below the zero line in the presence of visible gaseous inclusions. The horizontal lines denote the error in determining time from the oscillogram. The error in determining pressure is 5% at the minimum amplitude.

As may be seen from the graph in Fig. 3, under dynamic loading ordinary water without degassing and distillation can withstand negative pressures of about 2.5 atm at loading times of the order of 20–30 μsec. With increase in loading time the strength decreases, reaching 0.5 atm at 150 μsec, and then falls almost to the static value at times of the order ot 300–500 μsec.

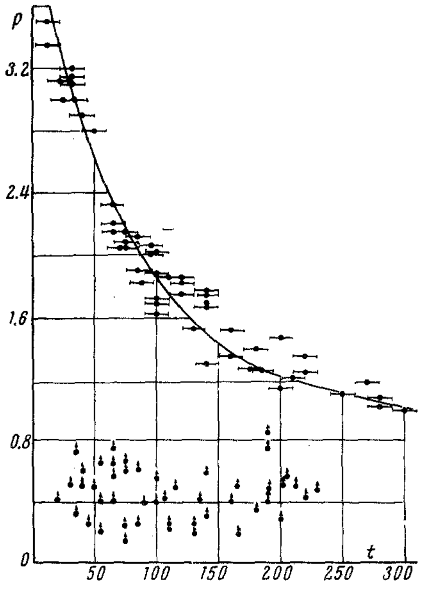

Fig. 3

With the selected dimensions and accelerations the water failed in the neighborhood of the upper end face of the working cylinder upon reflection of the rarefaction wave.

REFERENCES

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