SHEARING INTERFEROMETRY OF PREDISCHARGE PHENOMENA IN DEIONIZED WATER

I. M. Gavrilov, V. R. Kukhta,
V. V. Lopatin, and P. G. Petrov

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Although extensive studies of predischarge phenomena in water have now been performed using modern optical methods, both the role of diverse processes occurring in the gap in a strong electric field and their sequence remain controversial. In such studies the identification and measurement of the quantitative characteristics of hydrodynamic flows, shock waves (SW), the plasma of the developing discharge, phase transitions, vapor and gas formation and destruction of water in a strong field based on the recorded optical perturbations is a difficult problem.

In this paper we describe the interferometric studies of the structure of zones of optical perturbations arising in water in the range 10^{-6}-10^{-3} sec. It is well known that the recorded perturbations change both the amplitude and the phase of the diagnostic electromagnetic wave [1]. The character of the phase change in a sharply nonuniform field was determined with the help of a San'yak interferometer with a triangular beam path.

Measurement Procedure. The experimental arrangement is shown in Fig. 1 and consists of a pulsed generator 1 (it forms in the gap a positive pulse with an amplitude of 15-60 kV with a leading edge of ∿100 nsec and decays to one-half the amplitude in ~1500 μsec), a system for synchronizing the operation of the generator with the laser 2, a ruby laser with active mode locking 3, a discharge chamber 5 with a grounded, flat (60 mm in diameter) cathode, a sharp (the radius of the point varied in the range 100-250 μm) anode, a telescope 4, an input objective 6, a shearing interferometer 9, a camera 8, and an output objective 7. The duration of the laser radiation pulse (exposure) ~1 nsec; the frames are referenced to the voltage pulse applied to the gap with an accuracy of not worse than 10 nsec. The discharge chamber was filled with water with a specific conductivity of $5 \cdot 10^{-5}$ S/m.

When any one of the mirrors (M_1, M_2, or M_3) is turned by some angle two waves with identical wave fronts, but displaced in the recording plane by some distance relative to one another, are formed at the output of the interferometer. By varying this angle and by properly selecting the input and output optics employed, the sensitivity of the interferometer can be varied over a very wide range. For example, the sensitivity can be made to be no worse than that of a Mach–Zender interferometer for recording "weak" optical nonuniformities, or it can be reduced to such an extent that the interferometer will react only to nonuniformities that disrupt the lines in the Mach–Zender interferometer, and in this regime only "strong" nonuniformities are recorded. The advantages of the interferometer lie in the possibility of recording the perturbations of the refractive index n over a wide range of values and also the fact that the object can be placed outside the interferometer.

Experimental Results. It was established in [2] that in polar liquids two mechanisms of dendrite growth are realized – sub- and supersonic. Preliminary studies with the help of an ultrafast chamber enabled observing both mechanisms in purified water also. The development of an optical nonuniformity, appearing at a sharp point with electric fields in the range 10^7-10^8 V/m, is characterized by the following stages: growth of a dendrite into the gap with supersonic velocity, stopping of the growth, and expansion and decomposition of the dendrite. The last stages lead to the formation of microbubbles in place of the dendrite. The growth stage of such a dendrite is accompanied by generation of a large number of intense SWs, and interferograms that make it possible to judge the structure of the dendrite (Fig. 2) cannot be obtained.

In studying predischarge phenomena in water ($E = 10^7$-10^8 V/m) no perturbations of a hydrodynamic character, preceding the formation of nontransparent zones and dendrites (Fig. 3), were observed. In the experiments no significant difference between the distribution of the phase before and after application of the voltage was observed (Fig. 3a); this indicates

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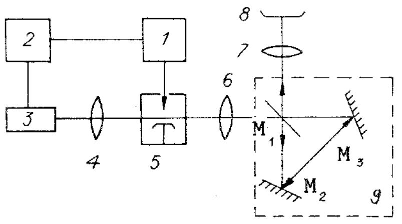

Fig. 1

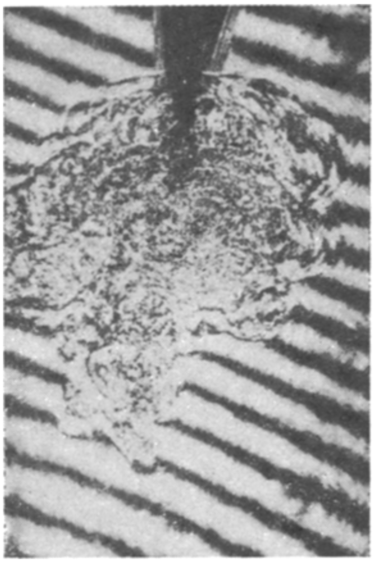

Fig. 2

that there are no strong flows leading to cavitation. These processes, as proposed in [3], are responsible for the nucleation of a discharge dendrite at the electrode. Under the conditions of our experiments the size of the region occupied by the flows, based on their velocity proposed in [3] 40-100 m/sec, must equal 100-400 μm and it should be possible to record this region with an interferometer. At the stage of nucleation, growth, and decomposition of a dendrite, shock waves are the only perturbations of a hydrodynamic character (Figs. 3b and c). At the stage of complete relaxation of a dendrite, when it consists of a cloud of microbubbles, the bending of the fringes in the interferograms in the cloud zone could be caused by a change in the temperature in the zone as well as a change in the structure of the liquid induced by the injected positive charge. One can see from Fig. 3e that the radius of this zone is approximately 2000 μm and the zone is associated with the sharp point, but the maximum perturbations are located ~1000 μm from the point. Figure 3d shows a dendrite after the growth stops, when the SW has receded from the core. After it stops growing the dendrite relaxes over a period of hundreds of microseconds, leaving behind it a cloud of microbubbles with a diameter of ~10 μm. Figure 3c shows a dendrite fragment at the starting stage of relaxation. As one can see from the photographs presented, the dendrite at the starting stage of relaxation consists of an open, diffuse structure. It is most likely a polycrystalline formation on charge centers [4]. Both the accumulation of volume charge and fluctuations of the temperature in the region of formation of microbubbles can be logically explained. The fluctuations in the temperature arise, according to the proposed model, with a transition of the water from one phase state (polycrystalline) into another (liquids, saturated with gas). It is difficult to give an acceptable interpretation of the experimental data on the basis of the "microbubble" model of a dendrite in the case of structural and thermal mechanisms of the change in n in its relaxation zone.

It is interesting that an increase in the intensity of the field accompanied by a decrease in the discharge time from 10^{-3} to 10^{-6} sec, i.e., a transition through the Maxwellian conductivity relaxation time, does not change the overall picture of the nucleation and development of a discharge dendrite; this indicates that heating of the liquid by the conduction currents has virtually no effect on dendrite nucleation and development.

Analysis of the Measurements. The successful application of an interferometer in these and other analogous studies is largely due to the possibility of obtaining quantitative information about the object studied. It was shown above that this problem, generally speaking, must be solved taking into account the defocusing factor, as well as diffraction and refraction of the diagnostic wave. Such an analysis involves well-known difficulties and goes beyond the scope of this paper. As an example of the measuring possibilities of this device, we shall examine the operation of an interferometer in the approximation of geometric optics, when defocusing is small and the characteristic dimensions of nonuniformities on which the amplitude and phase of the diagnostic wave change little are large compared with the wavelength λ.

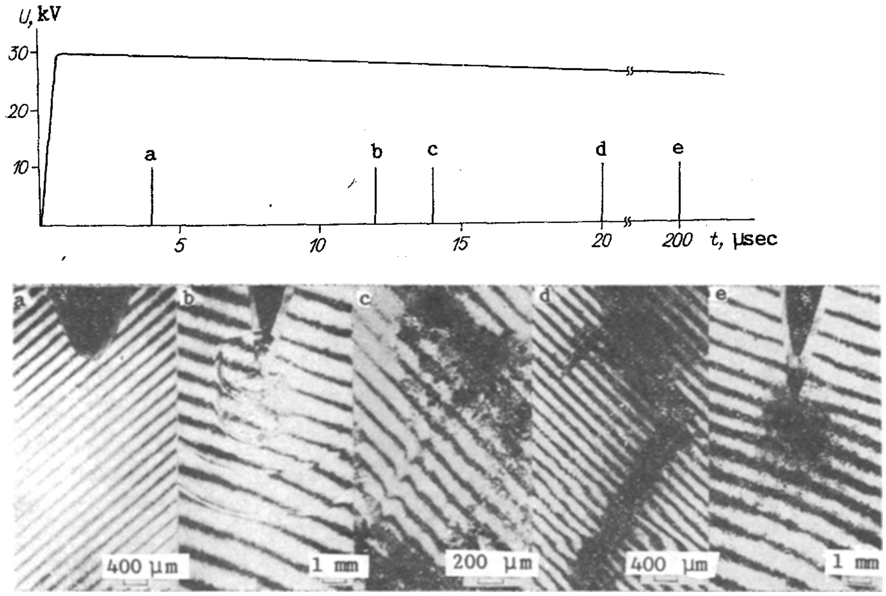

Fig. 3

Figure 4 shows schematically two waves at the output of an interferometer. The wave U' propagates along the z' axis and the wave U" propagates along the z" axis. We shall write the field of these waves in the form $U'(x', z') = A \exp(iS(x', z') + ikz')$, $U''(x'', z'') = A \exp(iS(x'', z'') + ikz'')$. Since $x'' = (x + a)\cos\alpha - z\sin\alpha$, $z'' = (x + a)\sin\alpha + z\cos\alpha$, $x' = (x - a)\cos\alpha + z\sin\alpha$, $z' = -(x - a)\sin\alpha + z\cos\alpha$, in the plane z = 0, where the photographic plate (PP) lies, the resulting field $U = U' + U'' = A\{\exp\{ik[-(x - a)\sin\alpha + z\cos\alpha)] + iS_{-a}\} + \exp\{ik[(x + a)\sin\alpha + z\cos\alpha] + iS_{+a}\}\}$, $S_{-a} = S(x', z')$, $S_{+a} = S(x'', z'')$ will operate. In the plane z = 0 the intensity distribution $I \sim UU^* = 2A^2 + 2A^2\cos(2kx\sin\alpha + (S_{+a} - S_{-a}))$.

Thus the formation of the interference pattern is affected by the phase difference $S_{+a} - S_{-a}$. In the first, eikonal-equation approximation $S(x', z') = \frac{k}{2}\int_0^{z'} \varepsilon(x', z')\,dz'$. Let $\varepsilon(x', z') = \hat{F}[\varphi(\varkappa, z')]$, where $\hat{F}$ is the Fourier transformation operator in the coordinate z; $\varphi(\varkappa, z)$ is the Fourier transform of the distribution function of the deviation of the dielectric constant from its average value in the object. Then, using the properties of the Fourier transformation, it can be shown that

$$\hat{F}^{-1}[S_{+a} - S_{-a}] = \frac{k\sin\varkappa a}{2}\varphi(\varkappa, 0). \tag{1}$$

In writing (1) it is assumed that $\cos\alpha \neq 1$, since $\alpha \simeq \lambda/a$ and $0.99 < \cos\alpha < 1$ for fringes separated by a distance of 10 μm and λ = 0.69 μm (this assumption is made in order to simplify the subsequent expressions and is not necessary). The formula (1) enables finding the distribution of ε in the object from the distribution of the phase difference $S_{+a} - S_{-a}$. If we are dealing with a symmetric phase object with radius R, so that $\varepsilon(x, z) = \varepsilon(\sqrt{x^2 + z^2}) = \varepsilon(r)$, it follows directly from (1) that

$$\varepsilon\left(\frac{r}{R}\right) = \frac{1}{\pi kR}\int_0^\infty \frac{1}{\sin\Omega d}\Phi(\Omega) I_0\left(\Omega\frac{r}{R}\right)\Omega\,d\Omega; \tag{2}$$

$$\Phi(\Omega) = \frac{2}{R}\int_0^1 \left(S_{+a}\left(\frac{x + a}{R}\right) - S_{-a}\left(\frac{x - a}{R}\right)\right)\sin\Omega\frac{x}{R}\,dx. \tag{3}$$

An interesting feature of the interferometer is that the zeroth harmonic of the phase difference is fully compensated, i.e., the average value of the phase over the object equals zero. This makes it possible to visualize more carefully the fine details of the object. The expressions (1)-(3) can be easily transformed for three-dimensional objects of the form $\varepsilon(x, y, z) = \varepsilon(\sqrt{x^2 + y^2 + z^2})$; the two-dimensional Fourier transform with respect to the coordinates must be used only in this case to find the spectrum of the phase (the corresponding expressions from [5] cannot be used, since the distribution of the phase difference is no

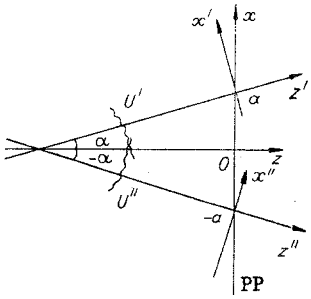

Fig. 4

longer radially symmetric). The pressure at the front of the SW can be evaluated using the foregoing results. The experiments showed that the maximum increase in the phase difference for sections of interferograms corresponding to the SW front varies in the range $\pi/3$-π for waves with radius R = 1000-3000 μm. The phase was measured on sections of interferograms corresponding to the perturbed U' and unperturbed U" sections of the wave. In the geometric-optics approximation such sections will be located at the edges of the object, the orientations of the normals to which are identical to that of the normals to the fringes in the interferogram. We shall assume that at the front of the SW ε is constant and equal to ε_0, while off the front $\tilde{\varepsilon} = 0$. It is not difficult to show that the maximum phase increase $S_{max} = k\varepsilon_0\sqrt{2R\delta}$ (δ is the width of the SW front). For SWs (Fig. 3c) with R ≈ 2500 μm, $\delta \approx 10$ μm (measured by the shadow method), $S_{max} \approx \pi/3$, $\varepsilon_0 \approx 5\cdot10^{-4}$. It is well known that the pressure p is related with the change in the refractive index by the relation [6] $p = (\Delta n/1.48)\cdot10^{10}$ N/m². In the notation adopted $\Delta n = \bar{n}\varepsilon_0/2$ ($\bar{n} = 1.33$ is the average value of the refractive index in water). Then $p = 2.2\cdot10^6$ N/m².

We note that the result obtained is a lower estimate of the pressure at the front of the wave, because the distribution of ε in the region of the front should have a more or less distinct maximum. It nonetheless falls in the range of pressures calculated from the velocity of the SW (the measurements were performed with a high-speed camera). Because the phase distribution depends on z, as discussed above, more accurate estimates of the distribution of ε for objects extended along z can be found only by using approximations that take into account the defocusing of the imaging system.

The results obtained demonstrate that shearing interferometry can be successfully used to study predischarge phenomena associated with a change in the density and phase composition of the medium under study. Interferometric measurements showed that in fields of 10^7-10^8 V/m in deionized water the nucleation of a discharge dendrite is not preceded by strong hydrodynamic perturbations: cavitation, electrohydrodynamic flows, electrostriction waves, and SWs.

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