Chapter 5

Structure and dynamics of "plasma" channels at the electric breakdown of dielectric liquids

The electric breakdown occurs when the electric field in dielectric liquid becomes sufficiently high. In chapter 4, the consequence of processes accompanying this phenomenon was described along with one possible mechanism of the generation of breakdown nuclei, the development of cavitation bubbles on the electrode surface. Further breakdown of gas inside bubbles when they reache the critical size results in generation of conductive regions. Such conductive regions can be generated also by other mechanisms. The fast growth of thin plasma channels (streamers) proceeds later from these regions. When a streamer reaches the opposite electrode, a conductive channel is formed.

In this chapter, the propagation of single streamer tip and the expansion dynamics of the discharge channel in liquid are considered taking into account the flux of fluid into channel plasma.

5.1 Streamer propagation in dielectric liquid

The flow of dielectric liquid was simulated by the LBE method. Computations were carried out on a square lattice with 4 values of particle velocity 0, 1, $\sqrt{2}$, and 2 (13 possible velocity vectors) [3, 32], fig. 1.4,*b*. This model allows one to introduce liquid temperature and to simulate energy release. If at a node the average kinetic energy per one particle ε ("temperature") exceeded the critical value ε_*, this node became conductive, and an energy release began at it. The energy release continued until $\varepsilon \leq \varepsilon_{max}$. Under such conditions, heat released in sufficiently thin layer near the channel boundary that corresponds to the real case. Indeed, conductive and radiative heat transport inside the channel is sufficiently fast, therefore, all the energy released is transferred from inner

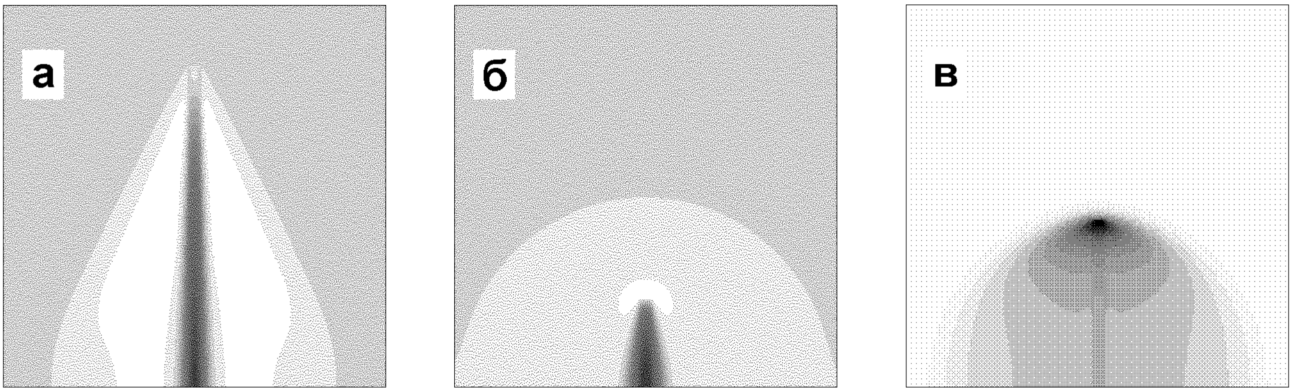

Figure 5.1. Density distribution. a — $v/c = 2{,}5$, $t = 100$; b — $v/c = 0{,}5$, $t = 140$ (darker color means lower density); c — pressure field, $v/c = 1{,}0$, $t = 130$ (darker color corresponds to higher pressure)

regions to the boundaries and it is absorbed in a thin layer of liquid. The inner structure of a channel boundary is considered more detailed in the following section.

Computations were carried out of the single streamer tip propagation at the breakdown of dielectric liquid (fig. 5.1). Expansion of the conductive channel and formation of compression waves were observed. These waves propagated with the sound velocity in a dielectric liquid (in this case, $c = 1$). When the velocity of the streamer tip was greater than c, a divergent shock wave having a nearly conical front was formed (fig. 5.1,a). Such waves were observed experimentally at pre-breakdown stages of streamer propagation in many works, e.g., in experiments [118]. When the the velocity of streamer tip was subsonic, the compression wave had spherical front (fig. 5.1,b,c).

5.2 Channel stage of the electric discharge in liquid

After the closing of the interelectrode gap by one of the initial streamers, the channel stage of the electric discharge begins.

For the one-dimensional problem of expansion of a conductive channel, a self-similar solution exists when the following three requirements are satisfied:

1. The power released in the channel $W = const$.
2. The heat conductivity inside the channel is high, and one can roughly consider that the energy released is completely transferred to the channel boundary by both the conductive heat flux and radiation.
3. The total heat flux from the channel is completely absorbed in a thin layer of liquid, leading to transition of the liquid to the plasma of the channel after dissociation and partial ionization of the fluid. The absorption of radiation in

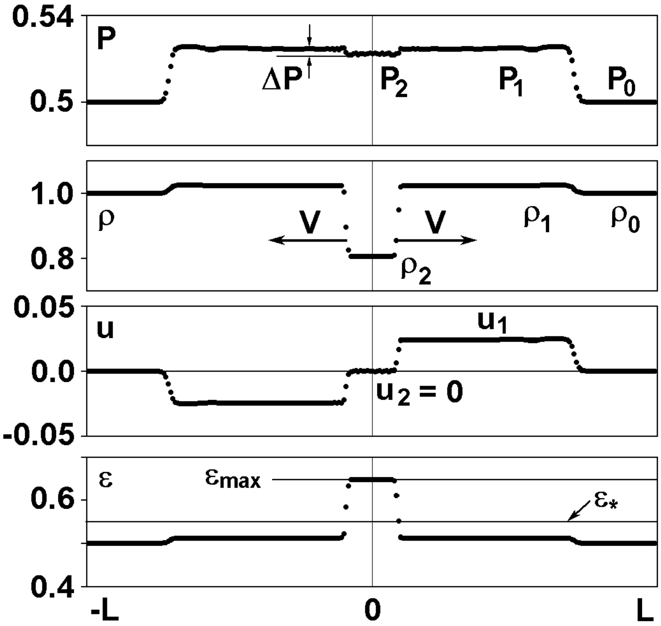

Figure 5.2. Structure of self-similar flow. Computations by the LBE method. P is the pressure, ρ is the density, u is the mass velocity, ε is the average kinetic energy per one particle ("temperature")

liquids increases sharply at the photon energy of order of 10 eV. Experimental data on the absorption spectrum of water in the far ultraviolet region [119] indicate that radiation with a wavelength $\lambda < 1600$ Å is almost entirely absorbed in a thin layer of liquid $\sim 10^{-4}$ cm.

Under these requirements, the mass velocity of "plasma" inside the conductive channel is zero, and the temperature, density and pressure are constant both over the channel cross-section and in time.

Figure 5.2 presents the flow structure for this self-similar solution obtained in simulation by the LBE method.

Transition of liquid to a conductive phase takes place in a transition layer liquid — "plasma". This transition proceeds through the flux of molecules of liquid to the channel plasma after their dissociation and partial ionization. At the channel stage of electric discharge, the molecular flux into the channel can be considerably greater than $j \sim 2 \cdot 10^{24}\ ^{-1} \cdot ^{-2}$ [120]. At the initial stage of streamer propagation, the temperature in conductive channel is comparatively low ($\sim$ 3000 K) [121], therefore, the density of substance in it differs slightly from the liquid density. Thus, the boundary between the conductive channel and the surrounding liquid is not an impenetrable piston. If the thickness of the transition layer is small comparing with the channel radius, the transition layer can be considered as a quasi-stationary gas-dynamic discontinuity. In the reference frame of the transition layer, the mass and momentum conservation laws are given by

$$\begin{aligned} \rho_1 D &= \rho_2 v_2, \\ p_1 + \rho_1 D^2 &= p_2 + \rho_1 D v_2. \end{aligned} \tag{5.1}$$

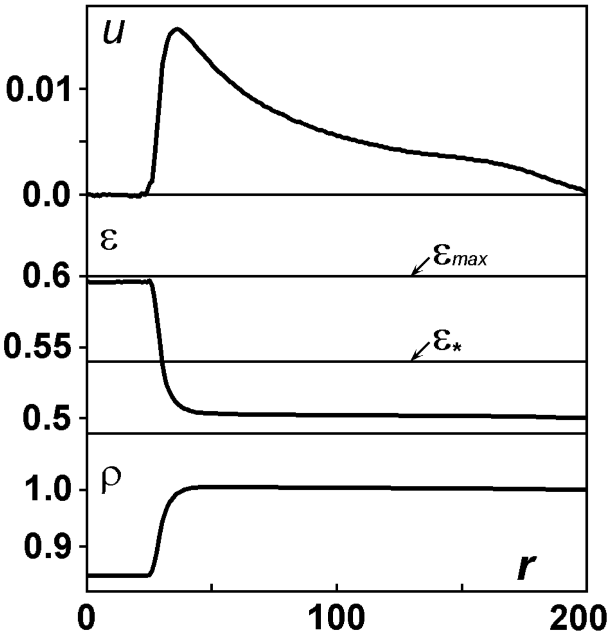

Figure 5.3. Self-similar liquid flow at the expansion of cylindrical streamer channel. Time is $t = 180$. ρ is the density, u is the mass velocity, ε is the average kinetic energy per unit mass ("temperature")

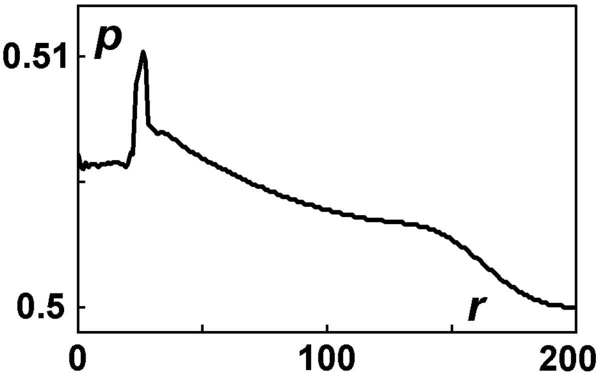

Figure 5.4. Pressure graph at the expansion of cylindrical channel. Time is $t = 160$

Here p is the pressure, ρ is the density, u is the mass velocity of liquid, D is the velocity of inflowing liquid, $v_2 = V - u_2$ is the plasma velocity relative to the discontinuity, $V = u_1 + D$ is the observable velocity of channel expansion (see fig. 5.2).

It follows from (5.1), that a small pressure jump $p_1 = p_2 + \rho_2 v_2 (v_2 - D)$ arises at the discontinuity (inside the channel the pressure is lower). This effect is caused by the mass inflow through the channel boundary. In the self-similar case, the mass velocity inside the channel is $u_2 = 0$, hence, $v_2 = V$, and the pressure difference is $\Delta p = p_1 - p_2 = \rho_2 V u_1$ that exactly coincides with the value obtained in the LBE computations (fig. 5.2).

The self-similar solution for the one-dimensional problem of the expansion of a cylindrical channel was also obtained (figs. 5.3 and 5.4). The only difference in conditions of its existence from those for the planar case is that the rate of energy release increases with time as $W = \alpha t$ [122].

Self-similar regimes of the expansion of a cylindrical streamer channel were

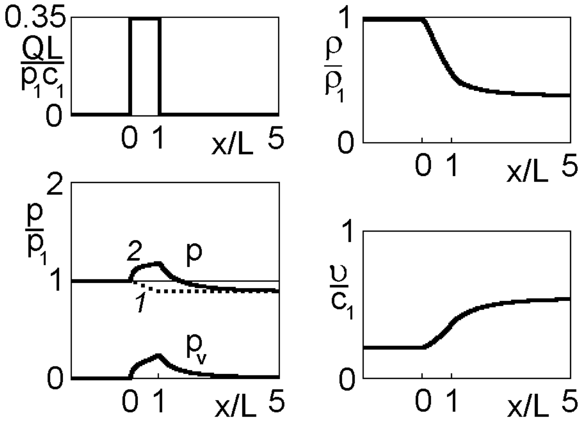

Figure 5.5. Structure of viscous transition layer for constant energy release

investigated for $W = \alpha t$ under conditions of energy release in a thin layer $\varepsilon_* < \varepsilon < \varepsilon_{max}$. Figure 5.3 presents the computation results. The mass velocity inside the channel was $u \approx 0$, and outside it approximately $u \sim 1/r$ up to the front of the divergent shock wave. The strength of this wave depended on the energy release and in the present case it was small. There were disturbances in the conductive channel, most noticeable on the velocity plots.

5.3 Model of the transition layer

Figure 5.4 presents the pressure graph corresponding to the computation of fig. 5.3. Besides the pressure difference Δp (5.1), there is a small pressure peak localized inside the transition layer. In order to explain this phenomenon, the one-dimensional model of viscous transition layer was considered.

Let the energy release takes place in a layer of thickness L. In the comoving reference frame, liquid flows into the zone of energy release with the velocity D. The conservation laws for mass, momentum and energy are given in the case of zero heat conductivity by:

$$
\begin{aligned}
&\rho v = \rho_1 D, \\
&p + \rho v^2 - (\frac{4}{3}\eta + \zeta)\frac{dv}{dx} = p_1 + \rho_1 D^2, \\
&\frac{\gamma}{\gamma - 1} p v + \rho v \frac{v^2}{2} - (\frac{4}{3}\eta + \zeta) v \frac{dv}{dx} = \frac{\gamma}{\gamma - 1} p_1 D + \rho_1 \frac{D^3}{2} + v \int\limits_0^x \frac{Q}{v} dx.
\end{aligned}
\tag{5.2}
$$

Here v is the current liquid velocity, γ is the adiabata index of the gas in transition layer, Q is the rate of energy release, η is the dynamic viscosity, ζ is the second viscosity.

The system (5.2) was solved numerically. Computation results are shown in fig. 5.5 for $p_1 = 1$, $c_1 = 1$, $D/c_1 = 0.2$, $\gamma = 5/3$ in the case of constant energy release in a layer of thickness $L = 1$ (dimensionless energy release was $QL/p_1c_1 = 0.35$, dimensionless viscosity was $(4/3\eta + \zeta)c_1/(p_1L) = 1$). Without viscosity, the pressure decreases monotonically in the zone of energy release (fig. 5.5, curve 1). The pressure peak can arise in the transition layer due to viscous part of the stress tensor $p_V = (4/3\eta + \zeta)dv/dx$ (fig. 5.5, curve 2). It follows from second equation of (5.2): the pressure is $p = p_1 + \rho_1 D(D - v) + p_V$. One can estimate the value of this peak for constant viscosity, assuming $dv/dx \approx V/L$. One obtains $p_V \sim 10^5$ Pa $\sim 1\%$ of p_1 for typical parameters of streamer channel expansion at the breakdown of liquids $V \sim 100$ m/s [118], $\eta = 10^{-3}$ kg/m·s $L \sim 10^{-6}$ m [120]. The pressure p_1 in liquid near the cylindrical discharge channel was estimated by its expansion velocity V [123]. For $V \sim 100$ m/s in water, one obtains $p_1 \approx 3 \cdot 10^7$ Pa. The relative value of the pressure peak in the transition layer for the LBE method is of the same order (fig. 5.4).

Summary

Use of the LBE method allows one to model qualitatively the flow of dielectric liquid at the streamer tip propagation and the flow at the channel stage of the electric discharge. In the case of the supersonic streamer velocity, divergent shock waves with conical front are observed. At the boundary of the discharge channel, the pressure jump is observed caused by the reactive force due to flow of fluid into the channel. The computed value of this pressure jump is equal to the theoretical one.

The channel boundary is a thin transition layer where the energy release occurs which forces the transition of liquid to the channel plasma. Inside the transition layer, the pressure changes non-monotonically due to viscous part of the stress tensor. Computed value of the pressure peak agrees with the theoretic estimates.