Streamer development in air with density discontinuity

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Abstract: Using two-dimensional numerical simulation of a streamer discharge developing through a shock wave it was shown that the streamer failed to penetrate to the high-density region when the ratio between the densities in these regions was sufficiently high (> 1.2). Thus, the gaseous medium demonstrates a unidirectional conductivity at short time scale: a gas density discontinuity formed a kind of "gas-dynamic diode" that allows the plasma channel to propagate in one direction and blocks its development in another.

Keywords: streamer development, shock wave, gas density discontinuity

1. Introduction

Development of streamers and streamer-like discharges in heterogeneous gas media is met under natural conditions and on a laboratory scale. Lightning discharges propagate in the cloud-to-ground gap along which the air density N changes gradually by several times [1, 2]. Lightning-initiated transient luminous phenomena develop at high altitudes and cover tens kilometers where the air density is subject to wide (up to orders of magnitude) variations [2, 3]. Experimental modeling of red sprites using a hot jet which imitates a gradient density in air was performed in [4] has shown the strong influence of the density variation on a streamer propagation. Streamers also interact with strong density discontinuities when the discharges propagate in a gas containing polarized solid particles [5] and water droplets [6, 7]. Streamer-like discharges intersect neutral particles density discontinuity in a shock wave formed in front of supersonic aircraft and spacecraft when lightning discharges develop from them. The influence of non-equilibrium weakly ionized plasmas generated in different (DC, RF and microwave) discharges on shock waves was thoroughly studied under laboratory conditions [8], whereas the effect of gas flow inhomogeneities on discharge plasmas was poorly understood.

Streamer and streamer-like (nanosecond surface dielectric barrier) discharges were widely used in plasma aerodynamics to control airflow by generating weak shock waves due to fast local gas heating [9-11]. These discharges can efficiently ignite combustible mixtures (see [12-15] and references therein). These mixtures may involve inhomogeneity (fuel jets and fuel aerosols or droplets). Therefore, studying the streamer interaction with shock waves and with some other inhomogeneities is of practical importance. For example, it is necessary to know the spatial distribution of deposited discharge energy and gas heating, as well as the distribution of energy input over various degrees of freedom of molecules.

These effects are difficult to study experimentally because a streamer discharge develops usually in the form of a number of filamentary channels (see, for instance, [1]). At present numerical calculations are widely used to simulate streamer development under various conditions (see, for instance, [16]). In particular, the influence of gas density gradients on streamer propagation was simulated for atmospheric high-altitude discharges [17, 18] and discharges intersecting bubbles and particles [19, 20]. In our previous work [21], a streamer discharge propagating through a shock wave from a high-density region to a low-density one was studied both experimentally and numerically. It was shown that the streamer properties change drastically when intersecting the shock surface.

In the present work we consider an opposite case – when a streamer discharge intersects a shock wave and develops from a low-density region to a high-density region. It was shown that a streamer behavior can change dramatically from the case when the discharge propagates in the opposite direction. In some cases, the streamer cannot penetrate into the high-density region and the discharge propagation is completely blocked by gas density discontinuity. In addition, we considered how the streamer develops through inhomogeneities in which the gas density changes gradually (the case of rarefaction and compression waves).

2. Results

To demonstrate the peculiarities of the interaction of a streamer with a shock wave, we simulated a single cathode-directed streamer propagating in a 15-cm discharge gap, in which the gas density n changed as a step function of the distance from the anode using the model [22-27]. The density was equal to n_1 for a distance less than 7 cm from the tip of the high-voltage electrode and was equal to n_2 for the gap between this point and the grounded cathode. The high-voltage electrode was a plate with a needle in the center. The needle shape was a semi-ellipsoid with a major semi-axis 8 mm and a minor semi-axis 0.8 mm. Both cases were considered: the start of the discharge in the region of high gas density and penetration into the low density region ($n_1 > n_2$), and the discharge start in the low density region and its development in the region of high gas density ($n_1 < n_2$). The voltage across the gap increased linearly over time 0-1 ns, and then remained constant at 100 kV level.

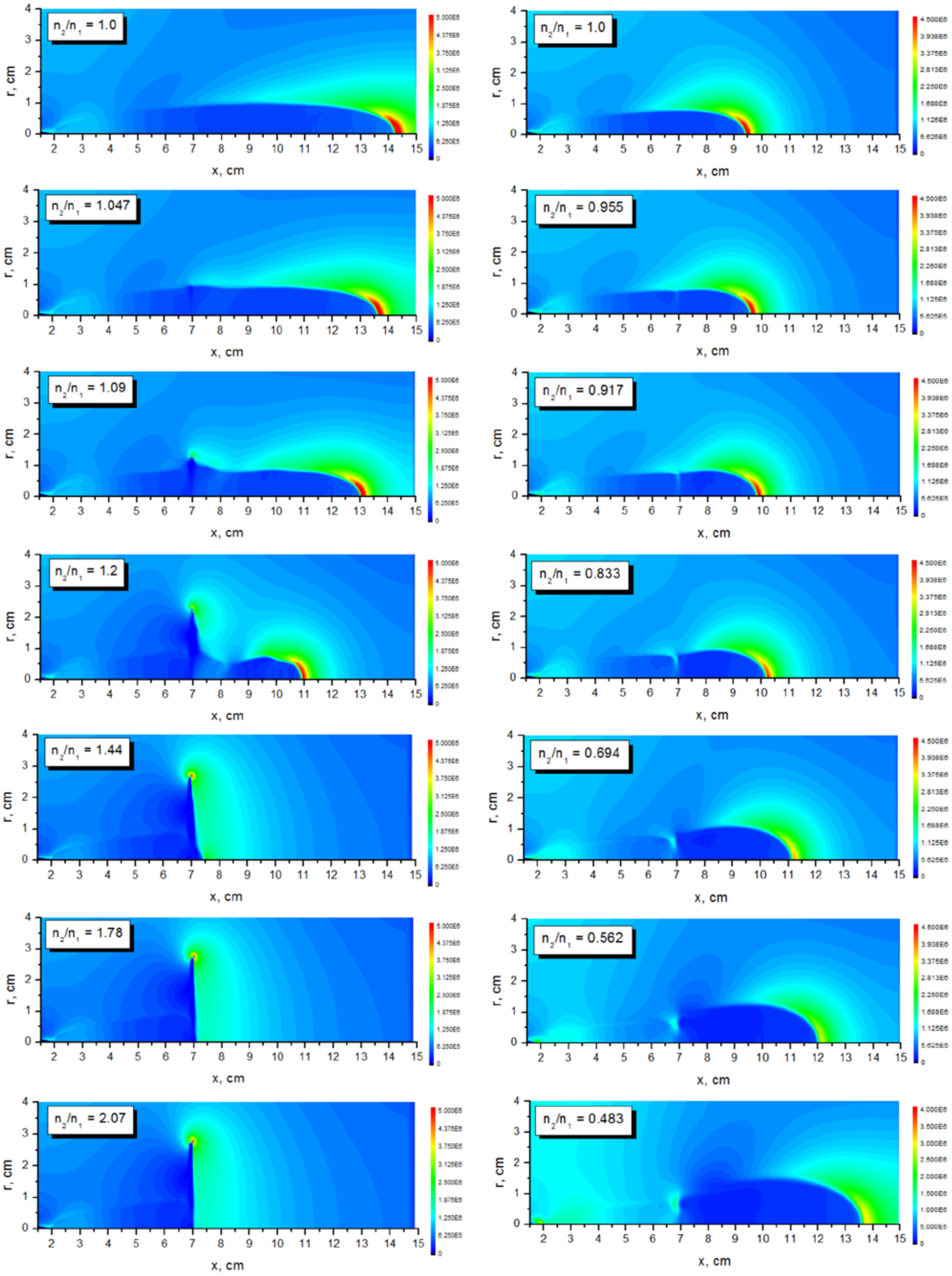

Figure 1. Interaction of a streamer with a discontinuity depending on the densities ratio.
t = 19.6 ns (left column); *t* = 14.0 ns (right column).

It becomes extremely interesting to trace the ratio at which the density discontinuity stops the streamer penetration into the medium with a higher density. Figure 1 shows the results of the calculation of streamer propagation in a medium with different density discontinuities – at the same time point. The right column demonstrates the transition of a streamer from a less dense gas to a more dense one (images show time t = 19.6 ns after the discharge start), and the left column shows a transition from a more dense to less dense medium (t = 14 ns). The difference in the streamer behavior at different intensities and the direction of the density discontinuity is clearly visible (Figure 1). Even with minimal disturbance (less than 5% - the second row of Figure 1), both in the case of a decrease and in the case of an increase in the density of the gas, the streamer channel shows noticeable distortions. In the case of the streamer passing into a high density medium, a local channel thickening is formed in the discontinuity plane, and in the case of passing into the a lower density medium, a local thinning of the channel and an area of increased electric field is observed.

An increase in the intensity of the discontinuity to 9% already leads to severe deformations of the streamer channel (third row of Figure 1). There is both a significant change in the channel diameter and electric fields near the discontinuity. The discontinuity of gas density with an intensity of 20% (fourth row) is the limit for the streamer propagation to a region of high gas density. The secondary off-axis field maximum emerges and leads to the formation of a conducting “plate” in the discontinuity plane, and the streamer propagation along the axis decelerates. Further, the instability develops near the discharge axis, which leads to the formation of a new head of a smaller diameter streamer, which continues to propagate in a high-density gas.

A further increase in the intensity of the discontinuity leads to an increase in the off-axis maximum of the electric field, and the rapid formation of a plasma layer at the boundary of the density discontinuity. In this case, the field on the discharge axis significantly decreases, and the instability, which leads to the formation of a streamer in a higher density medium, develops very slowly (row 5, Figure 1). Practically, the streamer cannot penetrate into the region of high-density gas at such an intensity of discontinuity. An increase in the ratio $n_2/n_1 > 1.7$ leads to a further enhancement of the effect: the streamer interacts with such a discontinuity practically as with a dielectric layer in the case of a barrier discharge.

A decrease in gas density ($n_2/n_1 < 1$) as expected, leads to an increase in diameter and a noticeable acceleration of the streamer (Figure 1, rows 6, 7). In this case, the “waist” on the streamer channel becomes more noticeable in the region of the transition to low-density gas, which is associated with the formation of a secondary ionization wave and mutual neutralization of charges on the surface of the discontinuity.

In this case, one can say that the medium for short times began to have unidirectional conductivity: a discontinuity in the gas density formed a kind of “gas-dynamic diode” that allows the plasma channel to propagate in one direction and blocks its development in the other. Obviously, such a “diode” is not able to operate for longer times, when due to the development of three-dimensional instability in the plasma layer forming the conductive “plate”, the symmetry of the electric field is broken, and the discharge begins to propagate to a region of high density as a new streamer of smaller diameter. But the development of such instability is a relatively slow process, and for short times the discharge gap with a discontinuity in the gas density can indeed work as a medium with unidirectional conductivity.

Note that the density discontinuity is not the only possible mechanism for the formation of such a directionally conducting medium. A significant factor is only a sharp decrease in the frequency of gas ionization rate at the discontinuity (see discussion below). Thus, instead of the density discontinuity, an interface between gases with different ionization cross-sections can be used to create a similar effect (a pair Ar-He, for example).

3. Conclusions

Modeling of the streamers development in highly inhomogeneous gas showed that the characteristics of the streamer change dramatically when the streamer reaches the boundary between areas with different gas densities.

With a small density difference, the streamer goes into a higher density gas, reducing its diameter, speed, and at the same time increasing the field at the head and the concentration of electrons in the channel. When a density increase exceeds n_2/n_1 = 1.2, the interaction leads to a sharp decrease in the ionization rate and the velocity of the streamer propagation along the axis. Simultaneously, there is a decrease in the radius of curvature of the surface of the ionization wave located closer to the lateral surface of the streamer channel. As a result, the off-axis maximum of electric field appears, and the ionization wave forming the streamer head loses its stability and the further development of the streamer generates a conductive “plate” located in the plane of discontinuity of the gas density. Thus, with a sharp increase in gas density above the critical value, the streamer can no longer overcome such a discontinuity. The critical value of the density jump is determined by the ratio of fields on the axis of the streamer head and on its side surface and, to a lesser extent, on the characteristics of nonlocal gas pre-ionization by high-energy photons emitted at the ionization wave front. In the air, this critical value is close to the coefficient of 1.2, which means that the streamer cannot overcome the discontinuity of densities created, for example, by a direct shock wave with a Mach number greater than M = 1.15. This conclusion demonstrates the fundamental limitations of the possibility of creating a nonequilibrium plasma in supersonic and hypersonic flows, where there are numerous intense shock waves. In such flows, in order to create nonequilibrium excitation, it is necessary to organize the development of a discharge from a region with a higher density in a region of low densities in order to achieve the desired effect.

Thus, we find conditions when the gaseous medium for short times began to possess unidirectional conductivity: a discontinuity in the gas density formed a kind of “gas-dynamic diode” that allows the plasma channel to propagate in one direction and blocks its development in another. It is noted that instead of the density discontinuity to create the effect of a directionally conducting medium, the interface between gases with different ionization cross sections can be used as well.

4.References

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