

# Streamer branching on clusters of solid particles in air and air bubbles in liquids

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**Abstract.** We present the results from a two-dimensional computational investigation of the intersection of a streamer with solid particles and density fluctuations and gas bubbles filled with air and immersed in liquids. We consider the evolution of a streamer propagating along the vector of the applied external electric field. The clusters of particles in air or bubbles in liquids have a symmetric form with branches elongated either in horizontal or vertical direction. The orientation of the cluster determines the branching patterns. We show that clusters having the prevailing horizontal branches facilitate streamer branching in liquids, while clusters in gases with vertical branches promote the splitting or reinitiating of a discharge filament. The phenomenon is mainly due to different polarization patterns of vertical or horizontal clusters in air and liquids and the ratio of dielectric permittivity of medium/particle or medium/bubble.

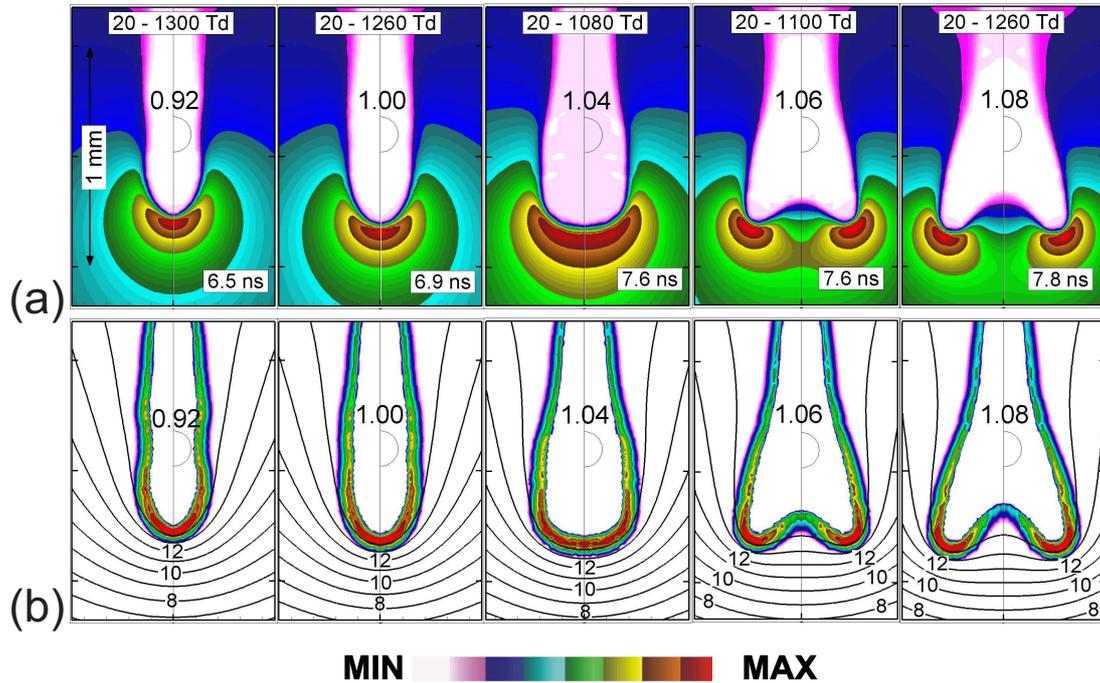
## 1. Introduction

Streamer branching—the splitting of a discharge filament into two or more streamers—is a common phenomenon that occurs in high pressure gases and liquids. The evolution of the streamer depends on the local environment in the path of a streamer. The streamer branching depends on many parameters such as the electrode geometry, the polarity of the applied voltage and gas composition [1]. Solid particles, water droplets and fluctuations of density, pressure in the streamer path can also initiate branching [2]. Discharges in liquids often involve the pre-existing gas phase bubbles or bubbles artificially injected in liquids. As a result, the discharges in liquids often have many branches similar to the streamer discharges in high pressure gases [3]. In this paper, we summarize and compare the patterns of a streamer branching on (i) background gas density fluctuations, (ii) solid particles and (iii) strings of bubbles immersed in liquids and oriented vertically or horizontally relative to the vector of the applied electric field. We consider two opposite cases when the dielectric permittivity of the medium is unity (air) and the dielectric permittivity of particles is greater than 2 and the case when the dielectric permittivity of bubbles (filled with air) is unity and the relative dielectric permittivity of medium (liquid) is 2.

## 2. Description of the model

The 2-dimensional model, nonPDPSIM, used in this study is analogous to that described in [4,5]. We simultaneously solve Poisson's equation for the electric potential and transport equations for charged and neutral species. We also account for the charge densities accumulated on the surfaces of particles and bubble–liquid interface.





**Figure 1.** (a) Reduced electric field  $E/N$  (Td) and (b) positive space charge and potential lines (kV) for a streamer intersecting a density fluctuation region (radius  $80 \mu\text{m}$ ) with  $P/P_0 = 0.92, 1.0, 1.04, 1.06, 1.08$ . The times are chosen so as to record the same position of the filament's tip shown in each frame.

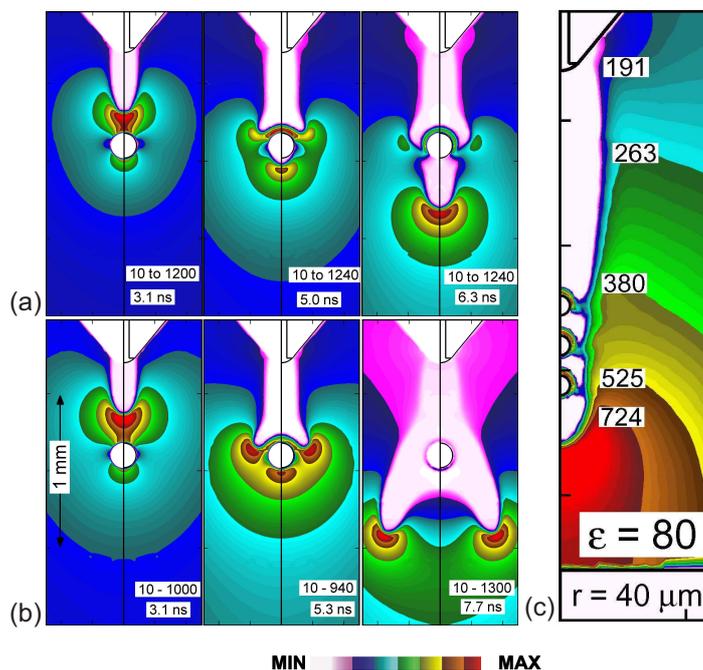
The electron temperature is obtained by solving an electron energy conservation equation with transport and rate coefficients coming from local solutions of Boltzmann's equation. Radiation transport and photoionization modules are also included. The gas mixture used for all cases is atmospheric pressure humid air  $\text{N}_2/\text{O}_2/\text{H}_2\text{O} = 79.5/19.5/1$  at 300 K. The numerical grid uses an unstructured mesh with triangular elements and multiple refinement regions.

Many features of streamer branching are governed by the polarization of dielectric particles in air or bubbles immersed in liquids in the uniform external electric field. If the external field is aligned with the polar axis of the spherical particle, then the electric field at the poles of the particle is enhanced compared with the unperturbed external electric field. At the equator the electric field at the surface of the particle is decreased compared with the applied field.

As the opposite case, for the spherical bubble filled with air and immersed in liquid, the electric field at the poles is decreased compared to the unperturbed external electric field. At the equator the electric field at the surface of the bubble is enhanced compared to the applied field. In our model, the polarization electric fields are a natural outcome of the numerical solution of Poisson's equation in and around the particles in air and bubbles in liquids.

### 3. Streamers intersecting with regions of density fluctuations

In this section, the intersection of a streamer with a spherical density fluctuation region having a lower or higher density than the ambient air is investigated. The pressure difference between the fluctuation region  $P$  and the ambient gas  $P_0$  were restricted to be less than 7%. In figure 1 the positive streamer propagates between the rod electrode and a flat grounded electrode separated from the rod by  $2 \mu\text{m}$  (only part of the simulation region is shown). The electrode is biased to 15 kV.



**Figure 2.** (a) Reduced electric field for a streamer intersecting a high permittivity solid particle; (b) reduced field for a streamer intersecting a low permittivity solid particle; (c) streamer hopping between the cluster of three particles. Contour labels are in Townsend. Each particle with high dielectric constant reinitiate a streamer.

For low density region (rarefaction  $P/P_0$  less than 1.06) no branching occurs. The streamer behaves quite differently when approaching the region with  $P/P_0$  greater than 1.06. In this case  $E/N$  becomes essentially lower in the spherical region than in the ambient gas. In this case the high density fluctuation acts as an obstacle in the streamer path. As a result, the streamer diverts from its path toward the region of higher ionization on its periphery. This diversion can be perceived as branching since two streamers are produced. Note that if the size of a region of density fluctuation is smaller than the width of a streamer—branching will not occur.

#### 4. Streamer interaction with solid particles

In this section we consider interaction of a streamer with solid particles as a limiting case of very dense spherical regions. Due to polarization, there is an enhancement of the electric field near the top and bottom of the dielectric particle (the electric field vector is directed from top to bottom). The polarization effect is more pronounced for particles with higher dielectric constant.

Streamer dynamics with a solid particle  $80 \mu\text{m}$  in radius with relative dielectric permittivity 25 and 2.5 are shown in figure 2a and 2b, respectively. The intersection of the streamer with high permittivity particle results in its high polarization. As a result, the streamer stalls upon intersecting the particle and reinitiates at the bottom of the particle where the field is high (figure 2a). When the streamer intersects the low permittivity particle (figure 2b) there is only a small enhancement in electric field near the bottom. As a result, there is no reinitiation of the streamer at the bottom of the particle. The streamer is deflected around the particle and this gives the appearance of a branching.

## 5. Streamer interactions with multiple particles

To investigate the consequences of streamers interacting with multiple particles, we simulated streamers incident on three vertically aligned particles 40  $\mu\text{m}$  in radius with dielectric permittivity 80). Particles in close proximity can act as a bridge that elongates the region of the enhanced electric field due to polarization [4]. This has an important implication on the streamer–particle interaction. After the intersection of the streamer with the top of the particle, a second streamer is launched from the bottom of the first particle. The second particle is within the polarization field of the first. The polarization field at the bottom of the second particle is seeded by photoionization, and a third streamer is launched from its lower surface. This process is repeated on the third particle resulting in launching of a fourth streamer from its bottom side. This process of successively launching streamers from the bottom of particles is very much like a relay in which the streamer is handed off between particles as shown in figure 2c.

## 6. Vertical string of bubbles

In this section we computationally investigate the properties of positive streamers propagating inside strings of bubbles filled with humid air at atmospheric pressure and immersed in liquids. Transformer oil is chosen as a liquid medium. The applied voltage with the rise time of 0.1 ns creates almost uniform electric field (120 kV/cm) at the location of the bubbles. The bubbles are totally immersed in liquid and the radii of the bubbles are 500 $\mu\text{m}$ . The orientation of the string and proximity of bubbles are crucial for the streamer formation and re-initiation in the neighboring bubbles.

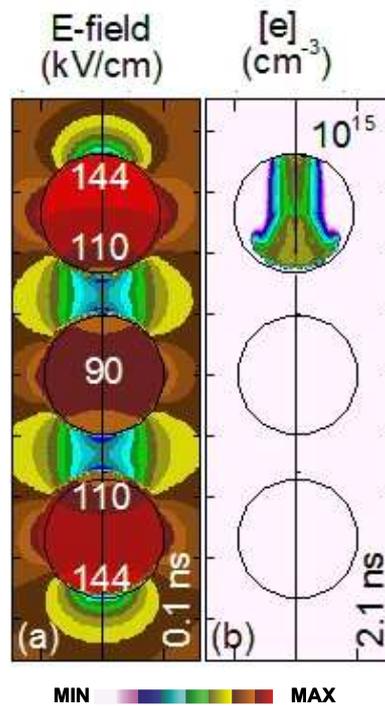
For the vertical string of bubbles (aligned along the electric field) there is a small field depletion inside the bubbles due to mutual polarization compared to the field in an isolated bubble. In figure 3a electric field contours in and around the bubbles due to the polarization in an external field are presented. The electric field in the middle bubble immersed in the transformer oil decreases from 144 kV/cm (this is a uniform electric field inside an isolated bubble) to 90 kV/cm (for the separation of 300 $\mu\text{m}$ ). As a result, in a vertical string the streamer propagation from bubble to bubble is more sensitive to the bubble separation. The streamer hopping is analogous to the hopping between the solid particles. However, it is observed only when the separation between the bubbles is smaller than 200–250  $\mu\text{m}$ . There is no streamer relay for the separation larger than 300  $\mu\text{m}$  and the streamer stalls in the upper bubble as shown in figure 3b.

Polarization of the horizontal string of bubbles results in higher electric field inside the bubbles as compared to that in an isolated bubble. In this case, streamer hopping is observed for the bubble separation 500  $\mu\text{m}$  or larger.

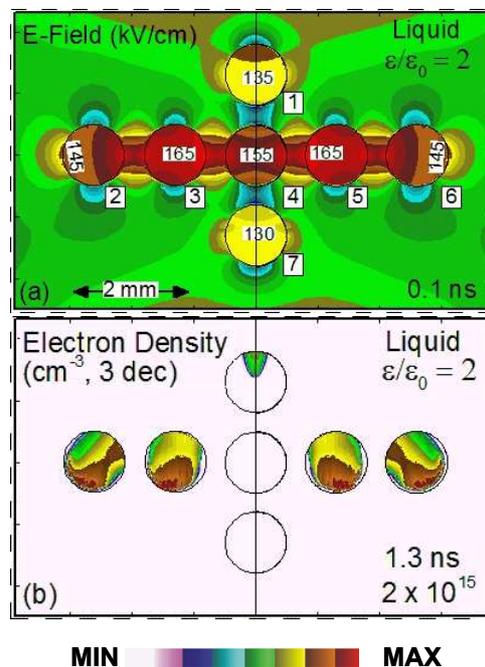
## 7. Arrays of bubbles with prevailing horizontal branch

We also investigated the arrays of five bubbles and showed that the enhancement of the electric field and streamer development depends on how many field depleting poles or field enhancing equators are in close proximity to the particular bubble.

The electric field contours in and around the string of bubbles with short vertical and long horizontal branches are shown in figure 4. The mutual polarization effect enhances the field inside the horizontal branch and depletes the field in vertical string. For example, the electric field in the 3rd and 5th bubbles increases from 144 kV/cm (an isolated bubble) to 165 kV/cm (for the separation of 300  $\mu\text{m}$ ), and a third streamer is launched from its lower surface. This process is repeated on the third particle resulting in launching of a fourth streamer from its bottom side. This process of successively launching streamers from the bottom of particles is very much like a relay in which the streamer is handed off between particles as shown in figure 2c.



**Figure 3.** (a) Electric field contours in and around the bubbles due to the polarization in an external field. (b) Electron density at 2.1 ns.



**Figure 4.** An array of bubbles with prevailing horizontal branch. (a) Initial electric field distribution and (b) electron density at 1.3 ns. Discharge successively develops through bubbles 2–3–4–5–6 and do not develop in the vertical branch.

## 8. Conclusion

We found that streamers tend to branch when (i) encountering a region of high density fluctuations, (ii) a solid particle depending on its permittivity and size (iii) clusters of bubbles in liquids having prevailing horizontal branches. However, vertical clusters of solid particles in close proximity can act as a bridge that initiates the process of successively launching streamers from particle to particle.

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