Modeling of SQS Propagation Induced by Alpha Ray in Gas Counters

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Abstract

With reference to optical images of the self-quenching streamer (SQS), we have already proposed a possible mechanism of SQSs induced by α-rays. To check the validity of the mechanism, we have been designing a model for the computer simulation of the SQS propagation based on the newly proposed mechanism.

In the present modeling, in order to calculate the growth of the discharge, a set of continuity equations for electrons and ions is numerically solved in a two-dimensional space. An electron supply process from the α-ray ionization track is assumed to be the dominant process for the streamer development instead of the conventional electron-supply process which is based on the photo ionization in the gas media. The streamer propagation is simulated under the concept of "two-region model". A first comparison between computed and experimental results shows a good agreement.

I. INTRODUCTION

We have reported various results of the optical observation of self-quenching streamers (SQSs) in gas counters induced by α-, β- and X-rays for the purpose of understanding the operation mechanism of the SQS mode. As described in our previous papers [1, 2], the dense ionization tracks significantly contribute to the streamer formation when α-rays are irradiated; those streamers develop only in the specific directions limited by the spatial charge distribution along the primary ionization tracks formed by α-rays. This is a direct evidence of another SQS-formation mechanism that is different from the conventional one based on the electron feeding by the photo-ionization process (Atac's mechanism [3]). From this view point, we have proposed an SQS formation mechanism for α-rays.

In order to check the validity of the newly-proposed mechanism, a computer simulation of streamer propagation may be very helpful. Until now, some computer simulations of streamers have been attempted under the condition of nonuniform electric field to investigate the properties of electrical breakdown in gases. On the other hand, to the authors' knowledge, no computational study of the SQS propagation in gas counters has been reported . In the present paper, we will describe a simple computation model of SQS propagation induced by α-rays inside a gas counter. Simulated results will be compared with observed ones.

II. STREAMER FORMATION PROCESS

In the conventional mechanism of the streamer formation, including the SQS mechanism by Atac et al. [3], streamers are promoted by the free electrons which are produced through the photo-ionization process around a streamer head. In contrast with this, we have proposed a streamer-formation mechanism which is based on the electron feeding from the high density ionization-tracks formed by incident α-rays [1, 2]. In this mechanism, the electrons that reach the anode wire first produce an initial avalanche near the anode surface; other delayed electrons are fed into the initial avalanche making secondary avalanches, one after another, along the electron-drifting path. Through the process mentioned above, a streamer-discharge channel spreads about a few mm away from the anode surface towards the cathode. The streamer stops the growing when all initial electrons have been consumed for the streamer development. A schematic representation of the mechanism of such a streamer formation promoted by the ionization tracks is shown in Fig.1.

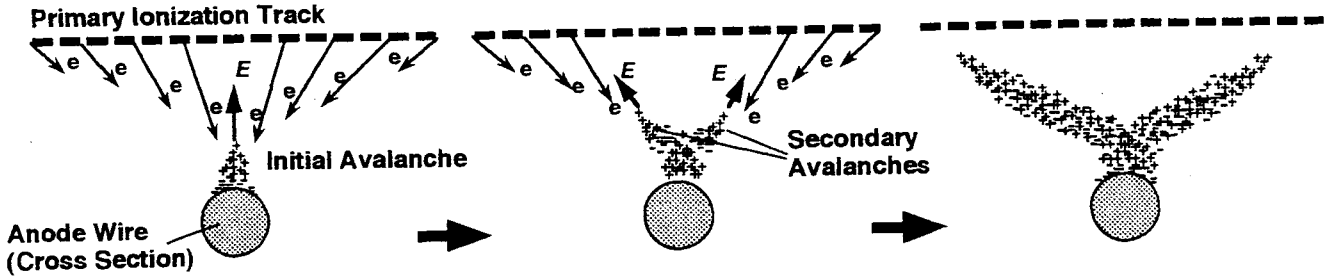

Fig.1 A schematic representation of the mechanism of the ionization-track induced SQS.

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III. COMPUTATION MODEL

In the calculation, an electron drifting process, an electron bombarded ionization process and a space charge effect on the electric field are taken into account as fundamental processes. An ion drifting process is not considered because the drift velocity is so slow that those ions almost do not move from their formation points during the electron drifting and the streamer growing.

A. Continuity equations and the characteristic-curve method

To simulate the electron-avalanche growth, a set of continuity equations for electrons and single-charged positive ions (Eqs.1 and 2) is numerically solved by the characteristic-curve method in a two-dimensional space [5, 6, 7].

$$\frac{\partial n_e}{\partial t} + \mathrm{div} n_e \boldsymbol{W} = \alpha n_e W , \qquad (1)$$

$$\frac{\partial n_p}{\partial t} = \alpha n_e W , \qquad (2)$$

where n_e and n_p (cm^{-2}) are the densities of electrons and single-charged positive ions, respectively, W ($= |\boldsymbol{W}|$) (cm/s) the drift velocity of electrons, α (cm^{-1}) the ionization coefficient by collisions. The following equations are derived from Eqs.1 and 2;

$$n_e(r, t+\Delta t) = n_e(r-\boldsymbol{W}\Delta t, t)\exp(A\Delta t) ,$$
$$A = \alpha W - \mathrm{div}\boldsymbol{W}, \qquad (3)$$

$$n_p(r, t+\Delta t) = n_p(r, t) + \alpha W n_e(r, t)\,\Delta t. \qquad (4)$$

Equation (3) represents the change of the electron density in a coordinate system moving along the drifting path (i.e. the characteristic curve).

The counting gas is assumed to be CH_4(100%) at atmospheric pressure. Since electron swarm parameters of CH_4, W and α, have been measured experimentally, it is expected to obtain reliable data. Analytical expressions of the electron drift velocity, W, and the ionization coefficient, α, in CH_4 are prepared by reference to experimental data [4, 8] as shown in Figs.2 and 3.

B. Space lattice and electric-field calculation

For the simulation, a cylindrical gas counter is supposed, whose inner diameter is 20 mm; the anode-wire diameter is 50 μm. The calculation is carried out in a semicircle region which is divided into 100 meshes at regular intervals in the radial direction (from 25 μm to 10 mm) and 90 meshes at regular intervals in the angular direction (from 0° to 180°) as sketched in Fig.4.

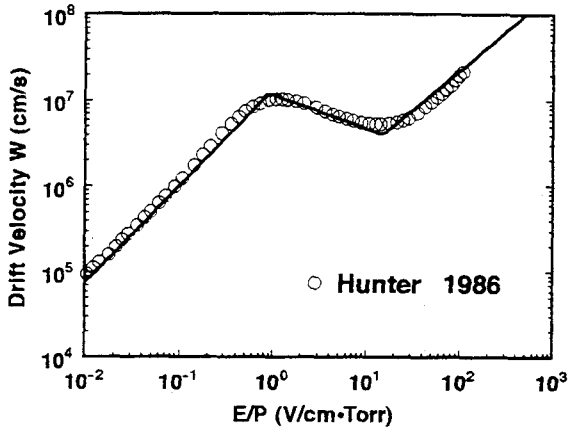

Fig.2 The electron drift velocity measured in a CH_4 gas [4]. The solid is expected in the present calculation.

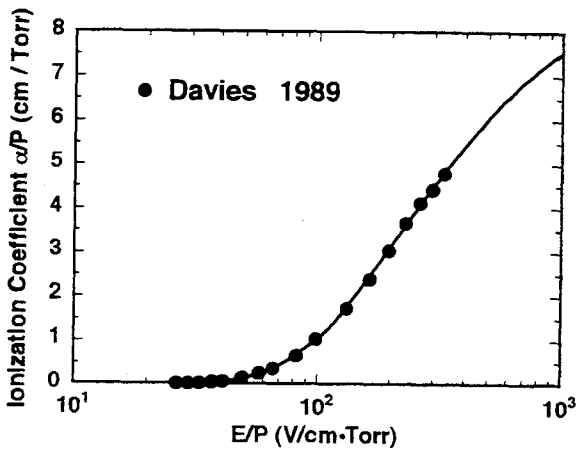

Fig.3 The ionization coefficient measured in a CH_4 gas [8]. The solid is expected in the present calculation.

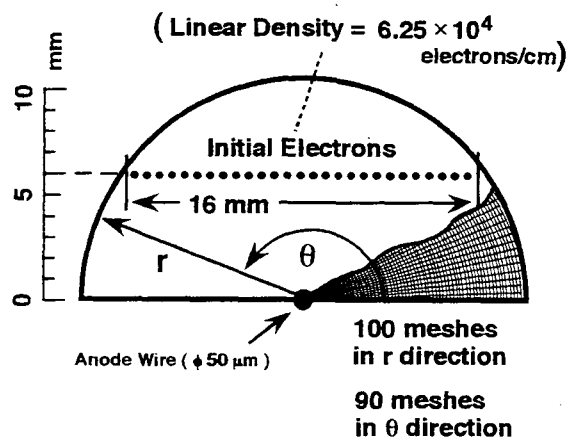

Fig.4 A space lattice used for the simulation and a typical arrangement of initial electrons (not in scale).

The strength of electric field produced by the space charges is simply evaluated using the Coulomb's law between all combinations of mesh points inside the calculation space at each time step. Then, their radial components are added to the static electric field produced by the applied electric potential to the anode wire.

C. Two-region model

According to the "two-region model" [5, 9], a streamer channel is classified as two different regions: an "active region" around the streamer head and a "passive region" which represents the path between the streamer head and the high-voltage electrode, as graphically shown in Fig.5. In the "active region", the charge density is relatively low and the ionization phenomenon is active because of the high electric field. On the other hand, in the "passive region", the charge density is rather high and the ionization phenomenon is inactive. Therefore, the contribution of the "passive region" to the streamer development may be very small. As the streamer develops longer, the "active region" changes to the "passive region" step by step. In the present calculation, the "passive region" is excluded from the calculation space in order to lighten the computer's calculation load. Consequently, the information inside the streamer is lost. Nevertheless, this approximation based on the two-region model may be adequate for the present purpose because only propagation characteristics of streamers are interesting and desirable to estimate.

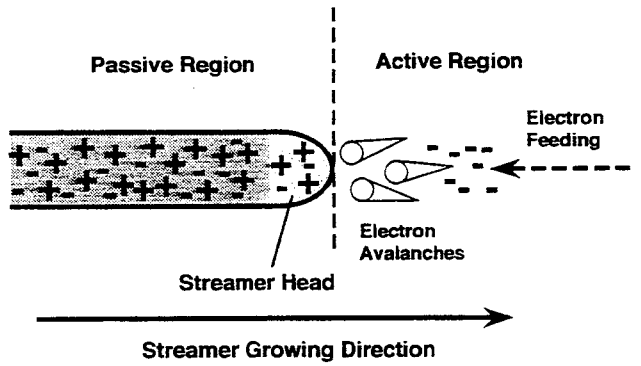

Fig.5 A graphical representation of the two-region model for the streamer simulation.

D. Flow of the calculation

Initial electrons are distributed in a line with simulating ionization tracks of α-rays for each incident condition. The line density is 6.25×10^4 (electrons/cm); therefore, for example, a 1.6 cm long ionization track is formed as the result of about 2 MeV energy loss of an α particle in the counting gas. A typical arrangement of initial electrons is indicated in Fig.4 (not in scale), which will be used for the calculation in Figs.6, 7 and 8(a). In the actual calculation, those initial electrons are put on the corresponding mesh points with proper density so as to reproduce the uniform distribution along the ionization track.

The Meek's streamer condition is adopted to judge a streamer generation (i.e. start of streamer development); when the static electric field on the anode surface is completely cancelled by the influence of space charges, it is assumed that a streamer departs from the anode surface. The streamer growing is treated under the concept of the two region model explained already. The region whose net-charge density reaches 1×10^{-7} (C/cm^2) is considered as "passive region" and the region becomes a new streamer head. The value of 1×10^{-7} (C/cm^2) corresponds to a typical net-charge density inside a streamer region [5]. (In the present case, net-charge density is obtained by subtracting the electron-charge density from the ion-charge density.) When the total number of electrons inside the calculation space falls less than 100, it is supposed that the streamer has stopped its growing.

The time step is ordinarily chosen to be 5 ns during the initial electron drifting, 0.1 ns during the initial avalanche growing and 0.05 ns during the streamer growing. If much smaller time step is required, the computer program automatically reduces the time step by the half and executes the calculation over again in that stage; this process is repeated until a proper result is obtained.

IV. Results and Discussion

Figure 6 shows a calculated time variation of a streamer represented by the streamer-head positions. The three-dimensional displays of net-charge distribution at 70.135 ns , 70.163 ns and 70.205 ns are given in Fig.7 (a), (b) and (c) respectively. For this calculation, initial electrons are arranged as sketched in Fig.4 with simulating a 1.6 cm ionization track. As indicated in Fig.6, the streamer starts the growing at 70.070 ns and ends at 70.205 ns to form an about 3500 μm streamer channel. The calculated streamer length shows fairly good agreement with observed one (about 4 mm) in a CH_4 gas [1]. The average speed of the streamer propagation is estimated at about 2.6 cm/ns, which seems to be rather faster than the typical ones of photo-mediated streamer propagation (for example about 0.1 cm/ns or less [5]). This may be due to the difference of electron-feeding process between both streamer types. Since a direct measurement of propagation speed of α-ray induced streamers has not been achieved, there are no appropriate data to be compared with this calculated result.

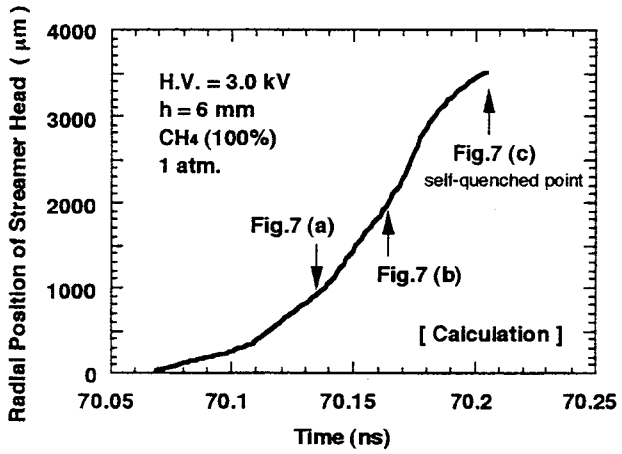

Fig.6 The variation of the streamer length with time.

As clearly indicated in Fig.7, the streamer develops only in the specific directions; the property of bi-directional streamer propagation which has been optically observed is adequately reproduced.

The variations of streamer shape are studied for some initial-electron arrangements. The calculated results in Fig.8 show the net-charge distributions at the moment when the streamers stop their elongation. The optical images obtained with similar initial-electron arrangements are indicated in the same figure [1, 2]. Those calculations are performed with assuming a different sort of counting gas from the one used for the observations#. And the geometrical configurations for the computations (the shape of the cathode electrode and the initial-electron arrangements) are slightly changed from those used in the observations for simplicity. In spite of these facts, simulated results show a good agreement with observed ones in their shapes and directions for each arrangement of initial electrons. This means the present simple computation model based on the newly-proposed SQS mechanism successfully interprets the essence of the SQS phenomenon induced by α-rays.

#The observations have been performed mainly in a Ne(70%)+ CH_4(30%) mixture because the range of α-rays (^{210}Po, 5.3 MeV) in this mixture is longer than that in a CH_4(100%) gas and the arrangements of initial electrons can be selected in full of variety. In Fig.8, the apparent disagreement in streamer length between the calculated results and the observed ones may be due to the fact that different gas mixtures are supposed.

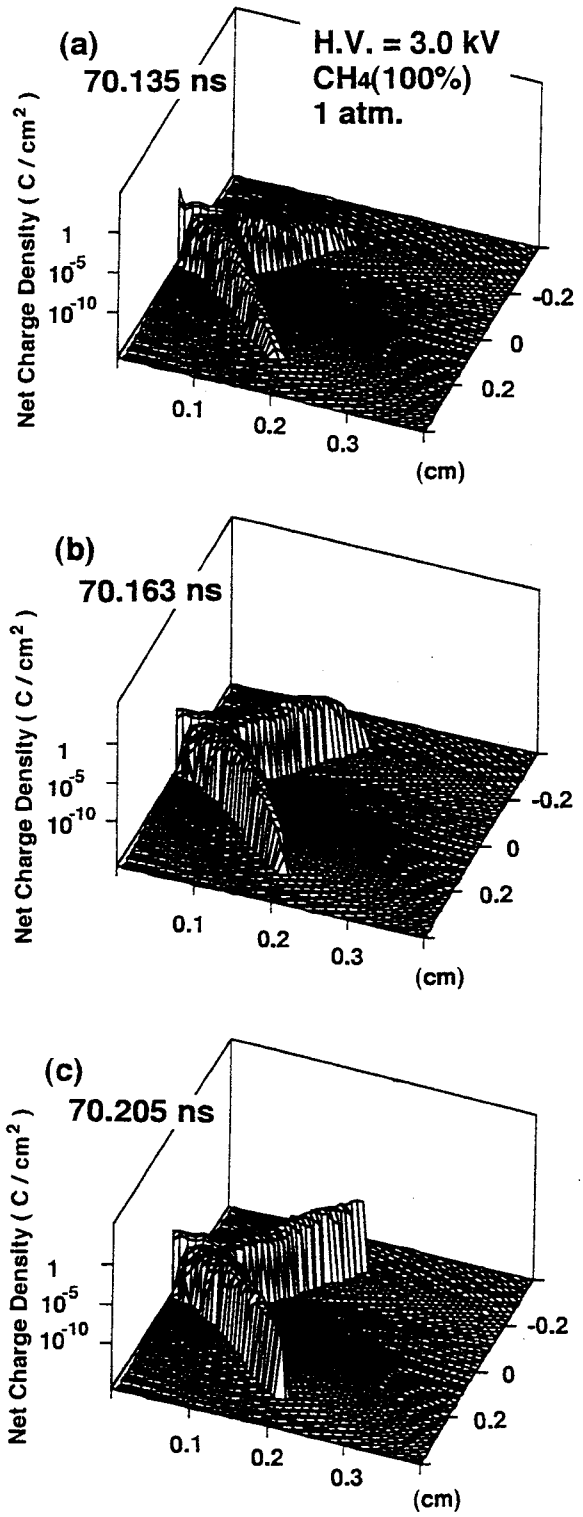

Fig.7 Three dimensional display of net-charge distribution.

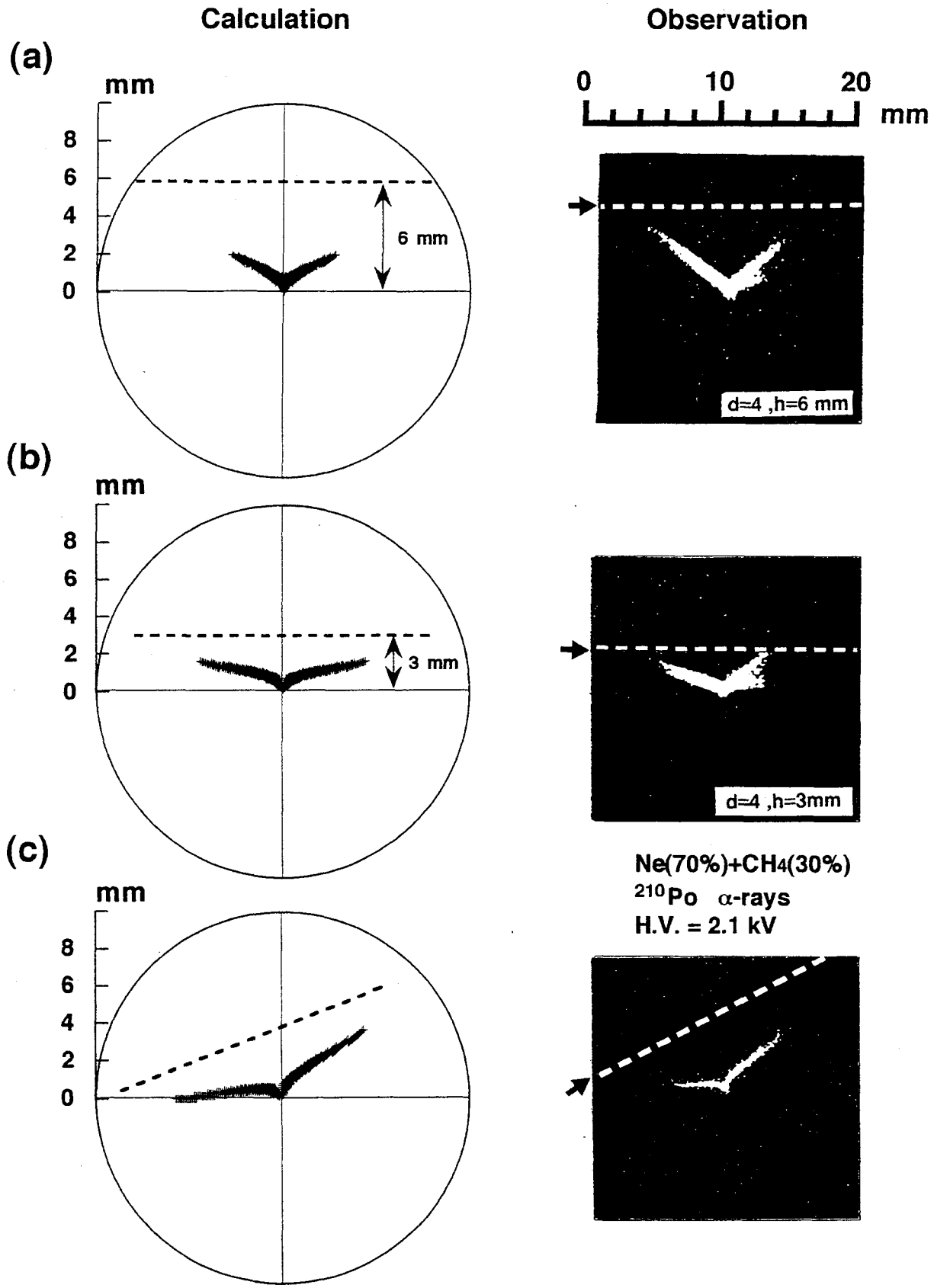

Fig.8 Streamer shapes calculated for different positions of initial electrons. The optical images taken with similar initial-electron arrangements in a Ne(70%)+CH_4(30%) mixture are shown in the right hand. In this figure, h is the distance from the anode wire to the initial ionization track and d the distance from the α-ray source to the mylar window of the counter. The broken lines represent the ionization tracks of α-rays.

V. SUMMARY

In order to check the validity of a newly-proposed SQS mechanism for α-rays, a modeling of the phenomenon is made and a computer simulation has been carried out. A set of continuity equations for electrons and single-charged positive ions is numerically solved to evaluate the avalanche growth in a two-dimensional space. The streamer development is treated under the concept of the two region model with an aid of the Meek's streamer condition. A comparison between computed and experimental results shows a good agreement in nature and the validity of the newly-proposed SQS-formation mechanism has been confirmed successfully.

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