Influence of Solid Dielectric Permittivity on Positive Streamer Characteristics in a Liquid-Solid Composite Dielectric

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***Abstract*- This paper presents a numerical investigation of positive streamers in a liquid-solid composite dielectric system, specifically in the context of wet-mate DC connectors. The study focuses on the influence of different materials and relative permittivity values of the solid dielectric on streamer behavior. The study employs a non-dimensionalized electric field-dependent molecular ionization streamer model to describe the initiation and propagation of streamers within a needle-sphere electrode system. A 2D-axisymmetric COMSOL model is utilized, where a solid tube-like dielectric is placed near the needle tip in an electrode system filled with transformer oil. The effects of varying relative permittivity values on the electric field distribution, streamer propagation velocity, ionization and attachment rates, and spatiotemporal evolution of charged species (electrons, positive ions, and negative ions) are studied. By analyzing these aspects, the paper aims to enhance the understanding of streamer dynamics and provide valuable information for optimizing the design and performance of equipment utilizing liquid-solid composite dielectric systems.**

I. Introduction

The development of fully integrated offshore systems located on the seafloor, such as those designed to extract, process, and distribute hydrocarbon resources, involves advanced subsea electrical systems. These systems utilize innovative technologies, including modular stacked DC transmission and distribution systems, leveraging high-voltage direct current (HVDC) converters to enhance power transmission over long distances while minimizing losses. Within this context, DC connectors, specifically wet-mate (WM) and dry-mate connectors, serve as vital plugs between cables and other power components in subsea installations. WM DC connectors excel in providing reliable electrical connections in underwater environments, delivering advantages such as enhanced conductivity, moisture protection, and effective sealing. However, these connectors encounter challenges, particularly in ensuring electrical insulation between contacts, which is paramount to guarantee the safe and dependable performance of WM DC connectors in subsea applications.

To address these challenges, the utilization of liquid-solid insulation combinations in different sections of a WM DC connector ensures reliable electrical insulation and effective sealing in underwater or harsh environments [1-3]. One such arrangement involves immersing the solid dielectric within the liquid dielectric. It is crucial to thoroughly investigate the characteristics of pre-breakdown and breakdown phenomena and discharge plasmas formed within these composite insulation systems when subjected to high voltage and possible surges. Computer simulations play a vital role in this investigation, surpassing the limitations of experimental studies by providing detailed insights into the microscopic processes occurring at the molecular level. These simulations facilitate optimization and design enhancements for wet-mate DC connectors, ensuring their reliable performance and enabling the development of more efficient and robust systems.

This study aims to investigate the sensitivity and responsiveness of the characteristics of positive streamers in a liquid-solid composite dielectric system to different values of solid relative permittivity within a WM DC connector. It is mathematically modeled, numerically simulated, and comparatively analyzed how different solid materials with various relative permittivity values affect positive streamer behavior; the streamer behavior will be characterized by studying the spatiotemporal distribution of the interelectrode electric field, changes in ionization and attachment rates over time, streamer propagation velocity, and the evolution of charged species in terms of their spatial and temporal variations.

The paper is structured as follows: Section II describes the theoretical framework, computational domain, and simulation setup used to study positive streamer behavior. In Section III, a case study is conducted, investigating the influence of different solid materials with varying relative permittivity values on streamer characteristics. Finally, Section IV concludes the paper by summarizing the key findings and their implications for optimizing liquid-solid composite dielectric systems.

II. Mathematical Model and Simulation Framework

This paper focuses on the dominant mechanism responsible for an increase in the number of charged particles in a liquid, namely electric field-dependent molecular ionization. To mathematically model and describe the behavior of positive streamers under applied high voltage with this mechanism, a set of continuity partial differential equations (PDEs) coupled with Poisson's equation is employed. The continuity PDEs consider the movement and interactions of three generic types of charged species: electrons, positive ions, and negative ions, while

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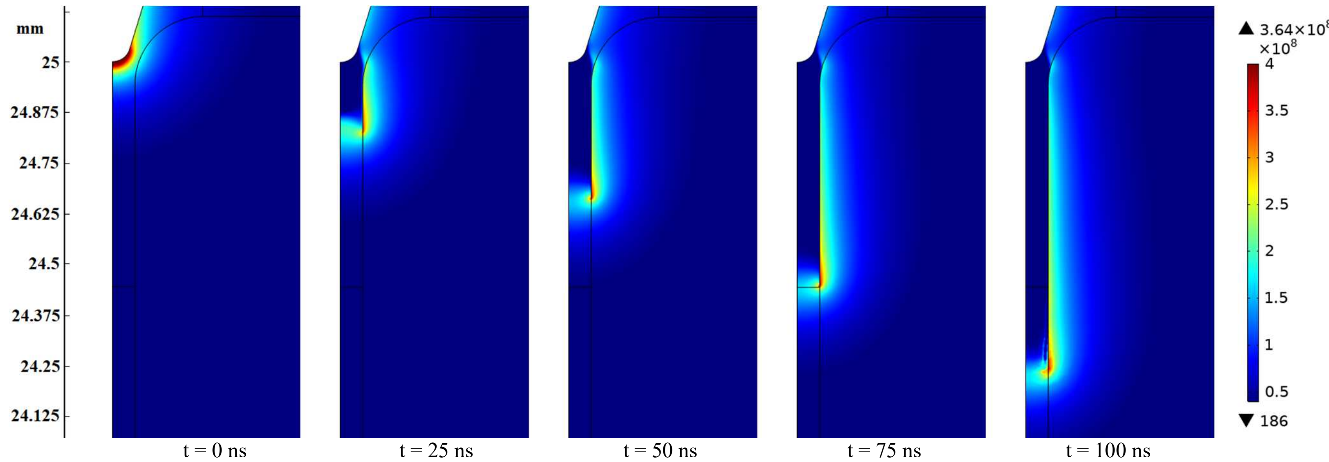

Fig. 1. Surface plots of electric field distribution for C1.

Poisson's PDE accounts for the mutual influence of space charge and the electric field between the electrodes.

The model encompasses various interactions and mechanisms that govern the generation and loss of charged particles. These mechanisms include impact ionization, attachment of electrons to neutral molecules, recombination of electrons with positive ions, and recombination of positive ions with negative ions. Such hydrodynamic (drift-diffusion) models have also been developed for gases [4-6] and solid dielectrics. To ensure the numerical stability of the simulations, a non-dimensionalized version of this model—namely the non-dimensionalized electric field-dependent molecular ionization streamer model—proposed and validated in [7, 8], is employed in this study. This approach enhances its generalization, allowing for a comprehensive understanding of positive streamer dynamics and associated phenomena.

The finite element method (FEM) and COMSOL Multiphysics software are employed to solve the model and simulate the formed discharge plasma behavior. Since the diffusion coefficient for charged species is set to zero, their motion is solely driven by convection. This gives rise to an infinite Péclet number, and consequently, numerical instabilities, unphysical solutions, and even a lack of convergence. To tackle this challenge a combination of software's built-in stabilization techniques including consistent Streamline and Crosswind (Codina) methods, along with an isotropic diffusion value of 0.1 is employed.

The computational domain comprises a needle-sphere electrode system sourced from [9] and verified through studies conducted by [7, 8, 10] with a composite liquid-solid dielectric. The needle electrode has a tip radius of 40 µm, while the spherical electrode has a radius of 6.35 mm. The distance between the electrodes is set to 25 mm. The solid dielectric, which is assumed as a perfect insulator, has a tubular structure, appearing as a cylindrical object with part of its hole enclosing the needle tip. This solid tube has a 2.5×1 mm rectangular cross-section with filleted corners. This geometry, as used in [8], is considered to simulate a WM DC connector configuration after the mating process. All parameters and variables, boundary conditions, and meshing configurations are adopted from [7, 8].

III. Case Study

In this section, a comparative numerical study is presented to investigate the impact of different solid materials with their respective common relative permittivity values on the behavior of positive streamers in a liquid dielectric. The study focuses on two commonly used solid dielectrics in wet-mate (WM) connectors: polytetrafluoroethylene (PTFE), also known as Teflon, and polyetheretherketone (PEEK). A total of five cases are considered in this paper. Three cases involve PTFE with relative permittivity values of 2.1 (C1), 2.2 (C2, matching the dielectric constant of the surrounding transformer oil), and 2.3 (C3). The remaining two cases involve PEEK with relative permittivity values of 3.2 (C4) and 3.6 (C5).

The relative permittivity, ε_r, also known as the dielectric constant, is a measure of how a material responds to an electric field compared to a vacuum. It quantifies the ability of a material to store electrical energy when subjected to an electric field. A higher relative permittivity indicates a greater capacitance, enabling the material to store more electrical energy per unit volume. Consequently, it can support a higher electric field for a given voltage. In the case of a solid dielectric, a higher relative permittivity allows the material to withstand higher electric field strengths before experiencing an electrical breakdown. This implies that, at the same applied voltage, a material with a higher relative permittivity can sustain a greater electric field within itself and the surrounding medium.

When a positive 200 kV DC voltage is applied to the needle (anode), an electric field reaching magnitudes on the order of 100 million $V \cdot m^{-1}$ is generated in the vicinity of the needle tip. This intense electric field triggers an intensive ionization activity, primarily concentrated near the needle tip, leading to the initiation of a positive streamer that propagates toward the sphere (cathode). In the meantime, negative ions are formed as free electrons attach themselves to neutral molecules in the oil. These processes contribute to an exponential increase in the density of charged particles, although the density of negative ions is one order of magnitude lower than that of other species.

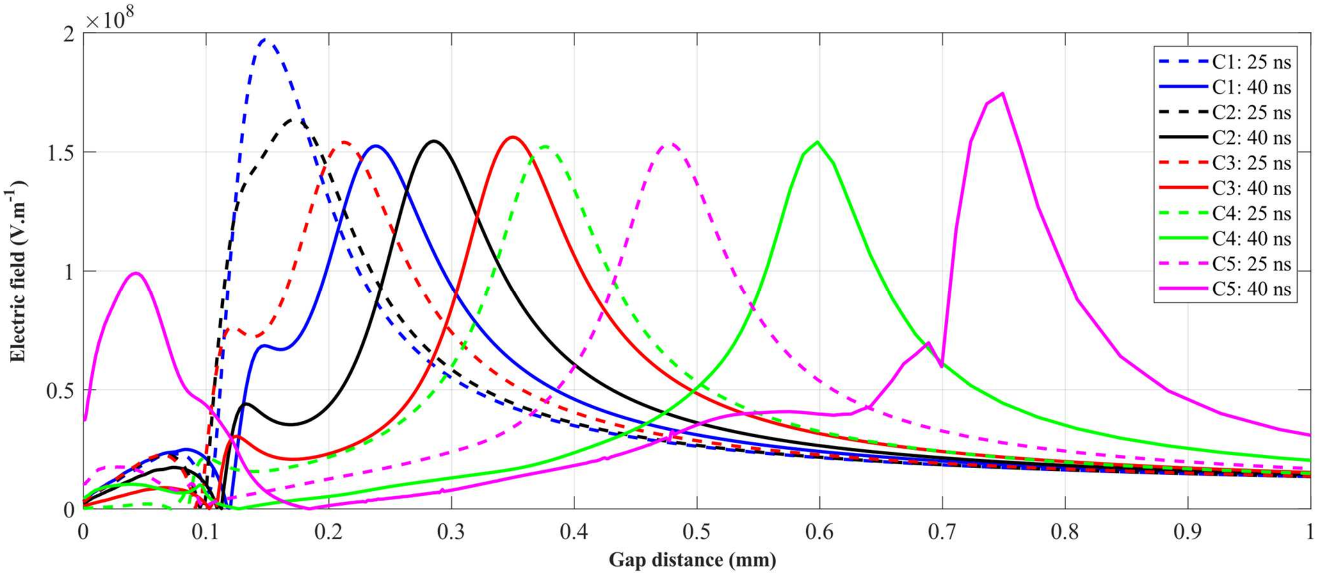

Fig. 2. Electric field variations with time along the symmetry axis for all cases.

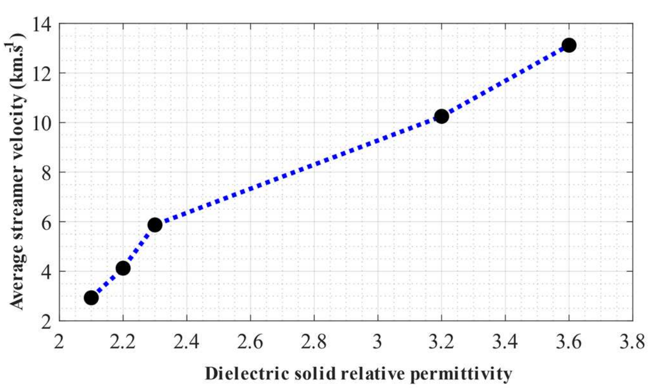

Fig. 3. Average Streamer propagation velocity per different solid dielectrics with varying relative permittivity

As the formed space charge is capable of producing an electric field comparable to that of the external applied voltage, the process of the streamer growth intensifies. The streamer growth corresponds to the development of an electric field wave which can be seen from both Fig. 1 and Fig. 2. Fig. 1 illustrates the surface plots of electric field distribution in C1 at five different time instances (0, 25, 50, 75, and 100 ns), while Fig. 2 displays the spatial distribution of the electric field along the symmetry axis—which does not cover the region with the peak interelectrode electric field stress—for various gap distances up to 1 mm in all cases at two selected time instances (25 and 40 ns).

As observed in Fig. 1, the maximum amplitudes of the propagating electric field wave are located at the tip of the streamer and the inner surface of the solid tube. The propagation of this peak along the inner surface of the solid tube corresponds to the evolution of charged species along the path of the streamer on the outer surface of the tube's hollow within the dielectric liquid. This significant evolution of charged species near the tubular solid dielectric, which is assumed to be a perfect insulator with zero space charge, is the main factor contributing to the high electric field strength at the inner border of the solid dielectric. Additionally, the position of the solid tube plays a role in shaping and confining the distribution of the electric field. This can be observed in [8], where the electrode system with only transformer oil as the dielectric produces a diffuse and bubbly streamer under the same applied voltage.

As regards the advancing electric field wave and evolving space charge at the liquid-solid interface, an important quantity to consider is the velocity of the streamer. Fig. 3 displays the average velocities of streamer propagation across all cases within the initial 40 ns time frame. As evident from this figure, the dielectric solid with the highest relative permittivity amount of 3.6 (C5) promotes the fastest streamer propagation. In the case of C2, which has the same relative permittivity as the surrounding oil, the streamer encounters a transition from oil to solid dielectric as it propagates from the needle. This transition causes a slowdown in the streamer propagation, resulting in a lower velocity compared to C3, C4, and C5. Conversely, in C1, which has the lowest relative permittivity compared to the dielectric liquid, the electric field strength within the solid dielectric and surrounding medium is weaker, leading to the slowest streamer propagation velocity. This direct relationship between the positive streamer's propagation velocity and the relative permittivity of the solid dielectric can be seen in Fig. 3.

Despite the significant evolution of charged species along the outer surface of the liquid-solid interface, the predominant accumulation point for these species is near the needle tip, as observed in Fig. 4. These figures depict the number density of the three charged species along the symmetry axis at a specific time instance of 25 ns. These density profiles are captured at a gap distance of 50 μm from the needle tip, which corresponds to the 40 μm radius of the needle and encompasses the main ionization and attachment activities. The concentration of electrons, positive ions, and negative ions bordering the needle surface is highest in the case of a PEEK dielectric with a relative permittivity of 3.6 (C5) and lowest in the case of PTFE with a relative permittivity of 2.1 (C1), as illustrated in these curves.

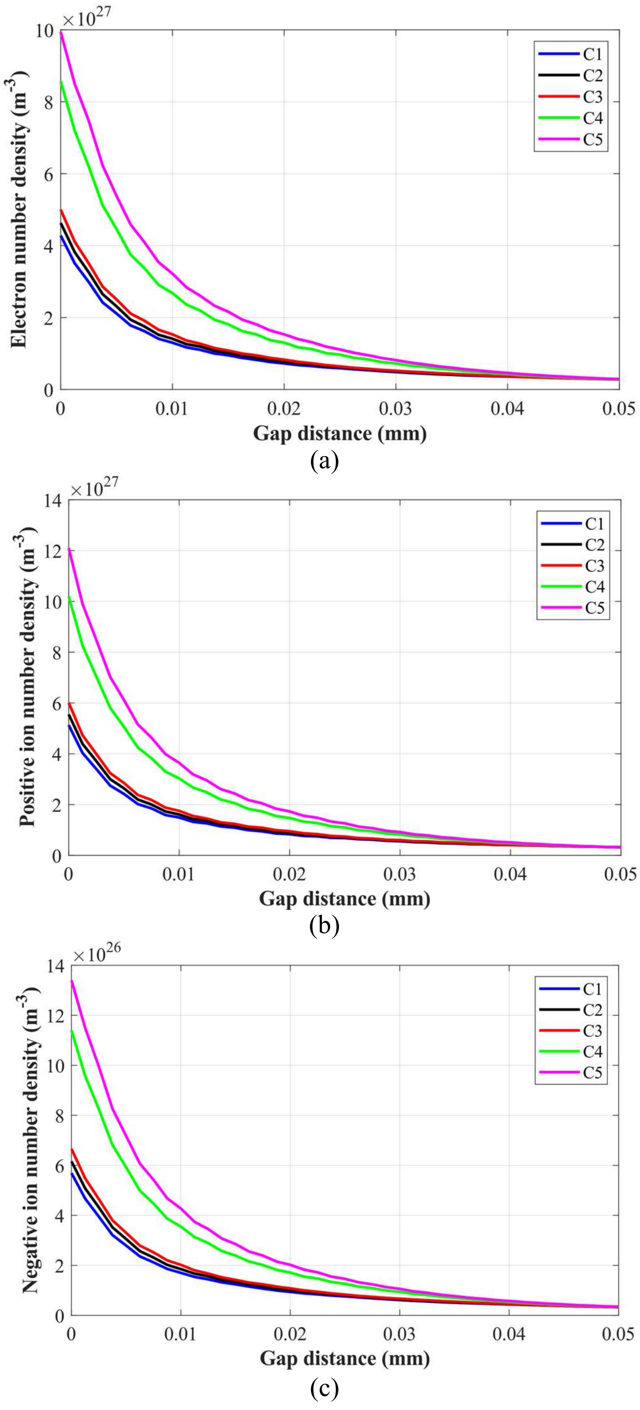

Fig. 4. Distribution of charged particles along the symmetry axis at t = 25 ns for all cases: (a) Electron, (b) Positive Ion, and (c) Negative ion

This behavior can be attributed to the effect of relative permittivity on the electric field distribution within the system. A higher relative permittivity generally corresponds to a stronger electric field within the solid dielectric and the surrounding medium. Consequently, the higher electric field strength in the case with a higher relative permittivity promotes increased ionization and attachment rates, resulting in a higher concentration of charged species near the anode surface.

IV. Conclusion

Through our numerical investigations of positive streamers in a liquid-solid composite dielectric system, we found that the relative permittivity of the solid dielectric significantly influences streamer behavior. We found the following key observations:

- Higher relative permittivity values of the solid dielectric resulted in a more intense and concentrated electric field distribution near the needle tip, leading to faster streamer propagation velocities.
- The ionization and attachment rates of charged species exhibited a direct correlation with relative permittivity, with higher values promoting more rapid charge evolution.
- The position of the solid dielectric, being near the needle tip, played a crucial role in shaping and confining the electric field distribution and streamers path.

These findings highlight the importance of selecting a solid dielectric material with an appropriate relative permittivity for optimizing designs and practical applications such as WM DC connectors.

Acknowledgment

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