Investigating RPC Gas Flow and Ion Transport Using Computational Models

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Resistive Plate Chambers (RPC) are notable for their rapid response, which is crucial for the system's triggering mechanism in high energy collider experiments. For example, the CMS RPC system features a 2 mm gas gap filled with a mixture of 95.2% C2H2F4, 4.5% iC4H10, and 0.3% SF6. This mixture reacts under high radiation levels and intense high voltage (approximately 10 kV), producing fluorine ions that contribute to the aging of the chambers. Recent studies indicate that increasing gas flux can help disperse these ions, thereby delaying the aging process. With the LHC Phase-2 upgrade, the CMS will introduce 72 new RPCs with a reduced gas gap of 1.4 mm in areas expected to experience significantly higher radiation levels. Understanding the relationship between gas flux and aging is crucial for this upgrade. This study builds on initial research to enhance RPC longevity by developing mathematical and computational models for gas flow and fluorine ion transport. Using the Navier-Stokes equations for fluid dynamics and incorporating ion diffusion, migration under electric fields, and convection, these models are discretized using finite element methods via the Gridap library. This research underscores the importance of optimizing RPC design by carefully considering geometry and flow dynamics to minimize aging effects. Such advancements not only enhance the performance and durability of RPCs but also contribute to more cost-effective and reliable detection technologies in high-energy physics.

Introduction

In the RPC, the intense high voltage and radiation environment can lead to the breakdown of C2H2F4 into fluorine ions (F-). These ions can react with H+ ions to produce hydrogen fluoride (HF) acid, which can damage the gap surface and accelerate chamber aging. Previous studies have shown that increasing gas flux can help disperse fluorine ions and delay aging [1].

To better understand the relationship between gas flux and aging, this work aims to model the ion concentration distribution within the RPC under various operating conditions. By simulating the Navier-Stokes equations for flow and the Advection-Diffusion equations for ion transport, we aim to quantify the impact of gas flow and electric fields on ion concentration and propose optimized operating conditions to minimize aging effects.

The methodology involves non-dimensionalizing the governing equations and using the finite element method to perform simulations under different scenarios. Although this work is still in its early stages, we will present some preliminary results that provide initial insights into ion transport dynamics within the RPC.

Gas Flow Simulation

To simulate the gas flow, we employed the Navier-Stokes equations for incompressible flow. These equations were non-dimensionalized to provide several benefits, such as reducing the number of parameters involved and enhancing numerical stability by maintaining numerical values within a more manageable range. The steady-state Navier-Stokes equations are represented as follows:

$$\nabla \cdot (\rho \mathbf{u}) = 0, \tag{1}$$

$$\rho\,(\mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla p + \mu_V \nabla^2 \mathbf{u} + \nabla \cdot (\rho f), \tag{2}$$

where ρ is the fluid density, u is the fluid velocity vector, p is the pressure, μ_V is the dynamic viscosity, f is the external body force vector [2].

The boundary conditions for velocity in this problem include a Dirichlet condition at the inlet, where the velocity is specified and fixed; a Dirichlet condition on the domain walls, where the velocity is set to zero due to the no-slip condition; and a homogeneous Neumann condition at the outlet, permitting the flow to exit perpendicular to the outlet surface.

As a result of imposing these Dirichlet conditions for velocity on certain parts of the domain, the pressure term in the weak formulation becomes negligible. Consequently, the pressure along these boundaries doesn't need to be explicitly defined and is instead determined by the internal equations governing the problem.

Ion Transport Simulation

The transport of ions in a gas is described by the advection-diffusion equation, which incorporates both diffusion and ion migration driven by an electric field. This equation is derived from the Boltzmann transport equation, simplified for the problem at hand. Additionally, a source term S is included to represent the ion generation caused by the particle flux in a high voltage and high radiation environment, following Gibbs' symbolic notation:

$$\mathbf{u} \cdot \nabla n = D(\nabla^2 n) - \mu_m(\mathbf{E} \cdot \nabla n) + S, \tag{3}$$

where n represents the ion density, $\boldsymbol{u}$ denotes the flow velocity, D is the diffusion coefficient, μ indicates the ion mobility, $\boldsymbol{E}$ stands for the electric field, and S accounts for the ionization source term associated with the creation of F^-.

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Results

The dimensionless Navier-Stokes equations were solved similarly to the approach outlined in [3]. The approximation of the problems described by Equations (2) and (3) is achieved using continuous Lagrange polynomial elements. The governing equations in 3D Cartesian coordinates are addressed on an unstructured tetrahedral mesh with linear basis functions using the Galerkin Finite Element Method. The domain is discretized with a mesh generated by the open-source finite element mesh generator Gmsh [4]. The weak form was implemented within a Julia framework using the Gridap library [5]. To ensure numerical stability, the SUPG/PSPG stabilization method [6] was applied.

We simulated a standard RPC 2mm gap with 2x2mm² inlet/outlet. For the results we presented here it was set a volumetric flow in the chamber of 3.0 vol/h. The gas flow is on the XY plane, with the gas going on X direction, the electric field is set on Z direction. Figure 1 shows cross-sectional view of the Ion concentration field, the z direction is stretched 300x better visualization. Figure 2 shows the ion field migration from the inlet (top left) to the outlet (top right). Additionally the speed of the gas in the chamber was calculated in the order of cm/s, as expected.

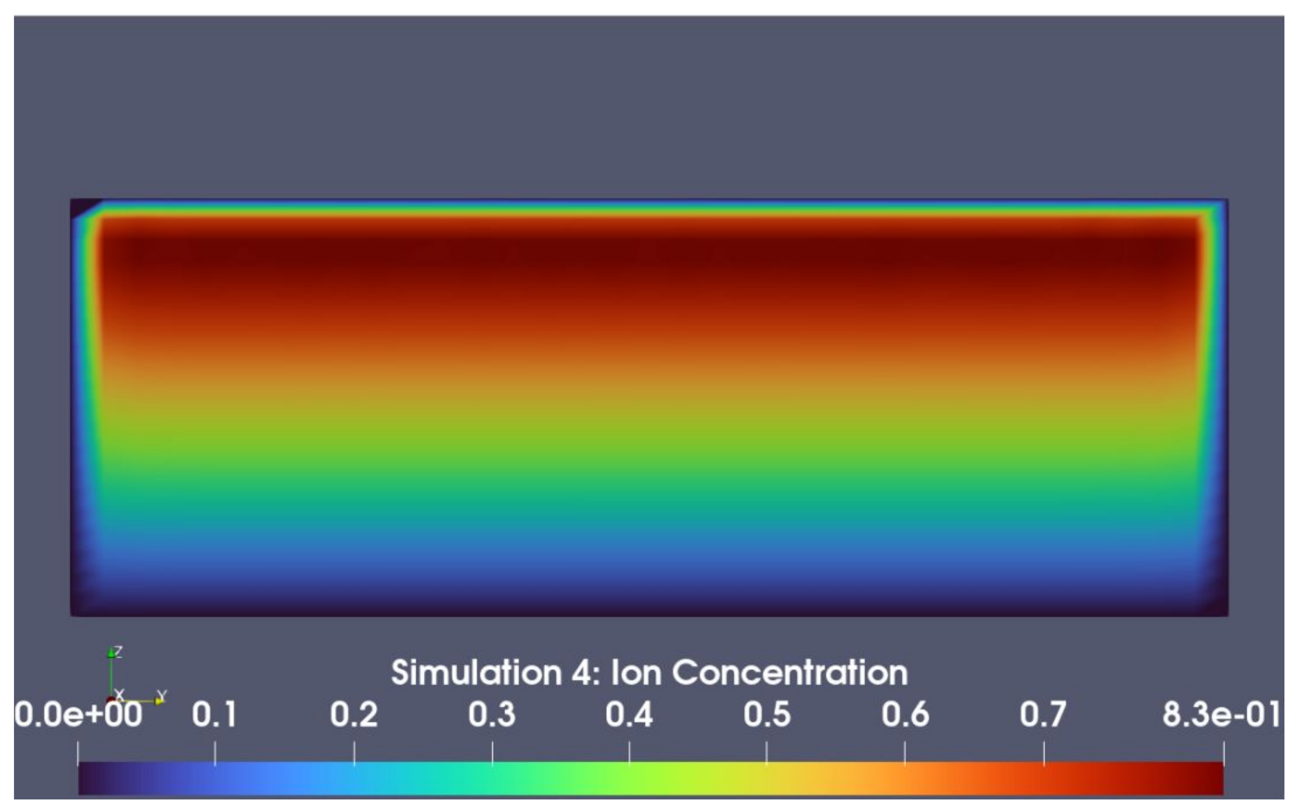

Figure 1: Cross-sectional view of the Ion Concentration Field. The mesh is stretched 300x in the z−direction for better visualization. The map is shown in arbitrary units.

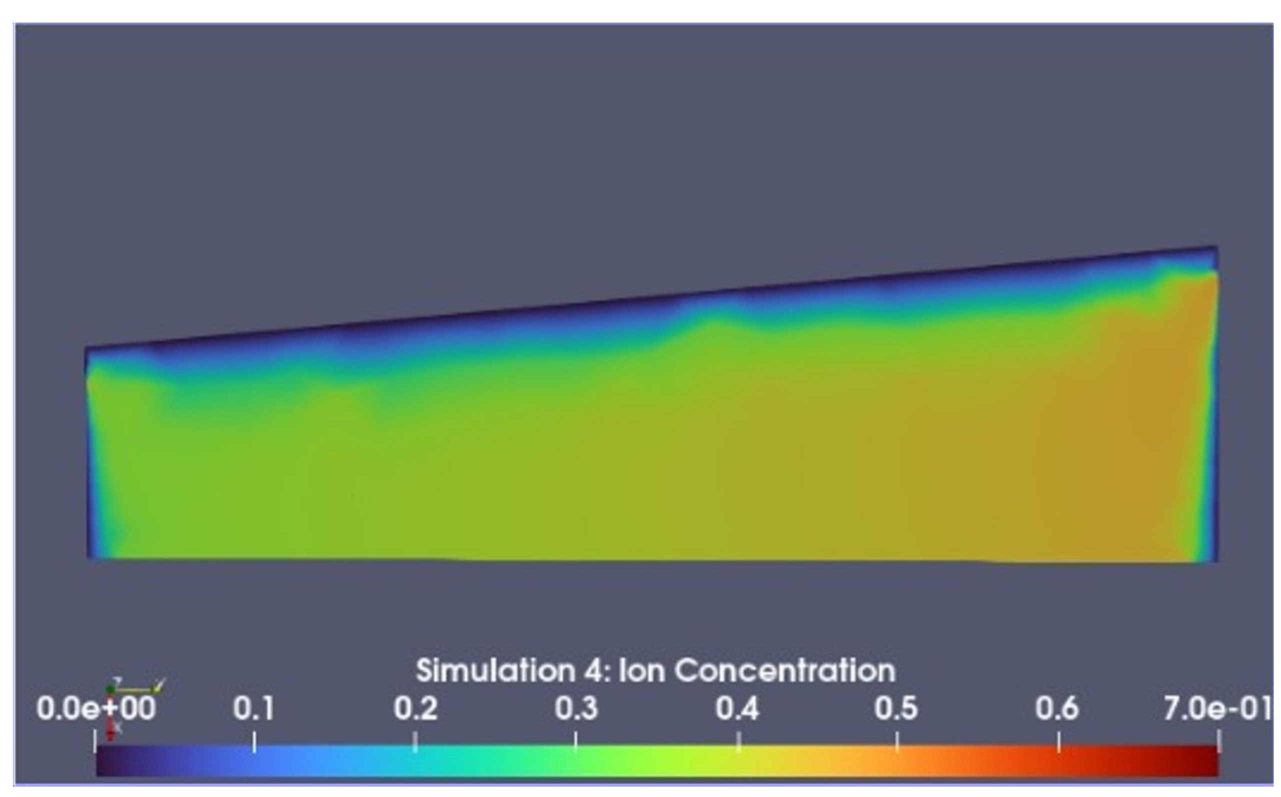

Figure 2: Ion Concentration Field in the XY plane. The gas inlet (outlet) is in the top left (right). The map is shown in arbitrary units.

Conclusion and Perspectives

This work is in its early stages, and the results obtained so far are very preliminary. However, they indicate that we are on the right path toward better understanding the impact of gas flow on mitigating aging effects in Resistive Plate Chambers (RPCs). The simulations conducted thus far suggest the importance of optimizing RPC design by considering flow dynamics to minimize aging.

Our next steps will involve refining the simulation by extending it to different gas flow rates, aiming to corroborate the findings presented in reference [1]. Additionally, we plan to expand our simulations to explore various gap sizes and electric field strengths. With these improvements, we hope to provide a stronger foundation for implementing strategies that enhance the durability and efficiency of RPCs, particularly in high-radiation environments