https://doi.org/10.69646/aob241107

Kinetic and fluid studies on Resistive Plate Cambers operated with new eco-friendly gas mixtures

Dujko, S.,[1] Simonović, I.B.[1] and Bošnjaković, D.V.[1]

[1]Institute of Physics Belgrade, Pregrevica 118, 11080 Belgrade, Serbia
E-mail: sasa.dujko@ipb.ac.rs

Resistive plate chambers (RPCs) are parallel plate gaseous detectors commonly used for timing and triggering purposes in many high-energy physics experiments. RPCs are employed at CERN-LHC (Large Hadron Collider) experiments due to their excellent time resolution, high-rate capability, and relatively low production cost (Rigoletti et al. 2020). They also play a key role in direct measurements of muons in air showers (Abreu et al. 2018) and in some neutrino observatories (Kumar et al. 2017). RPCs are operated with a gas mixture consisting of $C_2H_2F_4$ (between 90% and 95%), a smaller fraction of *i*-C_4H_{10} (around 5%) and SF_6 (usually between 0.3% and 1%). $C_2H_2F_4$ and SF_6 are well-known greenhouse gases with a global warming potential of respectively 1430 and 22800. The substitution of $C_2H_2F_4$ and SF_6 with environmentally friendly alternatives is one of the major challenges in current RPC technology. $C_2H_2F_4$ can be substituted with either a mixture of $C_2H_2F_4$ and CO_2, or a mixture of $C_3H_2F_4$ and CO_2, or eventually a mixture of $C_3H_2F_4$ and He (Rigoletti et al. 2020, Abbrescia et al. 2024). On the other hand, CF_3I, C_4F_7N and $C_5F_{10}O$ were considered as alternatives to SF_6 (Guida et al. 2022). The performance of the detector, including detection efficiency, time resolution, and streamer occurrence, with these gases and mixtures has only been tested experimentally so far. This work presents the first comprehensive modelling study of RPCs that operate with the new generation of environmentally friendly gases and corresponding mixtures.

We approached the problem in three stages. We start by presenting complete and consistent cross-section sets for electron scattering in $C_2H_2F_4$ and $C_3H_2F_4$. A cross-section set for electron scattering in C_3HF_5 is also developed, as this gas could also be considered as an alternative to $C_2H_2F_4$. The accuracy of cross-section sets was tested and validated through a series of comparisons between swarm data calculated using a numerical solution of Boltzmann's equation and Monte Carlo simulation (Dujko et al. 2010), and experimental data obtained under pulsed-Townsend conditions. In particular, kinetic calculations (and experimental measurements) have been performed for a range of gas pressures for each of these gases to determine the energy dependence of three-body attachment.

The second stage involves calculating electron swarm transport coefficients and distribution functions for environmentally friendly gases and mixtures across a

broad range of reduced electric fields. Values of mean energy, drift velocity, diffusion tensor, and rate coefficients for electron attachment and ionization are calculated in various $C_2H_2F_4/CO_2/i\text{-}C_4H_{10}/SF_6$ and $C_3H_2F_4/CO_2/i\text{-}C_4H_{10}/SF_6$ mixtures. In addition, calculations are performed in the same mixtures where SF_6 is replaced by a proper amount of CF_3I, C_4F_7N, and $C_5F_{10}O$. Critical electric fields are calculated in all considered mixtures, which in turn determine the minimum operating voltages of detectors. The study also examines the direct and indirect effects of electron attachment and ionization on electron drift and diffusion, as well as the occurrence of kinetic phenomena like negative differential conductivity.

The third stage of the research methodology Involves fluid modeling of the inception and propagation of streamers in new eco-friendly gas mixtures. We study the development of an electron avalanche and its transition into a streamer discharge under LHC-like conditions. The classical fluid model, which involves drift-diffusion and local-field approximations, is implemented in both axisymmetric and 3D settings in the AMReX environment (Simonović et al. 2024). AMReX is an open-source C++ library for massively parallel block structured adaptive mesh refinement applications (Zhang et al. 2019). AMReX is equipped with geometric multigrid solvers that can solve elliptical differential equations, and it supports MPI and OpenMP parallelization on CPUs as well as parallelization on GPUs. The inception and propagation of positive streamers are simulated by assuming a certain level of background ionization, as accurate models of photoionization for complex RPC gas mixtures are not yet available. We calculate the electron density, densities of positive and negative ions, and electric field as a function of the applied electric field for various eco-friendly RPC gas mixtures. Other streamer properties, such as streamer velocity and streamer radius, are also calculated and discussed.

Acknowledgments: This work is supported by the Science Fund of the Republic of Serbia, Grant No. 7749560, Exploring ultra-low global warming potential gases for insulation in high-voltage technology: Experiments and modelling EGWIn.

References

Abbrescia et al., 2024, Eur. Phys. J. C 84, 300.
Abreu P., et al., 2018, Eur. Phys. J. C 78, 333.
Dujko S., White R.D., Petrović Z.Lj., Robson R.E., 2010, Phys. Rev. E 81, 046403.
Guida R., Mandelli B., Rigoletti G., 2022, Nucl. Inst. And Methods A 1039, 167045.
Kumar A., et al., 2017, Pramana – J. Phys. 88, 79.
Rigoletti G., Mandelli B., Guida R., 2020, J. Instrum. 15, C11003.
Simonović I., Bošnjaković D., Teunissen J., Dujko S., 2024, Plasma Sources Sci. Technol. 33, 085012.
Zhang W., et al., 2019, J. Open Source Softw. 4, 1370.