7th Asia-Pacific Conference on Plasma Physics, 12-17 Nov, 2023 at Port Messe Nagoya

Similarity Rules for Inductive Radio Frequency Plasmas with Thermohydrodynamic Coupling Effects

Huihui Wang[1], Dong Yang[2], Bocong Zheng[3], Fei Wei[1], Yangyang Fu[2]
[1] Department of Chemical Engineering, Tsinghua University, [2] Department of Electrical Engineering, Tsinghua University, [3] School of Physics, Beijing Institute of Technology
e-mail: huihuiwang@tsinghua.edu.cn

Similarity theory and scaling laws describe how physical properties of plasma remain the same when control parameters are changed. It is useful for developing and optimizing plasma sources. Similarity rules have been successfully verified in discharges driven by direct current [1-5], radio frequency [6,7], microwave [8-11], and pulsed power supplies [12]. More recently, the similarity rules were rigorously demonstrated in low pressure plasmas with strong nonlocal kinetic effects using electrostatic particle-in-cell simulation [13-15]. However, similarity rules were not verified for discharges with electromagnetic and thermodynamic coupling effects.

In this presentation, we report similarity rules for inductively coupled plasma (ICP) with thermohydrodynamic coupling effects using two-dimensional fluid simulations and theoretical analyses of gas flow and heat transfer equations. The results show that the change of gas temperature with scaling factors causes the violation of similarity rule in the ICP. The increase of gas temperature with scaling factors causes the gas flow rate to increase, and the electron density in the plasma bulk to decrease. Further, it is found that the deviation of gas temperature can be mitigated by adding an external heat source, thus maintaining the validity of the similarity relations.

References

[1]. V. A. Lisovskiy, S. D. Yakovin, and V. D. Yegorenkov, Low-pressure gas breakdown in uniform dc electric field, J. Phys. D: Appl. Phys. 33, 2722 (2000).
[2]. Y. Fu and J. P. Verboncoeur, On the similarities of low-temperature plasma discharges, IEEE Trans. Plasma Sci. 47,1994 (2018).
[3]. M. Loveless and A. L. Garner, Scaling laws for gas break-down for nanoscale to microscale gaps at atmospheric pressure, Appl. Phys. Lett. 108, 234103 (2016).
[4]. Y. Fu, P. Zhang, and J. P. Verboncoeur, Paschen's curve in microgaps with an electrode surface protrusion, Appl. Phys. Lett. 113, 054102 (2018).
[5]. Y. A. Astrov, A. N. Lodygin, and L. M. Portsel, Dynamics and stability of the townsend discharge in nitrogen in narrow gaps, Phys. Rev. E 89, 033109 (2014)
[6]. V. Lisovskiy, J. P. Booth, K. Landry, D. Douai, V. Cassagne, and V. Yegorenkov, Similarity law for rf breakdown, Europhys. Lett. 82, 15001 (2008).
[7]. M. Pua˘c, D. Mari´c, M. Radmilovi´c-Radjenovi´c, M. Šuvakov, and Z. L. Petrovi´c, Monte Carlo modeling of radio-frequency breakdown in argon, Plasma Sources Sci. Technol. 27, 075013 (2018).
[8]. S. C. Brown, Basic Data of Plasma Physics (MIT Press, Cambridge, 1959).
[9]. C. M. Ferreira and M. Moisan, The similarity laws for the maintenance field and the absorbed power per electron in low-pressure surface wave produced plasmas and their extension to HF plasmas in general, Phys. Scr. 38, 382 (1988).
[10]. A. Sola, A. Gamero, J. Cotrino, and V. Colomer, Empirical similarity laws for argon plasmas produced by a surface wave at 2.45 GHz, J. Phys. D: Appl. Phys. 21, 1112 (1988).
[11]. A. M. Loveless and A. L. Garner, A universal theory for gas breakdown from microscale to the classical Paschen law, Phys. Plasmas 24, 113522 (2017).
[12]. G. A. Mesyats, Similarity laws for pulsed gas discharges, Phys. Usp. 49, 1045 (2006).
[13]. Y. Fu, B. Zheng, P. Zhang, Q. H. Fan, J. P. Verboncoeur, and X. Wang, Similarity of capacitive radio-frequency discharges in nonlocal regimes, Phys. Plasmas 27, 113501 (2020).
[14]. D. Yang, Y. Fu, B. Zheng, H. Wang, Q. H. Fan, X. Zou, X. Wang, and J. P. Verboncoeur, Similarity properties in capacitive radio frequency plasmas with nonlinear collision processes, Plasma Sources Sci. Technol. 30, 115009 (2021).
[15]. D. Yang, H. Wang, B. Zheng, X. Zou, X. Wang, and Y. Fu, Application of similarity laws to dual-frequency capacitively coupled radio frequency plasmas with the electrical asymmetry effect, Plasma Sources Sci. Technol. 31, 115002 (2022).