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# Dielectrophoretic-driven convection in the spherical shell experiment AtmoFlow

Yann Gaillard*, Peter S.B. Szabo*, Christoph Egbers*

Laboratory studies of large-scale flows in planetary atmospheres and interiors are typically conducted in cylindrical or spherical shell systems that preserve the essential physical dynamics. AtmoFlow is one such experiment, consisting of concentric spherical shells that simulate a planetary atmosphere with equatorial heating and polar cooling. Planetary rotation is replicated by shell rotation, while a central electric field generates an artificial gravity-like force. To eliminate buoyancy effects from natural convection, the experiment will be conducted aboard the International Space Station (ISS), planned for 2026. The central force, as investigated by Futterer et al. [1], is induced by a dielectrophoretic effect that decays proportionally to $1/r^5$. The arising thermo-electrohydrodynamic (TEHD) convection was previously studied in the Geophysical Flow Simulator (GeoFlow), which operated aboard the ISS from 2008 to 2017 to model geophysical flow fields. The present study builds upon the work of Futterer et al. [1], focusing on the AtmoFlow project with an aspect ratio of $\eta = 0.7$ to investigate the basic flow.

Dielectrophoretic thermo-electrohydrodynamic (TEHD) convection arises in a non-isothermal fluid subjected to an electric tension, resulting in an intrinsic or externally induced inhomogeneous electric field, such as one generated by curvature. The resulting central force field is governed by Gauss's law, producing convective flow analogous to Rayleigh-Bénard convection. By employing the continuity, momentum, and energy equations, a forcing parameter analogous to the Rayleigh number can be derived by

$$Ra_\mathrm{E} = \frac{\varepsilon_0 \varepsilon_\mathrm{r} \gamma_\mathrm{e} V_0^2}{2\rho_0 \nu \kappa}, \qquad \text{with} \quad \gamma_\mathrm{e} = e\Delta T \tag{1}$$

where $\varepsilon_0$ is the vacuum electric permittivity, $\varepsilon_\mathrm{r}$ the relative electric permittivity, $\gamma_\mathrm{e}$ the thermoelectric parameter, $V_0$ the applied electric tension, $\rho_0$ the reference density, $\nu$ the kinematic viscosity and $\kappa$ the thermal diffusivity.

In this study, we extend the parameter space of Futterer et al. [1] to investigate the flow fields within the parameter range of the AtmoFlow experiment, spanning $1 \times 10^5$ to $2 \times 10^7$. Three distinct flow regimes have ben identified: (1) steady-state plume structures with quadratic-shaped mode-6 patterns, (2) a transient periodic regime characterized by the emergence of sheet-like structures and mode reduction and (3) an irregular regime identified by structural variations and fluctuations in mode amplitude, forming structural clusters that diminish with increasing $Ra_\mathrm{E}$.

A quantitative analysis by integral values shows that the Nusselt number, $Nu$, increases with $Ra_\mathrm{E}$ and $\gamma_\mathrm{e}$. However, the kinetic energy, $E_\mathrm{kin}$, does not scale linearly with the forcing, indicating non-linear energy dissipation. Comparisons with Moore and Weiss [2] reveal similar but not identical $Nu$ trends, while steady-state simulations align well with GeoFlow results when normalized by the critical Rayleigh number. Furthermore, regime transitions exhibit margins comparable to those reported by Futterer et al. [1], with slight differences arising from variations in the definitions of transient and irregular regimes and the inclusion of a temperature-sensitive Gauss's equation in this study to account for thermal feedback. The relationship between $Nu$ and $E_\mathrm{kin}$ confirms independence from the Prandtl number and aspect ratio, consistent with findings by Futterer et al. [3]. This study offers novel insights into the dynamics of TEHD convection in spherical shells, its heat transport mechanisms, and their application to the experimental study of geophysical flow phenomena in small-scale laboratory experiments.

[1] Futterer, B., Hollerbach, R., & Egbers, C. (2008, November). GeoFlow: 3D numerical simulation of supercritical thermal convective states. In Journal of Physics: Conference Series (Vol. 137, No. 1, p. 012026). IOP Publishing.

[2] Moore, D. R., & Weiss, N. O. (1973). Two-dimensional Rayleigh-Bénard convection. Journal of Fluid Mechanics, 58(2), 289-312.

[3] Futterer, B., Krebs, A., Plesa, A. C., Zaussinger, F., Hollerbach, R., Breuer, D., & Egbers, C. (2013). Sheet-like and plume-like thermal flow in a spherical convection experiment performed under microgravity. Journal of fluid mechanics, 735, 647-683.

*Department of Aerodynamics and Fluid Mechanics, Brandenburg University of Technology Cottbus-Senftenberg, Siemens-Halske-Ring 15a, 03046 Cottbus, Germany