Exploring Jump Rope Vortex Dynamics in Turbulent Liquid Metal Rayleigh-Bénard Convection Under Diverse Mechanical Boundary Conditions

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The large-scale circulation (LSC) is a crucial dynamical feature of turbulent thermal convection, shaping the appearance of various geophysical and astrophysical systems, such as solar granulation or cloud streets (Akashi et al., (2022),[1] and Vogt and Horn et al., (2018)[2]). This study investigates the Jump Rope Vortex, one of the fundamental modes within turbulent Rayleigh-Bénard convection, besides torsion and sloshing. This mode is distinguished by its fully three-dimensional (3D) motion, reminiscent of a twirling jump rope. Through the application of high-resolution direct numerical simulations (DNS), we seek to elucidate the dynamics of the jump rope vortex under a diverse set of boundary conditions, encompassing rigid (no-slip), free-slip, periodic, and mixed configurations.
Existing research has primarily focused on no-slip boundary conditions on the characteristics of turbulent thermal convection. However, a comprehensive understanding of the role of various boundary conditions in modulating the fully 3D motion of the jump rope vortex, remains elusive. Each boundary condition, no-slip, free-slip, periodic, and mixed impose unique constraints on the flow, which consequently affects the LSCs and jump rope vortex dynamics, as well as the heat and momentum transport. In this study, we systematically quantify the effects of these diverse boundary conditions on the morphology, stability, and heat transfer properties of the jump rope vortex. We will present results from an array of DNS in liquid metal with $Pr = 0.025$, covering Rayleigh numbers in the range of $Ra = 1.0 \times 10^4$ to 1.0×10^6. Furthermore, we explore variations in the domain's aspect ratio, ranging from $\Gamma = 2$ to 5 with both square and rectangle bases.

This knowledge can be invaluable for the development of theoretical models and the interpretation of observational data in the context of convective systems.

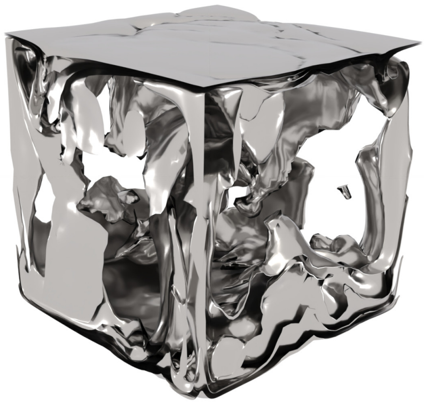

Figure 1: Temperature iso-surface for $T = [-0.5, 0.5]$ with $Ra = 1 \times 10^4$, $Pr = 0.025$ and $\Gamma = 5$. The boundary conditions are: isothermal at the top and bottom and periodic in the x & y directions respectively.

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[1]Akashi et al., *J. Fluid Mech.* **932**, 27 (2022)
[2]Vogt and Horn et al., *PNAS.* **115**, 50 (2018)