EXPERIMENTAL STUDY OF CONVECTIVE SUPERSTRUCTURES IN LOW-PRANDTL LIQUID METAL AT EXTREME ASPECT RATIO

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ABSTRACT

We report an experimental study of turbulent convective superstructures in a liquid-metal Rayleigh–Bénard layer of extreme aspect ratio ($\Gamma = 25$). The working fluid is GaInSn ($\mathrm{Pr} \approx 0.03$). Horizontal velocity fields were measured using ultrasound Doppler velocimetry (UDV) through the sidewalls, while a 21×19 thermocouple matrix embedded in the top plate, with sensors about 2 mm away from the liquid metal, resolved temperature fluctuations. At $\mathrm{Ra} = 2.17 \times 10^5$, the UDV space–time diagrams show inclined alternating velocity bands, and the top-plate temperature field displays aligned stripe patterns, both indicating a coherent, domain-spanning mode that organizes transport across the extended layer. The extracted nondimensional frequency fH^2/κ and wavelength λ/H follow trends established in earlier low-Pr experiments at smaller aspect ratios (Akashi et al., 2019; Vogt et al., 2018), demonstrating that the organizing mechanism persists at $\Gamma = 25$. These results highlight the robustness of large-scale convective modes in low-Pr fluids and carry implications for modeling turbulent convection in geophysical and astrophysical systems (Stevens et al., 2018; Pandey et al., 2018).

INTRODUCTION

Rayleigh–Bénard convection (RBC), the buoyancy-driven flow between heated and cooled plates, is a canonical system for studying turbulent transport in fluids. Its dynamics are primarily governed by the Rayleigh number, $\mathrm{Ra} = g\alpha\Delta T H^3/(\nu\kappa)$, which measures the strength of thermal forcing relative to dissipation. Here, g is the gravitational acceleration, α the thermal expansion coefficient, ΔT the imposed temperature difference across the layer, H the fluid height, ν the kinematic viscosity, and κ the thermal diffusivity. The second control parameter is the Prandtl number, $\mathrm{Pr} = \nu/\kappa$, which expresses the ratio of momentum diffusivity to thermal diffusivity. In low-Pr liquids such as liquid metals, rapid thermal diffusion tends to homogenize temperature variations, while weak viscous damping allows velocity fluctuations to remain vigorous, leading to a marked contrast between turbulent velocity fields and large-scale temperature organization. This contrast provides a unique opportunity to identify and characterize global modes of organization.

In large-aspect-ratio domains, multiple large-scale circulations can coexist and interact, giving rise to superstructures: long-lived roll or stripe patterns that span the entire layer and evolve on slow time scales (Stevens et al., 2018; Pandey et al., 2018). In liquid-metal convection, these superstructures are closely related to oscillatory large-scale modes such as the jump rope vortex (JRV) (Vogt et al., 2018), which has been established as a fundamental structural unit of low-Pr convection (Teimurazov et al., 2023). These superstructures are thought to underpin coherent transport in geophysical and astrophysical systems, from atmospheric cloud streets to solar granulation. However, most laboratory studies have been restricted to moderate aspect ratios ($\Gamma \lesssim 5$), leaving it unclear whether the same organizing mechanisms persist at extreme lateral extents where the degrees of freedom and interaction between circulations are greatly amplified. Addressing this gap, we experimentally examine whether coherent large-scale modes and their characteristic frequency–wavelength signatures survive in a liquid-metal convection layer at $\Gamma = 25$.

EXPERIMENTAL SETUP

The experiments are conducted in a Rayleigh–Bénard cell of extreme aspect ratio $\Gamma = L/H = 25$, with lateral length

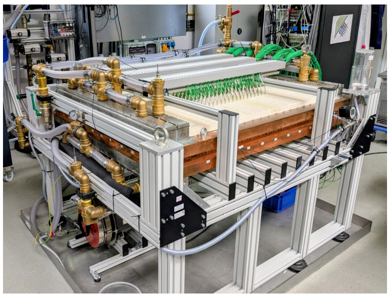

Figure 1. Photograph of the large-aspect-ratio Rayleigh–Bénard convection experiment ($L = 1$ m, $H = 40$ mm, $\Gamma = 25$). The GaInSn liquid metal layer is confined between temperature-controlled copper plates. Heating is supplied from below by a Huber Unistat, while cooling is provided from above by a laboratory chiller. The top plate hosts a 21×19 thermocouple array (green wiring), and ultrasound Doppler velocimetry (UDV) probes are mounted at the sidewalls for velocity measurements. The surrounding frame supports the copper plates and the inlet/outlet manifolds for thermal control.

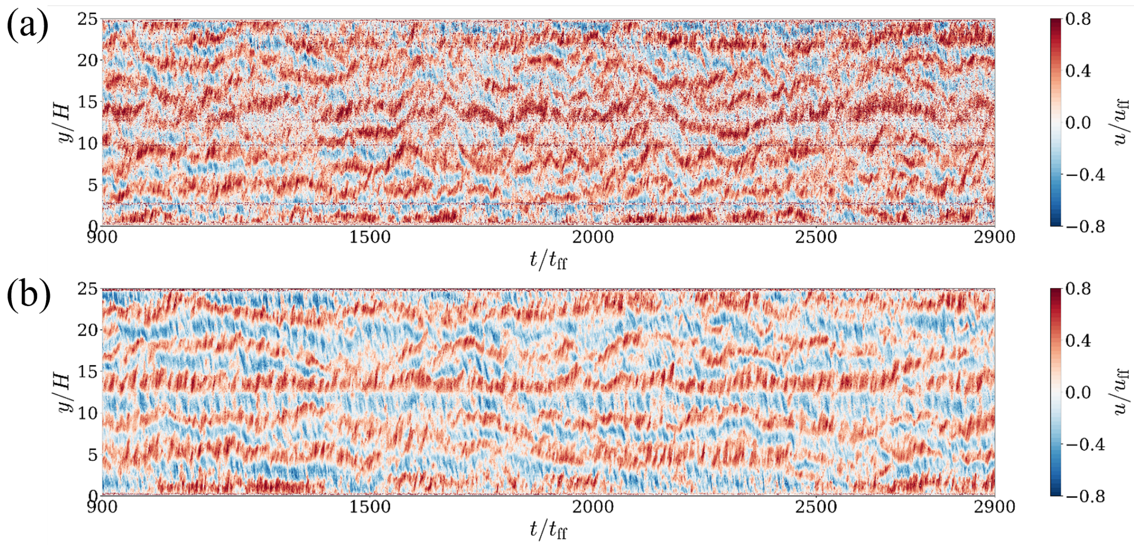

Figure 2. UDV space–time plots of the horizontal velocity at $z/H = 0.75$ in the $\Gamma = 25$ convection cell. Velocities are nondimensionalized by the free-fall scale u_{ff} and time by the free-fall time t_{ff}; the displayed interval is $900 < t/t_{ff} < 2900$. (a) $\mathrm{Ra} = 5.38 \times 10^4$ and (b) $\mathrm{Ra} = 2.17 \times 10^5$.

$L = 1$ m and fluid height $H = 40$ mm (figure 1). The working fluid is the eutectic alloy GaInSn ($\mathrm{Pr} \approx 0.03$ at room temperature), chosen for its low Prandtl number and high thermal conductivity. The convection layer is bounded above and below by oxygen-free copper plates, whose temperatures are controlled by external thermostats: heating is provided by a Huber Unistat 340 HT and cooling by a laboratory chiller. Both systems maintain temperature stability within ± 0.1 K. To ensure a homogeneous distribution across the plates, the manifold design was optimized to minimize lateral gradients. Residual variations remain near the fluid inlets and outlets; therefore, the analysis focuses on the central region of the plates where temperature differences stay below 10 %.

The velocity field is measured using ultrasound Doppler velocimetry (UDV) through the sidewalls. Multiple probes are mounted at opposing walls to access horizontal velocity components at selected heights; particular emphasis is placed on measurements at $z/H = 0.75$, where large-scale oscillations are most clearly resolved. In parallel, the temperature field near the top boundary is monitored using a 21×19 thermocouple array embedded in the top copper plate, with the sensor junctions located about 2 mm away from the liquid-metal surface. This array provides two-dimensional maps of temperature fluctuations across the top plate.

RESULTS

The velocity field reveals a clear evolution of large-scale organization with increasing Rayleigh number. At $\mathrm{Ra} = 5.38 \times 10^4$ (figure 2a), the UDV space–time plots at $z/H = 0.75$ show weakly modulated velocity fluctuations with intermittent banding. In contrast, at $\mathrm{Ra} = 2.17 \times 10^5$ (figure 2b), coherent inclined bands extend across the full lateral span of the cell. These streaks represent oscillations of horizontal velocity with a well-defined period and spatial drift, demonstrating the emergence of a domain-spanning global mode. The higher Ra state exhibits increased regularity and persistence of these bands, highlighting that the organizing mechanism becomes more pronounced with stronger thermal forcing. Comparable patterns have been identified in smaller-Γ liquid-metal experiments (Akashi et al., 2019, 2022), suggesting that the same large-scale mode persists even at extreme aspect ratio.

Spatial wavelengths λ were obtained from Fourier spectra of the horizontal velocity profiles $u(x)$ measured by UDV, as well as from spectral peaks in the top-plate temperature fluctuation field $T'(x,y)$. The latter is constructed by interpolating

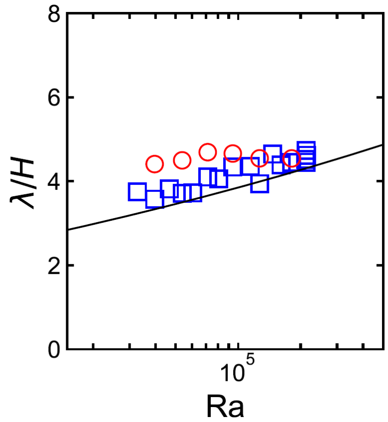

Figure 3. Dimensionless wavelength λ/H as a function of Rayleigh number. Blue squares denote wavelengths extracted from UDV velocity profiles (λ_U), and red circles represent wavelengths obtained from the top-plate thermocouple field (λ_Θ). The solid line indicates the empirical scaling $\lambda/H = 1.85Ra^{0.10} - 2$ reported in Ref. (Akashi et al., 2019).

the 21×19 thermocouple array onto a regular grid to obtain a continuous field beneath the top plate. To ensure that this field reflects only the fluid dynamics, we first subtract a quadratic conduction profile, thereby excluding contributions from the imposed mean gradient and residual lateral inhomogeneities caused by water circulation in the copper plate. The resulting fluctuation maps highlight alternating regions of enhanced and suppressed heat flux. These thermal stripes provide a robust imprint of the large-scale oscillatory mode and allow the dominant horizontal wavelength to be extracted from spectral peaks.

Figure 3 presents the resulting dimensionless wavelength λ/H as a function of Rayleigh number. The UDV data (blue squares) show a gradual increase of λ/H with Ra, consistent with well-established trends in low-Pr convection. In contrast, the thermocouple-derived values (red circles) yield systematically larger wavelengths, since thermal diffusion suppresses small-scale variations and the measurement reflects the large-scale modulation of heat flux at the top boundary. Despite this offset, both datasets lie close to the empirical scaling relation

$$\lambda/H \approx 1.85\,Ra^{0.10} - 2,$$

reported by Akashi et al. (2019) for liquid-metal convection in a $\Gamma = 5$ cell. This agreement demonstrates that the same large-scale organizing mode is captured by both diagnostics, and that the empirical trend identified at moderate aspect ratio persists even in the extreme $\Gamma = 25$ geometry. The systematic difference between velocity- and temperature-derived values highlights the complementary nature of the two approaches: UDV resolves the turbulent velocity field with fine detail, whereas the thermocouple array emphasizes the boundary-layer imprint of the coherent transport structures.

To characterize the oscillatory scales, the velocity signals were analyzed in detail. Frequencies were extracted from short-time Fourier transforms (STFT) of the horizontal velocity $u(t,x)$ along each UDV beam. The dominant ridge in the STFT spectrum was tracked to identify the characteristic oscillation. The resulting nondimensional frequency follows the

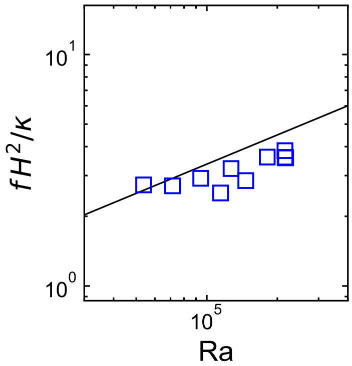

Figure 4. The nondimensional oscillation frequency fH^2/κ is examined as a function of the Rayleigh number. The present UDV measurements at $z/H = 0.75$ are in good agreement with the empirical scaling $fH^2/\kappa = 0.027\,\mathrm{Ra}^{0.419}$ reported in Ref. (Vogt et al., 2018).

empirical scaling

$$fH^2/\kappa \sim \mathrm{Ra}^{0.419},$$

previously reported by Vogt et al. (2018) for liquid-metal convection in a $\Gamma = 2$ cylindrical cell. This agreement demonstrates that, despite the richer spatio-temporal variability in the $\Gamma = 25$ geometry, the oscillatory dynamics retain the same scaling law as at moderate aspect ratio. The persistence of this frequency relation across geometries indicates that the underlying organizing mechanism is robust, and that large-scale oscillatory modes in low-Pr fluids are governed by universal dynamics relevant for transport in natural systems such as planetary interiors and stellar convection zones.

ACKNOWLEDGEMENTS

This work was supported by the Deutsche Forschungsgemeinschaft (DFG) within the Priority Programme SPP 1881 “Turbulent Superstructures” under Grant No. VO 2331/3, and by the DFG under Grant No. EC 217/5-1.

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