Experimental investigation of thermal boundary layers in turbulent liquid metal convection

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Abstract

Rayleigh–Bénard convection at low Prandtl number (Pr) plays a central role in heat transport and flow organization in liquid-metal systems, where thermal diffusion strongly exceeds momentum diffusion. As a result, thermal boundary layers are substantially thicker than velocity boundary layers, leading to a strong coupling between boundary-layer dynamics, bulk turbulence, and the large-scale circulation. In this study, we experimentally investigate turbulent Rayleigh–Bénard convection in the liquid metal GaInSn (Pr = 0.03). We perform measurements in two cylindrical convection cells with aspect ratios D/H = 1/2 and 1/3. In the D/H = 1/2 cell, we observe a location-dependent Rayleigh-number (Ra) scaling of the thermal boundary-layer thickness, accompanied by increasingly strong temperature fluctuations and growing deviations from the classical Prandtl–Blasius–Pohlhausen (PBP) profile with increasing Ra. Vertical temperature profiles are measured at two locations directly beneath the upper plate: a shear-dominated region near the plate center and a lateral region close to the sidewall, where thermal plumes either detach from or impinge on the plate after traversing the cell. Pronounced differences are found between these locations in terms of temperature profiles, fluctuation statistics, and boundary-layer thickness scaling. While the shear-dominated region exhibits temperature profiles close to the laminar PBP prediction, enhanced fluctuations near the sidewall lead to significant deviations from laminar behavior (1). To further probe the interaction between thermal boundary layers and the turbulent large-scale circulation, we extend our investigation to a second cylindrical cell with the same height as the D/H = 1/2 cell but a smaller aspect ratio of D/H = 1/3. The identical cell height allows a direct comparison over the same Rayleigh-number range. High-resolution thermal boundary-layer measurements using custom thermocouple arrays at five locations beneath the cooled plate are combined with simultaneous velocity measurements obtained by ultrasound Doppler velocimetry. This approach enables a systematic assessment of how aspect ratio influences boundary-layer dynamics and global flow organization in low-Prandtl-number Rayleigh–Bénard convection. (1) N. Kim et al., Thermal boundary layer dynamics in low-Prandtl-number Rayleigh–Bénard convection, J. Fluid Mech. 994, A4 (2024)

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