
Turbulent Prandtl number for Rayleigh-Bénard convection at very low Prandtl numbers

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Abstract

We employ a novel framework to compute the scale-resolved turbulent Prandtl number for the highly inertial well-mixed bulk of turbulent Rayleigh-Bénard mesoscale convection at a molecular Prandtl number of $Pr = 0.001$. The framework is based on Kolmogorov's refined similarity hypothesis of homogeneous isotropic fluid and passive scalar turbulence, which, in turn, is founded on log-normally distributed amplitudes of kinetic energy and scalar dissipation rates that are coarse-grained over variable scales in the inertial subrange. Our definitions of turbulent (or eddy) viscosity and diffusivity do not rely on mean gradient-based Boussinesq closures of Reynolds stresses and convective heat fluxes, since such gradients are absent or indefinite in the bulk. We base our present study on direct numerical simulation of plane-layer convection at an aspect ratio of 25 for Rayleigh numbers ranging from 100,000 to 10,000,000. We find that the turbulent Prandtl number is effectively up to 4 orders of magnitude larger than the molecular one. This holds particularly for the upper end of the inertial subrange, where the eddy diffusivity exceeds the molecular value (1). Highly inertial low-Prandtl-number convection becomes effectively a higher-Prandtl number turbulent flow, when turbulent mixing processes on scales that reach into the inertial range are included. This might have some relevance for prominent low-Prandtl-number applications, such as solar convection.

Reference:

(1) S. Bhattacharya, D. Krasnov, A. Pandey, T. Gotoh, and J. Schumacher, "Scale-resolved turbulent Prandtl number for Rayleigh-Bénard convection at $Pr = 10^{-3}$ ", *J. Fluid Mech* 1026, A6 (2026).

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