On heat-transfer efficiency scaling in Rayleigh–Bénard convection deduced from high-Rayleigh-number cryogenic experiments

Pavel Urban*[1], Pavel Hanzelka[1], Jan Chládek[1], Tomáš Králík[1], Jiří Krempl[1], Michal Macek[1], Věra Musilová[1], Katepalli R. Sreenivasan[2], and Ladislav Skrbek[3]

[1]Czech Academy of Sciences, Institute of Scientific Instruments – Czech Republic
[2]Department of Physics, Courant Institute of Mathematical Sciences, Tandon School of Engineering, New York University – United States
[3]Faculty of Mathematics and Physics, Charles University – Czech Republic

Abstract

Cryogenic Rayleigh–Bénard convection (RBC) at very high Rayleigh numbers (Ra) is a model system for studying buoyancy-driven flows and turbulent convective heat transport (1). Of particular interest is the possible existence of the ultimate regime, characterized by an asymptotic heat-transfer scaling Nu Raˆ1/2, and transition of the boundary layers to turbulence, which may occur via a non-normal nonlinear, and thus subcritical, transition (2).
We analyse new heat-transfer data obtained in Brno from two cylindrical cryogenic convection cells with aspect ratios = 1 and 2 (diameter 0.3 m), covering the range Ra = 1E8–1E13. A transition in the heat-transfer scaling is observed at Ra ≈ 1E11. These results are compared with published high-Ra measurements from Göttingen using SF6 at ambient temperature in larger cells (diameter 1.12 m, = 1, 0.5, and 0.33), where a corresponding transition has been reported at significantly higher Rayleigh numbers, Ra ≈ 1E13. In both experiments, the working points are located at similar positions in the p–T phase diagram relative to the critical point and the vapour–liquid saturation curve.

Remarkably, the heat-transfer efficiency in both data sets depends nearly uniquely on the dimensional parameter Ra/Lˆ3, where L is the cell height, and remains largely independent of the aspect ratio (3). The large discrepancy in the transition Rayleigh numbers between the Brno and Göttingen experiments therefore raises the question of whether the observed transition reflects (i) intrinsic ultimate-regime dynamics or (ii) is predominantly a manifestation of NOB effects and experimental imperfections or (iii) a non-normal nonlinear transition triggered by NOB fluid properties, which have not been excluded in recent comprehensive reviews (2).

Motivated by these considerations, we present a systematic analysis of experimental uncertainties and data-correction procedures relevant to Brno cryogenic RBC experiments, including parasitic heat leaks, adiabatic temperature-gradient effects, finite thermal conductivity of plates and sidewalls, NOB effects, and the selection of working points in the He p–T phase diagram based on available thermophysical property databases. Our results highlight

*Speaker

the importance of rigorous uncertainty quantification when assessing evidence for the ultimate RBC regime (4).

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