MODULATION OF THE WALL-HEAT TRANSFER IN TURBULENT THERMOMAGNETIC CONVECTION BY MAGNETIC FIELD GRADIENTS

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Abstract
We present combined experimental and numerical studies of the heat transfer of paramagnetic or diamagnetic fluid inside a differentially heated cubical enclosure subjected to the magnetic field gradients of different strength and orientation. In contrast to the previously reported studies in literature, which observed solely laminar flow regimes, here we focused on the fully developed turbulent flow regimes. That was possible by using a combination of the state-of-art superconducting magnets (with a strength up to 10 T and magnetic field gradients up to 900 T^2/m) and by selecting various paramagnetic or diamagnetic working fluids (in a range of $10 \leq \mathrm{Pr} \leq 1000$). Detailed comparison between experiments (integral wall-heat transfer, temperature time-series at different locations within the enclosure) and direct numerical simulations (DNS) are performed and generally very good agreements are obtained in predicting the integral heat transfer. In addition, analysis of the long-term averaged first- and second-moments of velocity and thermal fields is performed. Finally, budgets of the turbulent kinetic energy and of the temperature variance are analyzed and the mean mechanism of the thermal plume reorganization in terms of the proper-orthogonal decomposition (POD) modes is presented.

INTRODUCTION

An interesting case of thermal convection is when the working fluid becomes magnetized in the presence of an external magnetic field. Then, the working fluid can be attracted (paramagnetic fluid) or repulsed (diamagnetic fluid) by the imposed magnetic field gradient. In contrast to the electrically conductive fluids (liquid metals, salt water, plasma) there is no electrical current generated in paramagnetic and diamagnetic fluids. Additional important difference with electrically conductive fluids is necessity to impose magnetic field gradient that generates magnetization force. By changing strength and orientation of the imposed magnetic field gradient, as well as initial configuration of the heating scenarios (heated from below or heated from side), significant flow and turbulence reorganization can take place, providing scenarios for efficient enhancement or suppression of the wall-heat transfer. Besides its potentials in fundamental research, possible areas of application where magnetic fields can be used to control flow and heat transfer, include control of the growth rate and microstructure of materials [1], [2] or protein crystals [3]. In contrast to all previous studies dealing with combined effects of thermo-gravitational and thermo-magnetic convection, which were performed in stable laminar flow regimes ([4], [5], [6], [7]), in the present study we focus on the fully-developed turbulent regimes ([8], [9], [10]).

RESULTS

We performed experimental and numerical studies of combined natural and magnetic convection of paramagnetic or diamagnetic fluids within a cubical enclosure heated from below and cooled from above and subjected to magnetic field gradient. Values of the magnetic field gradient are in $9 \leq |\mathrm{grad}|b_0|^2| \leq 900$ T^2/m range for imposed magnetic field strengths in the center of the superconducting magnet bore of $1 \leq |b_0|_{max} \leq 10$ T, respectively. Very good agreement between experiments and simulation is obtained in predicting the integral heat transfer over entire range of working parameters (i.e. thermal Rayleigh number $1.15 \times 10^5 \leq \mathrm{Ra} \leq 8 \times 10^6$, Prandtl number $10 \leq \mathrm{Pr} \leq 1000$ and magnetization number $0 \leq \gamma \leq 60$ range).

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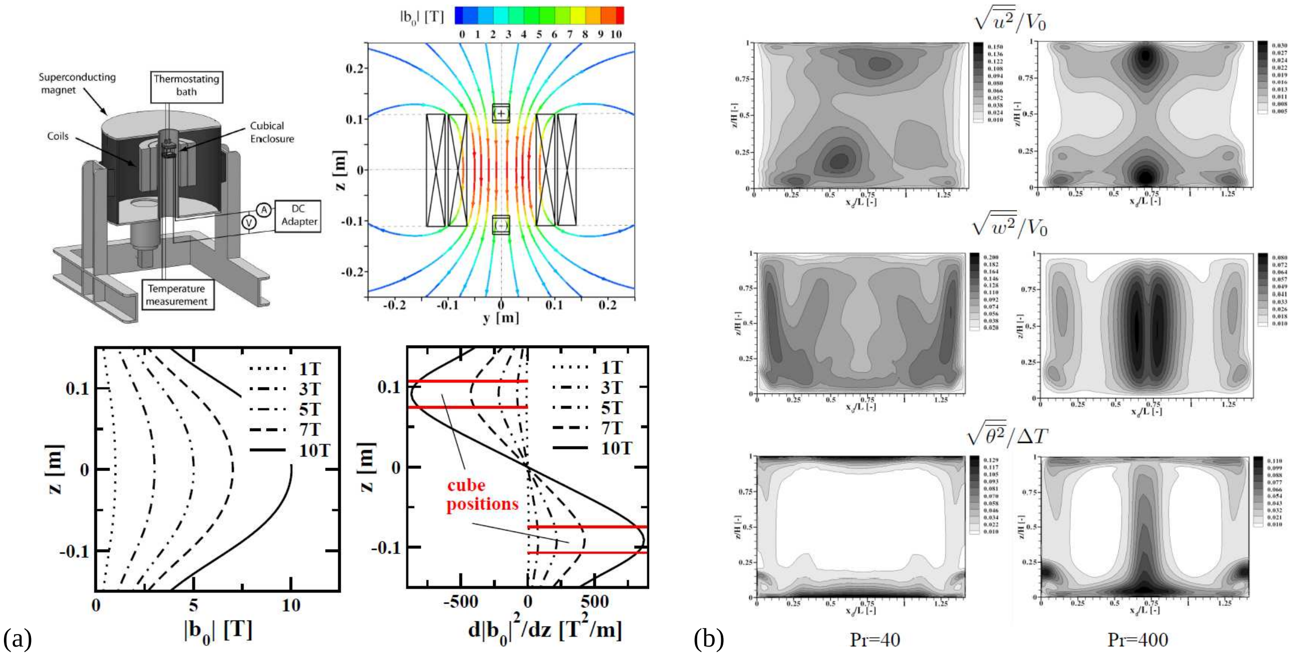

Figure 1. (a) The sketch of complete experimental setup (four coils of the superconducting magnet; locations of the cubical enclosure: upper where f_M^+, lower, where f_M^-; thermostating bath; DC adapter) (top/left) and magnetic field lines (colored with magnetic induction at $|b_0|_{max}$=10 T (top/bottom). The vertical profiles (extracted along the central magnet bore axis) of $|b_0|$ (bottom/left) and of $\partial|b_0|^2/\partial z$ (bottom/right) for different operating conditions, $1 \leq |b_0|_{max} \leq 10$ T; (b) Contours of the non-dimensional turbulent stress (horizontal and vertical) and temperature variance in the central vertical diagonal plane (x_d/L - z/H) (extracted along x/L=0, y/D=0 and x/L=1, y/D=1) for different values of Pr (Pr=40, Ra=2×10^6, top; Pr=400, Ra=2×10^5, bottom) and a fixed value of the imposed magnetic field ($|b_0|_{max}$=9 T.

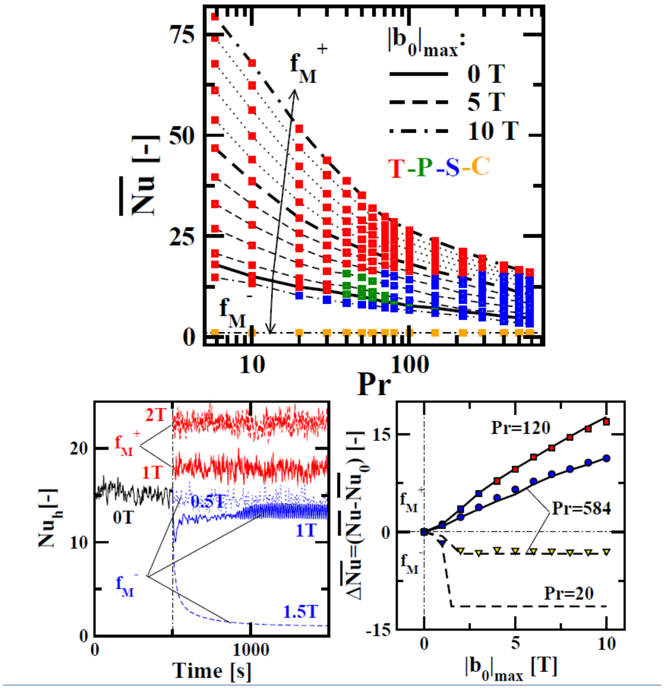

Figure 2. Top- the long-term time-averaged integral Nusselt numbers for different values of Pr, different strengths of magnetic fields and upper (enhancement) and lower (suppression) enclosure settings within magnetic bore. Different symbol colors indicate distinct flow regimes: red- turbulent, blue- laminar, orange- conductive (no motion). Bottom- the time evolution of the integral Nu at the lower wall for Pr=10 and different enclosure locations and imposed strengths of magnetic field (left). Comparison between experiments and simulation in heat transfer enhancement (f_M^+) or suppression (f_M^-) for different Pr (right).