Electromagnetic enhancement of turbulent heat transfer

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(Received 23 July 2008; published 18 December 2008)

We performed large eddy simulations (LES) of the turbulent natural convection of an electrically conductive fluid (water with 7% Na2SO4 electrolyte solution) in a moderate (4:4:1) aspect ratio enclosure heated from below and cooled from above and subjected to external nonuniformly distributed electromagnetic fields. Different configurations with permanent magnets (located under the lower thermally active wall, \(B_0 = 1\) T) and different strengths of imposed direct current \(I = 0-10\) A were compared to the case of pure thermal convection in the turbulent regime, \(Ra = 10^7\), \(Pr = 7\).

It is demonstrated that the electromagnetic forcing of the boundary layers caused significant reorganization of flow and turbulence structures producing significant enhancement of the wall-heat transfer (up to 188% for a configuration with 35 magnets and an applied direct current of 10 A).

DOI: 10.1103/PhysRevE.78.066309

PACS number(s): 47.27.-i, 47.65.-d, 47.85.-g

I. INTRODUCTION

Control of flow, turbulence, and heat transfer of electrically conductive working fluids is the basic prerequisite for the design and optimization of many technological processes. Examples include electromagnetic braking of continuous steel casting, free-surface stabilization of the aluminum reduction cells, joining metals by arc welding, crystal growth, electromagnetic mixing, and steering in metallurgy and liquid metal blankets in new generation of fusion reactors [1–3].

In previous studies, we analyzed the effects of imposed uniform magnetic fields of different orientation and strength on turbulent forced and thermal convection of highly electrically conductive fluids [4–7]. It was observed that the resulting Lorentz force significantly affected the underlying flow, turbulence, and wall-heat transfer. The wall-heat transfer was strongly reduced for a vertically oriented magnetic field, making it possible to totally suppress convective motions for sufficiently strong magnetic fields. The numerical simulations proved to provide results in very good agreement with available experiments over a range of Rayleigh (Ra), Prandtl (Pr), and Hartmann (Ha) numbers [8], where \(Ra = \beta g \Delta T \rho \nu H^2 / \mu^2\), \(Pr = \nu / \alpha\), and \(Ha = |B_0| H / \sigma / \rho \nu\). For a longitudinal orientation of the magnetic field, a two-dimensional alignment of flow structures with the direction of the imposed magnetic field is observed. When a full two-dimensionality of the flow is reached (total suppression of the flow variations in the spanwise direction), a saturation point in the effective reduction of the wall-heat transfer is achieved [6].

II. INVESTIGATED SETUP

In the present investigation, instead of applying uniformly distributed magnetic fields, we focus on the possibility to locally apply electromagnetic forcing in order to affect the boundary layers along the thermally active horizontal walls. In order to achieve that, different combinations of magnets and electrodes are imposed, resulting in various forcing patterns on the underlying flow. In contrast to the multiscale forcing applied in Refs. [9,10], where laminar two-dimensional flow patterns have been investigated, we focus on genuinely three-dimensional flow features in fully developed turbulent regimes with heat transfer. The heat transfer was not considered in our previous experimental and numerical studies of electromagnetically driven flows [11]. The no-slip boundary condition for velocity is applied for all enclosure walls and horizontal walls (upper cold, lower hot) are kept at the constant temperature. The all side walls are adiabatic. Special care is taken to choose simulation parameters close to experimentally reachable flow regimes. The turbulent thermal convection at \(Ra = 10^7\), \(Pr = 7\) is selected as a referent case. Despite the relatively weak electrical conductivity of the working fluid that is close to that of sea water (water with 7% Na2SO4, \(\sigma = 5.55 \times 10^{-2}\)), sufficiently strong electromagnetic forces can be generated in the proximity of the lower wall with support of the imposed electric dc current (distributed through two electrodes located at the top of the side walls). The two-magnet configuration generates a well-defined central vortical tornadolike flow pattern similar to those presented in Ref. [12]. The three-magnet configuration, the central alignment of which is rotated over 90° with respect to the two-magnet configuration, generates local flow patterns in the form of a horizontal wall jet along the lower wall [11]. Finally, an array of 35 magnets generates complex flow patterns that result from superposition of the above mentioned magnetic orientations.

III. NUMERICAL MODEL

The flow of an incompressible electrically conductive working fluid in the turbulent regime, subjected to temperature gradients and Lorentz force, can be described by conservation of momentum and heat:
\[
\frac{\partial (U_j)}{\partial t} + (U_i) \frac{\partial (U_j)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \nu \frac{\partial (U_j)}{\partial x_j} - \tau_{ij} \right) - \frac{1}{\rho} \frac{\partial (P)}{\partial x_j} - \beta g_i(T) \frac{T_{REF}}{T} + \frac{\sigma}{T_f} \mathcal{E}_{ij}(E_i)(B_j) + \frac{\partial (T)}{\partial t} + (U_i) \frac{\partial (T)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \frac{\nu}{Pr} \frac{\partial (T)}{\partial x_j} - \tau_{ij} \right),
\]

(1)

(2)

together with the solenoidal conditions \(\partial (U_j)/\partial x_i = 0\) and \(\partial (B_j)/\partial x_i = 0\). Here, \((\cdot, \cdot)\) stands for the spatially averaged (filtered) quantities in a large eddy simulation approach. In these equations, \((U_i, P, T, E_i, B_i)\) are velocity, pressure, temperature, electric field, and magnetic field, respectively. The magnetic and electric field distributions are calculated from the simplified set of Maxwell’s equations by applying the Biot-Savart law for permanent magnets and electrodes. For magnetic and electric field distributions are calculated from the particle image velocimetry (PIV) measurements \([11]\). A numerical mesh consisting of \(182 \times 182 \times 92\) control volumes clustered \((x^+_n = 0.5)\) in the proximity of thermally active and side walls is used. This mesh is designed such that it fully resolves estimated flow and turbulence scales in the proximity of the walls \((1−2) \eta_k\) where \(\eta_k = (v^3/\varepsilon)^{1/4}\) is the Kolmogorov length scale. A coarser resolution of \((5−10) \eta_k\) is used in the central part of the enclosure. These estimates are based on the case for the highest intensity of imposed current \((I = 10\ A)\). The resulting maximum ratio between subgrid turbulent and molecular viscosity was \(v_t/v < 0.1\) for the strongest forcing case with 35 magnets, proving sufficiency of the spatial resolution. For the isothermal case, LES results showed good agreement with available PIV data—for velocity and turbulent stresses in two- and three-magnet configurations and different strengths of imposed current \([11]\). Simulations of pure turbulent thermal convection over a range of \(Ra\) and \(Pr\) have been validated in Refs. \([6,14,19,20]\). Now, for the nonisothermal case with electromagnetic fields, distributions of the Lorentz force lines and imposed magnetic field beneath the lower wall \((B_i)\) and resulting flow and temperature patterns (for fully developed flow) are shown in Fig. 1. It can be seen that the generated Lorentz force is mainly concentrated in the lower part of the setup (first 10% of the total height, Fig. 2), where characteristic spiraling flow patterns are generated. Those locally imposed vortical patterns change the initial morphology of both the thermal and hydrodynamical boundary layers along the horizontal thermally active walls. The difference in the vertical extension of the thermal boundary layers along horizontal walls is clearly visible in vertical planes showing contours of as shown in Fig. 1. Superimposed streamlines and temperature contours of the long-time averaged fields in the central vertical plane for different magnet setups are shown in Fig. 3. Figure 3(a) shows the neutral (no magnet) situation, where two characteristic convective rolls occupy the central part of the cavity and two secondary rolls are located in the upper corners. The convective rolls show very similar morphology to those analyzed in Ref. \([20]\), whereas the temperature field portrays “mushroomlike” thermal plumes that closely resemble structures observed in Refs. \([17,18]\). Although direct forcing by the Lorentz force is locally confined to the boundary layers, due to mutual coupling of velocity and temperature fields (thermal buoyancy), any changes in the near-wall regions lead to relocation of the thermal “mushroomlike” plumes (vertical up drafts of the hot fluid) that in turn define the intensity and size of convective and roll structures. Already for the two-magnet situation, Fig. 3(b), the horizontal extension of the downward thermal plume, originating from the top-cold surface, is significantly

IV. RESULTS

Prior simulations with heat transfer, a detailed comparison was performed between LES and experimental data [obtained from the particle image velocimetry (PIV) measurements] \([11]\). A numerical mesh consisting of \(182 \times 182 \times 92\) control volumes clustered \((x^+_n = 0.5)\) in the proximity of thermally active and side walls is used. This mesh is designed such that it fully resolves estimated flow and turbulence scales in the proximity of the walls \((1−2) \eta_k\) where \(\eta_k = (v^3/\varepsilon)^{1/4}\) is the Kolmogorov length scale. A coarser resolution of \((5−10) \eta_k\) is used in the central part of the enclosure. These estimates are based on the case for the highest intensity of imposed current \((I = 10\ A)\). The resulting maximum ratio between subgrid turbulent and molecular viscosity was \(v_t/v < 0.1\) for the strongest forcing case with 35 magnets, proving sufficiency of the spatial resolution. For the isothermal case, LES results showed good agreement with available PIV data—for velocity and turbulent stresses in two- and three-magnet configurations and different strengths of imposed current \([11]\). Simulations of pure turbulent thermal convection over a range of \(Ra\) and \(Pr\) have been validated in Refs. \([6,14,19,20]\). Now, for the nonisothermal case with electromagnetic fields, distributions of the Lorentz force lines and imposed magnetic field beneath the lower wall \((B_i)\) and resulting flow and temperature patterns (for fully developed flow) are shown in Fig. 1. It can be seen that the generated Lorentz force is mainly concentrated in the lower part of the setup (first 10% of the total height, Fig. 2), where characteristic spiraling flow patterns are generated. Those locally imposed vortical patterns change the initial morphology of both the thermal and hydrodynamical boundary layers along the horizontal thermally active walls. The difference in the vertical extension of the thermal boundary layers along horizontal walls is clearly visible in vertical planes showing contours of as shown in Fig. 1. Superimposed streamlines and temperature contours of the long-time averaged fields in the central vertical plane for different magnet setups are shown in Fig. 3. Figure 3(a) shows the neutral (no magnet) situation, where two characteristic convective rolls occupy the central part of the cavity and two secondary rolls are located in the upper corners. The convective rolls show very similar morphology to those analyzed in Ref. \([20]\), whereas the temperature field portrays “mushroomlike” thermal plumes that closely resemble structures observed in Refs. \([17,18]\). Although direct forcing by the Lorentz force is locally confined to the boundary layers, due to mutual coupling of velocity and temperature fields (thermal buoyancy), any changes in the near-wall regions lead to relocation of the thermal “mushroomlike” plumes (vertical up drafts of the hot fluid) that in turn define the intensity and size of convective and roll structures. Already for the two-magnet situation, Fig. 3(b), the horizontal extension of the downward thermal plume, originating from the top-cold surface, is significantly

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reduced due to the centrally located swirling pattern. This
swirling pattern creates a low-pressure region that attracts the
surrounding fluid and moves convective rolls towards the
lower side corners, reducing their size. In contrast to this
“central forcing,” the configurations with 3 and 35 magnets
produce multiple cells in the proximity of the lower horizon-
tal wall, Figs. 3(c) and 3(d). Vertical long-time and spatially
averaged temperature profiles show an interesting shift to-
ward higher values in the central part of the enclosure when
electromagnetic control is active, Fig. 4(a) and 4(b). This is a
consequence of the asymmetrical forcing since only the
lower part of the enclosure is subjected to the locally distrib-
uted Lorentz force. Compared to the neutral situation, the
temperature variance profiles exhibit lower peaks and
are moved closer to the lower wall, indicating thinning of the
thermal boundary layer, Fig. 4(c) and 4(d). In contrast to
that, in the proximity of the upper wall, the temperature vari-
ance profiles show higher peak values compared to the neu-
tral situation. The spatially averaged horizontal velocity
component exhibits changes in the sign and in the mag-
nitude for the 2- and 35-magnet configuration and strong (I

FIG. 1. (Color online) Considered [4:4:1] wall-bounded enclo-
sure Ra=10^7, Pr=7. Above: Contours of the vertical magnetic field
cOMPONENT (B_z in T) at the bottom wall and the Lorentz force line
distributions (colored by temperature). Below: tracers of the time
averaged velocity field colored by non-dimensional temperature
variance (√(P^2)/ΔT) and its contours in two characteristic vertical
planes. All enclosure dimensions are in m.

FIG. 2. Profiles of the z and y components of the imposed Lor-
enz force (in N/m³) in the central vertical plane at different dis-
tances from the lower wall for a configuration with 35 magnets
(|B_0|=1 T and I=1 A).

FIG. 3. (Color online) Long-time averaged stream traces and
temperature contours in the central vertical plane for configurations
with 0, 2, 3, and 35 magnets from top to bottom, respectively. I
=1 A, Ra=10^7, Pr=7.
The table shows the Nusselt numbers for different magnet configurations and different strengths of applied electric currents. The lower and upper range of Re are for weak (1 A) and strong (10 A) currents, respectively. Ra=10^7, Pr=7, Ha=10, |B_0|=1 T.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Applied dc: $I=1$ A</th>
<th>$I=10$ A</th>
<th>Re^a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral</td>
<td>15.35</td>
<td>15.35</td>
<td>200</td>
</tr>
<tr>
<td>2 magnets</td>
<td>16.27 (+6%)</td>
<td>25.75 (+68%)</td>
<td>1200-4000</td>
</tr>
<tr>
<td>3 magnets</td>
<td>15.70 (+2.3%)</td>
<td>25.05 (+63%)</td>
<td>900-3000</td>
</tr>
<tr>
<td>35 magnets</td>
<td>20.58 (+34%)</td>
<td>44.28 (+188%)</td>
<td>1300-4500</td>
</tr>
</tbody>
</table>

^aRe=\max(\langle U_i \rangle /H/\nu, |U_i| = \sqrt{\langle U^2 \rangle + \langle V^2 \rangle + \langle W \rangle^2}.

FIG. 4. (Color online) Long-time and spatially averaged vertical profiles of temperature (a-b), temperature variance (c-d), horizontal velocity ($V$) (nondimensionalized by $U_0 = \sqrt{\beta g \Delta T H}$) (e), and kinetic energy of turbulence (f) for 2 and 35 magnet configurations and different intensities of applied electric currents $I=0,1,10$ A, respectively.

V. CONCLUSION

It was demonstrated that application of a steady, locally distributed Lorentz force can produce a very large increase in the wall-heat transfer in turbulent thermal convection. In addition to its potential in various technological applications, this localized electromagnetic forcing can be used for fundamental studies of turbulence subjected to external body forces (modulated turbulence).

ACKNOWLEDGMENTS

The high-performance computing facilities were provided by the NWO/NCF and SARA Computational and Network services, Amsterdam, The Netherlands [25].