Numerical Flow Simulation I

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Summary

The influence of a constant uniform magnetic field on a turbulent thermal convection is investigated using direct numerical simulation. The problem is simplified by utilization of the homogeneity assumption. Namely, we study the flow in a box with periodic boundary conditions driven by a constant imposed mean temperature gradient. The case of small Prandtl number and both the magnetic field and temperature gradient in vertical direction is considered. The main feature of the flow is the development of two antiparallel vertical jets providing an effective mechanism for the vertical heat transfer. The magnetic field is shown to stabilize the jets and, thus, to increase heat transfer and enhance the anisotropy of the flow.

1 Introduction

The ability of a constant uniform magnetic field to suppress the turbulent motions of electrically conducting fluids is a subject of growing interest. This phenomenon is particularly important for the problems including heat transfer such as construction of liquid metal cooling blankets for fusion reactors or optimization of semiconductor crystal growth because the magnetic field can lead to substantial changes of the flow structure and transfer properties. It was shown analytically [1], [2], [3], experimentally [4], [5], and numerically [6], [7], [8] that responsible for this suppression is the anisotropic Joule dissipation. For many laboratory and technical flows of liquid metals the assumptions of low magnetic Reynolds and Prandtl numbers
\[
Re_m \equiv \frac{uL}{\eta} \ll 1, \quad P_m \equiv \frac{\nu}{\eta} \ll 1
\]  

(1.1)

are valid. In (1.1) \(\nu\) is the kinematic viscosity, \(u\) is the mean velocity, \(L\) is the typical length scale, and \(\eta = (\sigma \mu_0)^{-1}\) is the magnetic diffusivity, \(\sigma\) and \(\mu_0\) being the electric conductivity and magnetic permeability of the liquid. Under such assumptions, the quasi-static approximation can be applied for the perturbations of the magnetic field due to fluid motions [9]. The rotational part of the Lorentz force reduces to a linear functional of the velocity

\[
F[u] = -\frac{\sigma B_0^2}{\rho} \Delta^{-1} \frac{\partial^2 u}{\partial z^2}
\]  

with the Fourier transform

\[
\hat{F}[\hat{u}] = -\frac{\sigma (B_0 \cdot k)^2}{k^2} \hat{\dot{u}}(k,t) = -\frac{\sigma B_0^2}{\rho} \cos^2 \phi \hat{\dot{u}}(k,t),
\]  

(1.3)

where \(B_0\) is a constant magnetic field directed along the z-axis, \(k\) is a wavenumber vector, and \(\phi\) is an angle between \(B_0\) and \(k\).

The additional Joule dissipation represented by (1.2) or (1.3) is anisotropic. It is maximum for modes with \(B_0 || k\) and zero for modes independent of z-coordinate. The dissipation tends to eliminate velocity gradients in the direction of \(B_0\) and elongate the velocity structures in this direction. The magnetic field tends to transform the flow into a two-dimensional state where the velocity field depends only on the coordinates in the plane perpendicular to \(B_0\). An opposite tendency is due to the nonlinear energy transfer which tends to restore isotropy of the flow.

The estimate of the ratio of Joule to nonlinear term is given by the magnetic interaction parameter

\[
N \equiv \frac{\sigma B_0^2 L}{\rho u}
\]  

(1.4)

that can also be defined as the ratio of the large-eddy turnover time \(\tau_u = L/u\) to the typical time of Joule dissipation \(\tau_J = \rho/\sigma B_0^2\).

An extensive numerical study of the transformation of an initially isotropic liquid metal flow under the influence of imposed constant magnetic field was performed in [8]. The case of a homogeneous flow in a cubic box with periodic boundary conditions was considered. To force the flow, an artificial energy supply into large scale modes was employed. It was shown that there are three types of the flow transformation dependent of the interaction parameter \(N\). If \(N\) is small, the flow remains three-dimensional, turbulent, and approximately isotropic. In the case of large \(N\) (strong magnetic field) the rapid irreversible transformation into purely two-dimensional steady state was observed. An intermediate value \(N \approx 1\) was found to lead to the intermittent solution with the periods of quasi-two-dimensional, laminar and three-dimensional, turbulent behavior interchanging.
From the point of the scalar transfer problem, one interesting result found in [8] is that even in the case $N \gg 1$, when the flow becomes independent of the coordinate $z$ in the direction of the magnetic field, the velocity component $u_3$ in this direction does not vanish (for a review of experimental indications see [10]). This implies the possibility of non-zero scalar transfer in the direction of $B_0$. Being very interesting for the industrial applications this possibility has not received yet proper consideration.

In the present paper we study the turbulent Rayleigh–Benard convection under the influence of a constant magnetic field. The case of low Prandtl number is considered. Aside from the possibility of studying the effect of magnetic field on the heat transfer, this formulation allows us to replace an artificial forcing used in [8] by the natural mechanism of buoyancy. On the other hand, the problem remains highly idealized (and numerically treatable) because we consider the case without rigid boundaries. The flow in a three-dimensional box with periodic boundary conditions is driven by an imposed constant temperature gradient parallel to the magnetic field. Such a flow without magnetic field was first considered in [11] where the term “homogeneous thermal convection” was proposed.

2 Basic equations and method of solutions

We consider the three-dimensional convective motion of an electrically conducting viscous fluid (e. g. liquid metal). The flow is assumed to be homogeneous and contained in a box of a square horizontal cross-section with the horizontal side length $2\pi$ and vertical side length $8\pi$. There can be a uniform magnetic field imposed in vertical direction. The energy supply into the system is provided by the buoyancy force created through the imposed mean temperature gradient $\nabla T = -ez$.

Assuming the Boussinesq approximation for the fluid and the quasi-static approximations for the perturbations of the magnetic field the basic equations can be given as

\[
\partial_t u + (u \cdot \nabla) u = -\nabla p + \nu \Delta u + \theta e_z - \sigma B_0^2 \Delta^{-1} \partial^2 u / \partial z^2 \quad (2.5)
\]

\[
\partial_t \theta + u \cdot \nabla \theta = \kappa \Delta \theta + u_3 \quad (2.6)
\]

\[
\nabla \cdot u = 0. \quad (2.7)
\]

We suppose here that the temperature field can be decomposed into the fluctuating part $\theta(x,t)$ subject to periodic boundary conditions and the constant mean part $T(z) = T_0 - z$. The boundary conditions for the velocity perturbations $u = (u_1, u_2, u_3)$ are also periodic. We adopt for this study the mean density $\rho_0 = 1$ and the Boussinesq coefficient $\alpha g = 1$. The Prandtl number $Pr = \nu / \kappa$ is 0.025 (liquid mercury) and the Rayleigh number $Ra$ was proposed.
After application of the operator $\text{rot}^2$ to (2.5) and Fourier transform to (2.5) and (2.6) the system is solved using the standard pseudo-spectral technique based on the fast Fourier transform. The aliasing errors are not removed, which allows one to reduce the cost of calculations by a factor of about 2. The time-stepping technique includes a second-order leap-frog scheme for nonlinear term and exponential solution for the linear terms. To suppress the oscillatory instability inherent in leap-frog methods, the solutions at two subsequent time layers are averaged every 20th time step.

The system considered here seems to be a reasonable model for the turbulent convection in the regions with approximately constant mean temperature gradient far from the walls, e.g. in the middle of the long vertical cavity heated from below. An advantage of this system is the possibility of effective numerical simulation. There is also a specific disadvantage stemming from our highly idealized formulation. One can easily see that the most unstable modes of the linear stability problem are those with the zero horizontal velocity components and the only nonzero Fourier modes being

$$u_3, \hat{\theta} \text{ with } k = (1,0,0) \text{ or } k = (0,1,0). \quad (2.9)$$

Spatially, this solution have a form of two (one ascending and another descending) vertical jets. Such a solution is usually forbidden by rigid or stress-free boundary conditions applied in $z$-direction.

The degeneration of our formulation manifests itself in the fact that the exponentially growing modes (2.9) are exact solutions of the nonlinear problem. One consequence is that the statistically steady turbulence state is difficult to achieve starting from arbitrary initial conditions if one uses a square computational box and low resolution $32^3$ (high viscosity). The modes (2.9) grow and the other modes are dissipated before the nonlinear interaction becomes able to establish an effective energy transfer. Even in the case of an elongated box we had to start the calculations using the full resolution.

Another consequence of the degeneration described above is that the calculations with strong magnetic field do not provide physically reasonable solutions. If the magnetic interaction parameter $N$ is large and the flow approaches a kinematically two-dimensional state in accordance with [8], the modes (2.9) become dominating since they are not affected by the Joule dissipation and the efficiency of the nonlinear energy transfer is poor in a two-dimensional flow at moderate Reynolds number. Therefore, the case $N \gg 1$ was not considered.
3 Numerical experiments

Two numerical runs were performed. Numerical resolution was $64^2$ functions in horizontal plane and 256 functions in vertical direction. The kinematic viscosity was $\nu = 0.027$ in both cases. This corresponds to the Rayleigh number (2.8) $Ra \approx 1.37 \times 10^7$. The initial conditions at $t = t_0$ were common for both runs and presented the developed turbulent flow obtained in the result of calculations without magnetic field starting from arbitrary initial conditions and lasting several turnover times $\tau_{tu}$. In the first run the magnetic field was switched on at $t = t_0$ and remained constant till the end of calculations, the initial value of the magnetic interaction parameter (1.4) being $N(t_0) = 2.0$. In the second run, which was performed for comparison, the magnetic field was zero.

Figures 1–4 show the temporal behavior of different integral characteristics of the flow. Corresponding time averages are given in table 1. The averaging was performed using 2000 time points taken with the step 0.05. One can see in figure 1 that the mean energies of the velocity components and temperature perturbations

$$E_i = \frac{1}{2} \langle u_i^2 \rangle, \quad i = 1, 2, 3, \quad E_T = \langle \theta^2 \rangle$$

(symbol $\langle \ldots \rangle$ stands hereafter for the space averaging) are strongly fluctuating with time. These fluctuations described early in [11] are relatively slow. Their typical time scale is of the order of several turnover times $\tau_{tu}$ (it can be seen in table 1 that our time unit is about $2\tau_{tu}$ at $N = 0$ and $3\tau_{tu}$ at $N > 0$). It was also shown in [11] and is discussed below in the present paper that the fluctuations appear in the result of the instabilities of large scale vertical convective jets developing in the flow.
Table 1  Time averages and variances of the integral characteristics of the flow

<table>
<thead>
<tr>
<th></th>
<th>$N = 0$</th>
<th>$\bar{f}$</th>
<th>$\sigma_f$</th>
<th>$N(t_0) = 2.0$</th>
<th>$\bar{f}$</th>
<th>$\sigma_f$</th>
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<tbody>
<tr>
<td></td>
<td>$f$</td>
<td>$u$</td>
<td>$v$</td>
<td>$w$</td>
<td>$\theta$</td>
<td>$N_u$</td>
</tr>
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<td>$u$</td>
<td>1.98</td>
<td>0.25</td>
<td>2.30</td>
<td>0.26</td>
<td>6.21</td>
<td>2.13</td>
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<tr>
<td>$v$</td>
<td>1.97</td>
<td>0.27</td>
<td>2.28</td>
<td>0.25</td>
<td>0.40</td>
<td>0.05</td>
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<tr>
<td>$w$</td>
<td>3.58</td>
<td>0.65</td>
<td>7.47</td>
<td>0.88</td>
<td>2.16</td>
<td>0.42</td>
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<td>$\theta$</td>
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<td>0.42</td>
<td>4.86</td>
<td>0.61</td>
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<tr>
<td>$N_u$</td>
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<td>27.79</td>
<td>7.07</td>
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</tr>
<tr>
<td>$G_1$</td>
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<td>0.40</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G_2$</td>
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<td>0.09</td>
<td>0.36</td>
<td>0.04</td>
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<tr>
<td>$2w^2/(u^2 + v^2)$</td>
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<td>0.87</td>
<td>10.68</td>
<td>1.49</td>
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<td>$L_1$</td>
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<td>0.73</td>
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<td>$L_2$</td>
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<td>$L_3$</td>
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<td>$\epsilon_1$</td>
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<td>4.42</td>
<td>1.62</td>
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<tr>
<td>$\epsilon_2$</td>
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<td>4.26</td>
<td>1.53</td>
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<td>$\mu_1$</td>
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<td></td>
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<tr>
<td>$\mu_2$</td>
<td>3.81</td>
<td>1.05</td>
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<td>4.45</td>
<td>0.92</td>
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</tbody>
</table>

Figure 2  Nusselt number for the flow without (———) and with (— — —) magnetic field

The amplitude of the vertical velocity component is much larger than the amplitudes of horizontal components. This difference becomes more pronounced when the magnetic field is applied because, as can be seen in figure 1 and table 1, the magnetic field increases considerably vertical velocity as well as the amplitude of the temperature perturbations. Obviously, this leads to the growth
of the heat transfer in vertical direction. As an illustration figure 2 and table 1 show the Nusselt number calculated as

\[ Nu = 1 + \frac{H}{\kappa}, \]  

(3.11)

where \( H = \langle u_3 \theta \rangle \) is the mean vertical heat flux. In the case with magnetic field the averaged Nusselt number is about 4.5 times larger than without magnetic field.

The imposed mean temperature gradient as well as the magnetic field leads inevitably to the flow which is anisotropic in a vertical cross-section. The coefficients quantifying the anisotropy are shown in figures 3-4 and table 1. Figure 3 presents the integral length scales in different directions

\[ L_i = \frac{\pi}{2E_i} E_i(0), \quad i = 1,2,3, \]  

(3.12)

where \( E_i(k) \) is an one-dimensional longitudinal spectrum of the velocity component \( u_i \) and \( E_i \) in the denominator is defined by (3.10). In an isotropic case all \( L_i \) must be equal to the integral length scale \( L = \pi/2u^2 \int_0^\infty k^{-1} E(k)dk \) used usually for homogeneous turbulence [12]. One can see in figure 3a and table 1 that in the case without magnetic field the vertical length scale \( L_3 \) is only slightly larger than \( L_1 \) and \( L_2 \). The magnetic field elongates the flow structures in vertical direction decreasing \( L_1 \) and \( L_2 \) and increasing \( L_3 \).

Another way to quantify anisotropy of the flow is to calculate different anisotropy coefficients such as

\[ A = \frac{2E_3}{E_1 + E_2}, \]  

(3.13)

where \( E_i \) are the energies of the velocity components (3.10), and
Figure 4 Anisotropy coefficients for the flow without (-----) and with (-----) magnetic field. (a) Large scale anisotropy coefficient (3.13). (b) Moderate scale anisotropy coefficient (3.14)

\[
G_1 = \frac{\langle (\partial u_2/\partial z)^2 \rangle}{2\langle (\partial u_2/\partial y)^2 \rangle}, \quad G_2 = \frac{2\langle (\partial u_3/\partial z)^2 \rangle}{\langle (\partial u_3/\partial y)^2 \rangle}.
\]  

(3.14)

All three coefficients must be equal to unity in an isotropic flow. The coefficient \(A\), calculated for homogeneous thermal convection in [11], is an estimate of the large-scale anisotropy of the flow. The coefficients \(G_1\) and \(G_2\) were used in [6], [8] to follow the damping of vertical velocity gradients by the Joule dissipation and can be considered as characteristics of the anisotropy at smaller scales. \(G_1\) and \(G_2\) must be zero in a purely two-dimensional flow independent of \(z\)-coordinate.

One can see in figure 4a that even the flow without magnetic field possesses considerable anisotropy at large scales. The time-averaged value \(\bar{A} = 3.34\) is in agreement with [11] where \(\bar{A}\) varied with numerical resolution between 2.7 and 3.9. The coefficients \(G_1\) and \(G_2\) demonstrate for this flow a moderate degree of anisotropy at smaller scales. In the presence of the magnetic field both \(A\) and \(G_1, G_2\) change considerably implying the substantial growth of anisotropy at large and moderate scales. On the other hand, the magnetic field is clearly not strong enough to dissipate all the vertical gradients and the flow remains three-dimensional.

During the numerical runs the time-averaged two-dimensional energy distributions \(E(k,\phi)\), \(E_T(k,\phi)\) were calculated. Here \(E(k,\phi)\) and \(E_T(k,\phi)\) correspond to the energies of velocity and temperature perturbations contained in the Fourier modes with \(|k| = k\) and the angle between \(k\) and the \(z\)-axis equal to \(\phi\). The results are partly shown in figure 5.

Figure 5a presents the wavenumber spectra obtained by integration of \(E(k,\phi)\), \(E_T(k,\phi)\) over \(\phi \in [0,\pi/2]\). One can see that the magnetic field does not change greatly the velocity and temperature spectra. Our resolution is too poor to make any reliable conclusions about the inertial range scaling. We can only
Figure 5  (a) Wavenumber spectra and (b) angular distributions (3.15) of the velocity ($E, \Phi$) and temperature ($E_T, \Phi_T$) perturbations. ———, flow without magnetic field; ———, flow with magnetic field.

state that in a region near $4 < k < 10$ the velocity spectra are approximated to some degree by $k^{-5/3}$ which is in agreement with the retention of three-dimensionality of the flow $^1$. The spectra $E_T(k)$ of the temperature fluctuations are much steeper than $E(k)$. What is more, they are steeper than $k^{-4}$ in whole range of $k$. This seems to be in agreement with the theoretical predictions and experimental data relevant for our case of small Prandtl number and moderate Rayleigh number. The experiments [13] with sodium ($Pr \approx 5 \times 10^{-3}$) provided scaling $E_T \sim k^{-3.96}$. For a theoretical explanation we can use a classical Kolmogorov-Oboukhov phenomenology and estimate the so-called conductive (diffusive) wavenumber $k_c$ for the temperature spectrum (see e. g. [14]). At $Pr < 1$ the estimation is $k_c \sim Pr^{3/4}k_d$, where $k_d$ is Kolmogorov dissipative wavenumber. In our calculations the estimation gives $k_c$ between 1 and 2 and we can conclude that the temperature spectrum consists of inertial-conductive (at small $k$) and viscous-conductive (at larger $k$) ranges. For the former, the classical scaling is $E_T(k) \sim k^{-4}E(k)$.

The angular energy spectra are shown in figure 5b. Instead of the angular distributions

$$E(\phi) = \int_0^\infty E(k,\phi)dk$$

we use the integrals

$$\Phi(\phi) = \int_0^\phi E(\lambda)d\lambda \quad (3.15)$$

$^1$ It was shown in [8] that in the two-dimensional flow developing under the influence of a strong magnetic field at moderate Reynolds number the velocity spectrum is even steeper than $k^{-3}$. 

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corresponding to the total energy of the modes contained in the cone of vertical axis and semiangle $\phi$. In a purely two-dimensional flow independent of the $z$-coordinate this spectrum becomes

$$\Phi(\phi) = \begin{cases} E & \text{at } \phi = \pi/2 \\ 0 & \text{at } \phi < \pi/2 \end{cases}.$$ 

On the contrary, in an isotropic flow, $\Phi(\phi)$ is a linear function of $\phi$. The angular velocity spectra for the flow without magnetic field shown in figure 5b confirm the conclusion drawn above using the anisotropy coefficients. The flow is anisotropic, with the energy concentrating in the modes with wavenumber vectors in horizontal plane. This concentration is visibly enhanced by the applied magnetic field. Very interesting are the angular spectra of the temperature perturbations. One can see that the deviation from the isotropic form is much more pronounced for the temperature than for the velocity field. This can be related to the fact that, according to the wavenumber spectra, the energy of temperature perturbations is more concentrated in the large scale modes and the anisotropy is stronger at these scales.

Additional information can be drawn from the mean viscous ($\epsilon_i$) and magnetic ($\mu_i$) dissipations calculated for each velocity component. The time averages of $\epsilon_i$ and $\mu_i$ are given in table 1. One can see that the relative dissipations $\epsilon_i/E_i$ and $\mu_i/E_i$ of the vertical velocity component are much smaller than the corresponding values for the horizontal velocity components. This can be explained using the analysis of two-dimensional spectra. The difference between the value of $E_3$ on one hand and values of $E_1$, $E_2$ on the other hand is mostly due to the presence of modes (2.9) in the vertical velocity component. Clearly, the magnetic dissipation is zero and viscous dissipation is very small for these modes.

It is known (see e. g. [15]) that there is an exact relation between the mean heat flux and mean viscous dissipation expressing the energy balance in the Boussinesq equation. In our case this relation can be rewritten as

$$(Nu - 1)\kappa = \sum_i \epsilon_i + \mu_i. \quad (3.16)$$

Simple calculations demonstrate that (3.16) is satisfied by the time averages in table 1 with the accuracy within 5%. Taking into account the variances shown in table 1 this seems to be a good accuracy.

The spatial structure of the flow was analyzed using the snapshots of the vorticity and temperature fields. The main conclusion is in full agreement with [11]. The flow dynamics is determined by the evolution of two vertical jets. One jet is ascending and hot and another is descending and cold. An illustration is presented in figure 6 where the snapshots of the temperature field are shown using the isosurfaces of the temperature perturbations $\theta$. 

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As was mentioned above the modes (2.9), which are the main participants of the formation of the jets are exponentially growing exact solutions of the basic equations (2.5–2.7). The viscous dissipation alone is not able to damp this growth created by the buoyancy force. The only mechanism that can prevent the full solution from the exponential growth is the nonlinear energy transfer manifesting itself as the inherent instability of the jets. The instability leads to their bending (see figure 6a) and, from time to time, to disintegration. This process is responsible for the fluctuations of flow energy, heat flux and other integral characteristics shown in figures 1–4.

It can be seen when comparing figures 6a and 6b that the applied vertical magnetic field stabilizes the jets. This is clearly due to the additional Joule dissipation acting primarily on the modes with $k \parallel B_0$, that is on the modes responsible for the instability.
4 Concluding remarks

We have studied the influence of a uniform vertical magnetic field $B_0$ on the homogeneous turbulent convection driven by a mean temperature gradient directed parallel to $B_0$. The utilization of the quasi-static approximation and the assumption of spatial homogeneity allowed to reduce the problem to an extremely simple model that can be easily treated numerically. On the other hand, the use of periodic boundary conditions introduces a degree of ambiguity into the formulation. We can only assume that the model is appropriate for real flows such as, for example, the convective flow in a long vertical cavity heated from below.

The part of our results concerning the flow without magnetic field is in full agreement with [11]. The flow consists primarily of the two vertical jets, one ascending and another descending, accelerated by the buoyancy force and subject to the jet instability. The jets provide an effective mechanism for the generation of the mean heat flux in vertical direction. The flow is anisotropic, especially at large scales. Its integral characteristics fluctuate strongly with time as the jets disintegrate and reappear.

The main conclusions concern the influence of a constant vertical magnetic field on the flow. Additional Joule dissipation tends to eliminate vertical velocity gradients and, thus, to stabilize the jets. This leads to increase of the amplitudes of vertical velocity component and temperature perturbations. As a result, mean heat flux grows substantially. The jets are elongated in vertical direction, their typical horizontal scale decreasing and vertical scale increasing. The flow becomes more anisotropic but remains turbulent and three-dimensional.

The last conclusion is especially interesting when being compared with the results of [8]. Considering the homogeneous turbulence with an artificial forcing it was found that at moderate Reynolds number there are three types of the evolution of an initially isotropic flow under the influence of a constant magnetic field. The flow remains three-dimensional, turbulent and approximately isotropic if the magnetic interaction parameter $N \ll 1$, transforms into purely two-dimensional steady state if $N \gg 1$, and has temporarily intermittent two-dimensional, laminar — three-dimensional, turbulent behavior at an intermediate value of $N$. The results of the present work demonstrate the realization of another scenario proposed early in [5]. The flow becomes highly anisotropic but remains three-dimensional and turbulent, and retains a statistically steady level of the anisotropy.

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