IOPscience iopscience.iop.org

Home Search Collections Journals About Contact us My IOPscience

Parametric modulation of thermomagnetic convection in magnetic fluids

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2008 J. Phys.: Condens. Matter 20 204135

(http://iopscience.iop.org/0953-8984/20/20/204135)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 129.252.86.83
The article was downloaded on 29/05/2010 at 12:01

Please note that terms and conditions apply.

IOP PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **20** (2008) 204135 (5pp) doi:10.1088/0953-8984/20/20/204135

Parametric modulation of thermomagnetic convection in magnetic fluids

H Engler and S Odenbach

Chair of Magnetofluiddynamics, Technische Universitaet Dresden, Dresden 01062, Germany

E-mail: harald.engler@tu-dresden.de

Received 22 November 2007, in final form 26 February 2008
Published 1 May 2008
Online at stacks.iop.org/JPhysCM/20/204135

Abstract

Previous theoretical investigations on thermal flow in a horizontal fluid layer have shown that the critical temperature difference, where heat transfer changes from diffusion to convective flow, depends on the frequency of a time-modulated driving force. The driving force of thermal convection is the buoyancy force resulting from the interaction of gravity and the density gradient provided by a temperature difference in the vertical direction of a horizontal fluid layer. An experimental investigation of such phenomena fails because of technical problems arising if buoyancy is to be changed by altering the temperature difference or gravitational acceleration.

The possibility of influencing convective flow in a horizontal magnetic fluid layer by magnetic forces might provide us with a means to solve the problem of a time-modulated magnetic driving force. An experimental setup to investigate the dependence of the critical temperature difference on the frequency of the driving force has been designed and implemented. First results show that the time modulation of the driving force has significant influence on the strength of the convective flow. In particular a pronounced minimum in the strength of convection has been found for a particular frequency.

1. Introduction

Thermal convection in a horizontal fluid layer develops if a temperature difference in the vertical direction exists. The temperature gradient causes a density gradient in the fluid layer, since the density of a fluid depends on temperature. Therefore a vertical temperature gradient ∇T gives rise to a density gradient $\nabla\rho$ antiparallel to ∇T. A fluid element moved adiabatically from the bottom to the top of the gap has a density different from that of the surrounding fluid. Due to the density difference between the fluid element and the surrounding fluid the fluid element feels a force in the direction of the initial movement. This resulting buoyancy force has a force density given by $f_b = g\rho$. The direction and the strength of the buoyancy force depend directly on the direction and the magnitude of the applied temperature difference. If a horizontal fluid layer is cooled from below, the buoyancy force acts as a stabilizing force on the system, and therefore no convective flow arises for any applied temperature difference. The direction of the buoyancy force changes if the fluid is heated from below. In this situation the buoyancy force acts as a destabilizing force on the system. The status of the fluid layer can be described by the dimensionless Rayleigh number Ra, which is given by

$$Ra = \frac{\beta_T g\rho\Delta T d^3}{\kappa\eta} \quad (1)$$

where ΔT denotes the temperature difference over the height of the fluid layer d, g the acceleration of gravity, and β_T, ρ, κ and η the thermal expansion coefficient, the density, the temperature conductivity, and the dynamic viscosity of the fluid respectively. If Ra exceeds a certain critical value heat transfer will change from conduction to thermal convection. The critical Rayleigh number depends on the thermal and geometric boundary conditions of the system. For a horizontal fluid layer heated from below and contained within rigid boundary plates of high heat conductivity like copper, the critical Rayleigh number is 1708 [1].

The main aim of this work is to investigate the influence of a time-modulated driving force on the convection and the critical Rayleigh number. The required frequency of the driving force, where the most prominent effects are expected, depends on the geometry of the system and the fluid properties, providing the characteristic momentum diffusion time [2], which is given by $\tau = d^2/\nu$. This characteristic time and therefore the critical frequency of our system is approximately 3 Hz.

 © 2008 IOP Publishing Ltd Printed in the UK

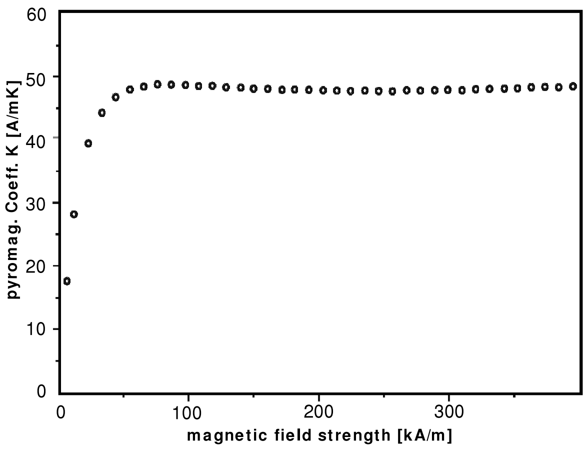

Figure 1. Pyromagnetic coefficient.

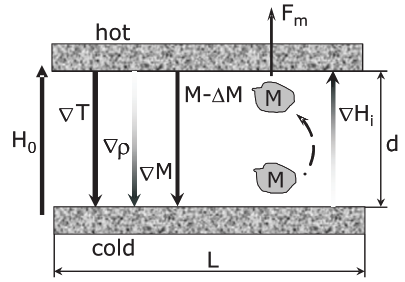

Figure 2. Sketch of the explanation of thermomagnetic convection. Further explanations are given in the text.

A change of driving force for thermal convection can principally be achieved by altering either the temperature difference or the gravitational acceleration. Previous studies investigated theoretically the critical Rayleigh number of a horizontal fluid layer heated from below and subjected to a time-modulated driving force [3–5]. If an additional time-dependent temperature perturbation were applied to the plate temperatures, the temperature difference in the system would change accordingly, leading to a time-dependent buoyancy force. The disadvantage in a thermal system is that the characteristic times for temperature changes are too large to enable respective experiments, since the required frequency of the driving force exceeds the maximum possible frequency of the temperature variations. A second possibility would be a modulation of gravitational acceleration. The gravity force could be modulated by moving the experimental setup up and down with the required acceleration and amplitude. However, the technical requirements for an experimental setup capable of providing the necessary acceleration and the amplitude hinder a practical realization of this idea.

A way out of these experimental difficulties is the use of magnetic fluids subjected to a magnetic field. Magnetic fluids, also called ferrofluids, are suspensions of magnetic monodomain particles in an appropriate carrier liquid. The ferrofluid can be magnetized by an external magnetic field, aligning the magnetic particles with the direction of the magnetic field. The strength of magnetization depends on the applied magnetic field strength and on the fluid's temperature [6]. The magnetization of the ferrofluid increases with an increase of the applied magnetic field and decreases with an increase of the fluid temperature. The relation between the magnetization of the fluid and the fluid temperature is described by the pyromagnetic coefficient $K = -\frac{\partial M}{\partial T}|_H$. The pyromagnetic coefficient can be determined by measuring the magnetization curve for different fluid temperatures. Figure 1 shows the pyromagnetic coefficient as a function of magnetic field strength. For the further argumentation, a horizontal ferrofluid layer within two rigid boundary plates, cooled from below and heated from above is considered, see figure 2. Additionally a magnetic field H_0 parallel to the temperature gradient is applied. Due to the temperature gradient in the fluid gap, the magnetization of the ferrofluid shows a gradient parallel to ∇T. The inner magnetic field H_i, within the fluid gap, is given by $H_i = H_0 - DM$. The magnetization factor D approaches 1 if the length L of the experimental setup is much larger than the thickness d. Therefore an inner magnetic field gradient, given by $\nabla H_i = -D\nabla M$ arises which is antiparallel to the magnetization gradient of the fluid.

If a fluid element has been adiabatically moved from the bottom to the top of the gap, a magnetization difference between the fluid element and the surrounding fluid exists. This difference of magnetization leads, in the presence of the gradient of the inner magnetic field, to an additional magnetic force with a force density $f_m = \mu_0 M \nabla H$. The magnetic force acts in the same direction as the initial movement, so that it provides a destabilization of the fluid layer.

This magnetic force is thus able to drive a convective flow, called thermomagnetic convection, which is only controlled by the external magnetic field. As for thermal convection the status of the fluid layer is characterized by a dimensionless parameter, the magnetic Rayleigh number

$$Ra_m = \frac{\mu_0 K \nabla H \Delta T d^3}{\kappa \eta} \quad (2)$$

where ∇H denotes the field gradient, μ_0 vacuum permeability, K, κ, and η the pyromagnetic coefficient, the temperature conductivity, and the dynamic viscosity of the fluid respectively.

This kind of heat and mass transfer phenomena in a ferrofluid was theoretically investigated by Finlayson [7] and experimentally reviewed by Schwab [8]. Both works consider the case where both the magnetic and the buoyancy mechanism are working simultaneously. For a horizontal fluid layer the thermal Rayleigh number and the magnetic Rayleigh number can be summed up to a total Rayleigh number Ra_{tot}, which is given by $Ra_{tot} = Ra + Ra_m$.

Obviously a time-modulated driving force for the coupled system can be generated by a temporal variation of Ra_m using a time-modulated magnetic field $H(t)$.

2. Experimental setup

The magnetic field necessary to generate the magnetic force in our experiment is produced by two pairs of coils placed in a Fanselau arrangement. The magnetic field is directed

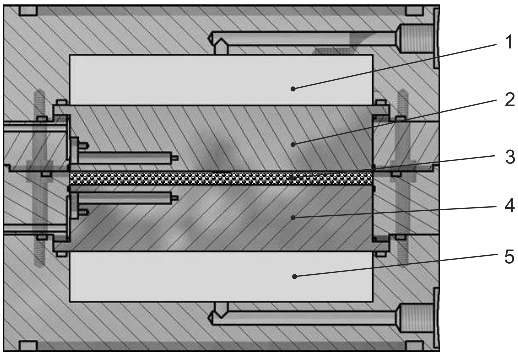

Figure 3. Technical sketch of the fluid cell for the convection experiments with the positions of the two thermistors placed closest to the fluid surface shown in the cut: (1) T_1 (temperature chamber); (2) copper plate containing the temperature sensor; (3) gap filled with ferrofluid; (4) copper plate; (5) T_2 (temperature chamber), where $T_1 < T_2$.

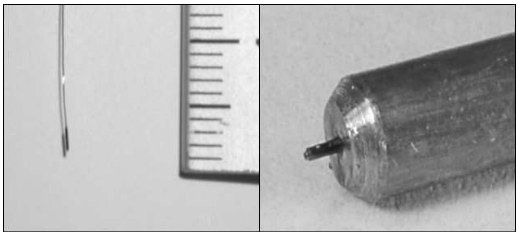

Figure 4. Thermistor fastening (right) and its geometrical dimension (left). The copper cylinder with the sensor is fixed in the copper plate.

perpendicular to the horizontal fluid layer and its homogeneity in the center of the coils is better than 0.5% in the horizontal direction and better than 0.1% in the vertical direction. This homogeneity is valid for a vertical range of 10 mm. In the useable area for experiments (300 mm in diameter), it is possible to produce a magnetic field with a strength of up to 25 kA m^{-1}. To provide the required frequencies between 0 and 5 Hz, a frequency synthesizer connected to the coil arrangement is used.

The lower part is symmetric to the upper part of the actual measuring cell with respect to the horizontal gap which can be filled with fluid (see figure 3). The gap has a height of 4 mm and a diameter of 88 mm leading to an aspect ratio of 22. For an aspect ratio larger than 15, the influence of the vertical boundaries on the heat flux phenomena in the gap is insignificant [9]. The gap is bounded by two horizontal copper plates, a material which has a heat conductivity of 378 W K^{-1} m^{-1}. This high heat conductivity makes it possible to measure a time-dependent temperature progress in the copper plates driven by the additional heat flux due to the time-modulated magnetic force. Furthermore, the high heat conductivity equalizes temperature differences on the surface and within the copper plates influenced by the temperature distribution of the convective flow. Three temperature sensors are located at different vertical positions within one of the copper plates (see figures 3 and 4). One of these sensors is placed as near as possible to the boundary between the copper and fluid layer in order to measure the variation of temperature in time driven by the additional heat flux due to the time-dependent magnetic force.

Thermistors with negative temperature coefficient are used to measure the temperature inside the copper plate. The basic resistance of the thermistors at a temperature of 20 °C is 20 kΩ and they have a response time of 30 ms. The sensitivity of the thermistors is 2000 Ω/1 °C, so that the temperature resolution is quite high, if a normal resistance measurement with a typical resolution of 1 Ω is used. The thermistors have a diameter of 0.38 mm and a length of 1.38 mm. They are contained in a glass cylinder and the cables for the data transmission are isolated.

To generate the temperature difference over the fluid gap two temperature chambers are located above and below the copper plates. Tempered water with a temperature stability of 0.01 K flows through the chambers. It is possible to generate a maximum temperature difference of 65 K over the gap.

For the investigations of the relation between a time-modulated driving force and a convective flow, a commercial ferrofluid APG 513A from the company Ferrotec is used. The magnetic material is magnetite (7.2 vol%) and the carrier liquid is a synthetic ester. The saturation magnetization is 34 kA m^{-1}. The pyromagnetic coefficient K is 42 A m^{-1} K^{-1} for the maximum possible field strength of 25 kA m^{-1}. Further fluid properties are the thermal expansion coefficient $\beta_T = 8.6 \times 10^{-4}$ K^{-1}, the temperature conductivity $\kappa = 5 \times 10^{-8}$ ms^{-1} and the dynamic viscosity $\eta_{(T=20\,^\circ\mathrm{C})} = 170$ mPa s.

3. Experimental results

As a first test we have measured the heat flux through the system as a function of the applied temperature difference ΔT for a fluid layer heated from below. In this situation the magnetic force will support convection driven by the buoyancy [7]. Without an applied magnetic field the heat flux increases with an increase of ΔT and by passing the critical temperature difference the heat flux changes from diffusion to convective flow. In this case the convective flow is driven only by the buoyancy force. To increase the temperature difference in the gap, the temperature on the bottom and the top have been changed stepwise by 1 K symmetrically, so that the mean temperature in the gap could be kept constant at 40 °C. The change from conduction to convection is seen in figure 5 as a change of the slope of heat flux with temperature difference. This change of slope provides a direct measure of the critical temperature difference. If the maximum possible field strength of our system, which is 25 kA m^{-1}, is applied, the critical temperature difference decreases, due to the additional driving force induced by the magnetic field. For a magnetic field strength of 25 kA m^{-1} the critical temperature difference is $\Delta T = 19$ K and for zero magnetic field it is $\Delta T = 32$ K. After this first test a temperature difference on the system has been applied in the range, where a convective flow is already established. The magnetic field has been modulated with a rectangular profile. The driving force, following the magnetic field modulation, develops a time-dependent additional heat flux and therefore a time-dependent temperature variation T_n

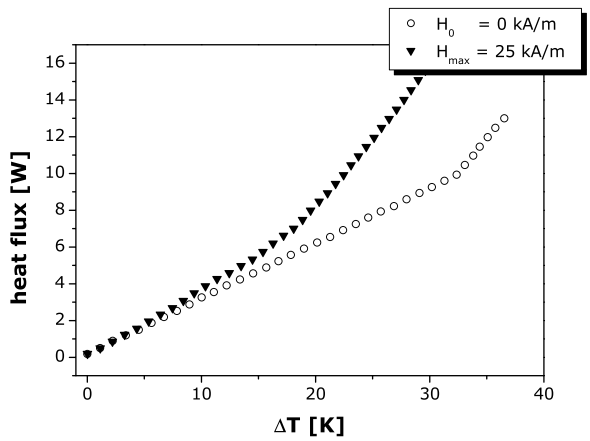

Figure 5. The figure shows the heat flux through the fluid gap for $H_0 = 0$ kA m^{-1} and $H_{max} = 25$ kA m^{-1}.

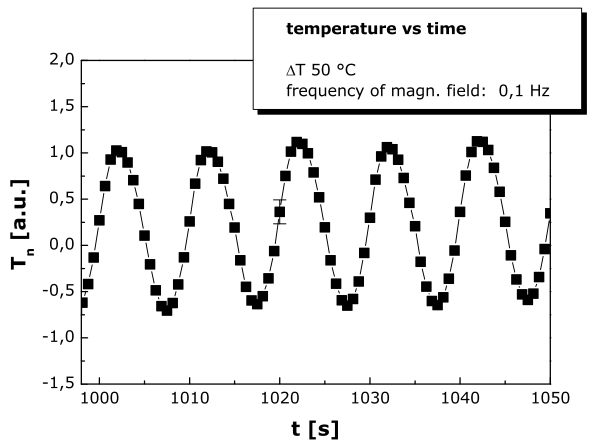

Figure 6. Temporal development of the temperature in the upper bounding plate.

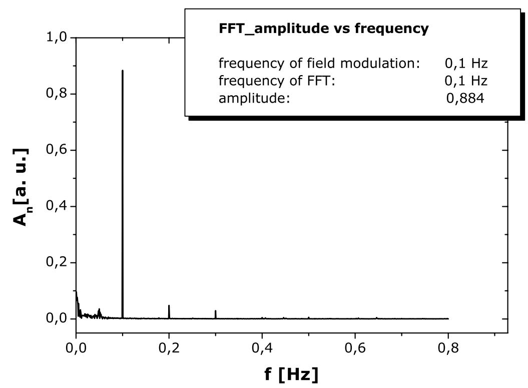

Figure 7. Typical result of the fast Fourier transformation (FFT) of the temperature signal in the copper plate shown in figure 6.

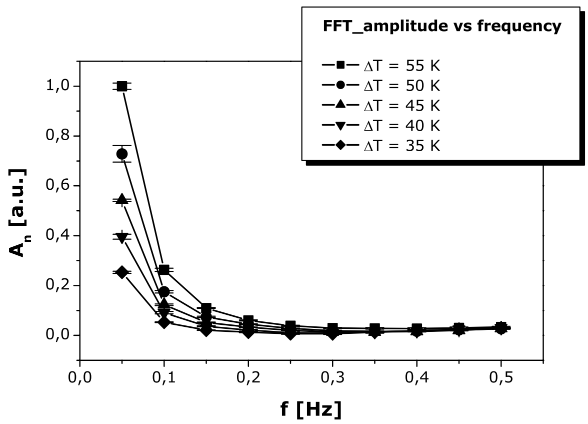

Figure 8. Amplitude, analyzed by the FFT, versus frequency of the driving force.

in the copper plate. The temporal evolution of T_n measured by the thermistor in the upper plate is shown in figure 6.

The curve shows a sinusoidal shape following the magnetically induced heat flux. The signal of T_n for high temperature differences or for low frequencies of the driving force can be measured accurately, providing the possibility to determine the amplitude of the temperature variations—which is a measure for the variation of the strength of convection—directly. But for low temperature differences or high frequencies the signal is much weaker and a direct analysis is almost impossible. For that case, a fast Fourier transformation (FFT) is used to analyze the temperature variations in the copper plate. Figure 7 shows the typical result of the FFT corresponding to figure 6. The height of the main peak in figure 7 represents the amplitude A_n of the temperature variation. This amplitude A_n of the FFT is used as an indicator for the strength of the convective flow. The main peak in the FFT also expresses the frequency of the temperature variations in figure 6, which corresponds directly to the magnetic field modulation.

Finally we have measured the amplitudes T_n as a function of the frequency of the driving force, the temperature difference ΔT, and the magnetic field strength H. In figure 8 the full range of amplitudes is shown, documenting that A_n decreases with increasing frequency of the driving force. That behavior can be explained by the fact that the time to build up the temperature progress in the copper plate becomes shorter with higher frequencies. Furthermore figure 8 shows that the level of the measured amplitudes decreases with decreasing temperature difference ΔT. This is easily understood by the fact that decreasing ΔT leads to a general decrease of the strength of the convective flow.

Figure 9 shows a more detailed view of the diagram in figure 8. Here we can see that the amplitudes A_n show a pronounced minimum at a distinguished frequency which moves to lower values with a decrease of the temperature difference. The frequency at which minima appears is in the range of 0.3 Hz.

4. Conclusion

For the investigations of a time-dependent convective flow in a horizontal ferrofluid layer, an experimental setup to measure the temperature variations in the fluid layer has been designed. A thermistor is used to measure the temperature variations in the copper plate. The sensitivity of the thermistors

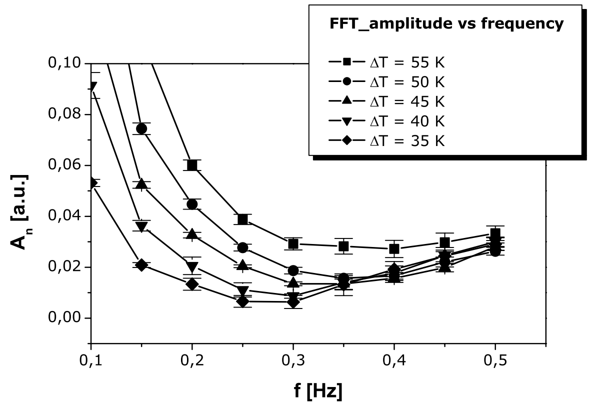

Figure 9. More detailed view of figure 8. Minima of the amplitudes analyzed by the FFT for different temperature differences are shown.

is high enough to enable sufficiently precise temperature measurement. With a Fanselau arrangement a magnetic field with a strength of up to 25 kA m^{-1} can be applied.

The experimental results, presented here, have shown that the temperature variation in the bounding copper plate takes place with the frequency of the magnetic field. Further, the amplitudes A_n of the temperature variations depend on the frequency of the driving force and they decrease with an increase of the frequency. The amplitudes A_n, and therefore the strength of the convective flow, reach a minimum for a certain value of the frequency. Furthermore it is observed that the minima of the amplitudes A_n move to lower frequencies with decreasing temperature difference.

In the future the experimental setup will be modified to enable a direct measure of the heat flux through the system. This will allow us to measure the critical temperature difference as a function of the frequency of the driving force and the magnetic field strength and thus the critical Rayleigh number.

Acknowledgments

We are grateful to Professor M Luecke (Universitaet des Saarlandes) for enlightening discussions. Financial support by Deutsche Forschungsgemeinschaft (DFG) under grant Od18/7-1 and by DLR 50 WM 0639 which provided the basis for our investigations is gratefully acknowledged.

References

[1] Chandrasekhar S 1961 *Hydrodynamic and Hydromagnetic Stability* (London: Oxford University Press)
[2] Donnelly R J 1964 *Proc. R. Soc.* A **281** 130
[3] Rosenblatt S and Tanaka G A 1971 *Phys. Fluids* **14** 1319–22
[4] Venezian G 1969 *J. Fluid Mech.* **35** 243
[5] Gresho P M and Sani R L 1970 *J. Fluid Mech.* **40** 783806
[6] Rosensweig R E 1985 *Ferrohydrodynamics* (New York: Cambridge University Press)
[7] Finlayson B A 1970 *J. Fluid Mech.* **40** 753
[8] Schwab L 1989 Konvektion in ferrofluiden *Dissertation* LMU Muenchen
[9] Roche P E, Castain B, Chaband B and Hebral Sommeria J 2001 *Side Wall Effects in Rayleigh–Benard Experiments* (Heidelberg: Springer)