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AN ANALYSIS OF THERMO-MAGNETIC CONVECTION OF PARAMAGNETIC FLUID IN RECTANGULAR ENCLOSURE

Abstract

The thermo-magnetic convection of paramagnetic fluid in a strong magnetic field is studied. The fluid is aqueous solution of glycerol with gadolinium nitrate hexahydrate. Experimental enclosure – rectangular vessel with aspect ratio equal to 2 – was heated from the bottom, and cooled from the top. Temperature difference between top and bottom walls was kept constant ΔT=5K. The magnetic induction was increased stepwise from 1 to 10 [T]. On the basis of temperature measurements, analysis of heat transfer and fluid flow were performed, showing that magnetic field strongly enhance heat transfer (over 300%) and that aspect ratio of the enclosure has a great influence on heat exchange in the system.

Key words

thermo-magnetic convection, strong magnetic field, experimental analysis, paramagnetic fluid

Introduction

Natural convection processes include tremendous number of situations in industrial, astrophysical and environmental applications. In all cases, controlling convection processes is a very important aspect. However, before concepts for convection control can be applied to real systems, they need to be studied fundamentally and experimentally. Fluids, in terms of magnetic properties, can be characterized as follows: diamagnetics (i.e. water), paramagnetics (i.e. air) and ferromagnetics (i.e. cobalt, nickel, iron), and so one of the ways to control natural convection is by applying a strong magnetic field to the system. Due to technological progress, it became possible to build strong superconducting magnets with relatively low costs which allowed to study the influence of strong magnetic field on non-ferromagnetic fluids. Ever since, enhancement or suppression of convection phenomena with strong magnetic field, and so the betterment of heat and mass transfer, have been a research topic for many researchers. In 1991 Braithawaite [1] used the magnetic field to both enhance and suppress the Rayleigh-Benard convection in a paramagnetic solution, and showed that the effect depends on the orientation of the magnetic force and temperature gradient. Tagawa [2] developed a simple model equation to thermo-magnetic convection. Bednarz [3] studied numerically and experimentally the influence of the magnetic field on a convection processes in a system with one side wall heated, and the opposite one cooled. Fornalik [4] studied effects of magnetic field influence on natural convection in thermosyphon-like configurations. Pyrda [5] studied thermo-magnetic convection in transient and turbulent flow regimes. Also, new studies are carried out in the field concerning use of nanofluids as magnetic fluids [6]. Phenomena related to the magnetic field and its effect on convection processes have found applications in biology [7], chemistry [8], [9], medicine [10], [11] and engineering [12]–[14].

Turan [15] performed two-dimensional simulations of laminar natural convection in systems with different aspect ratios (AR=height/width) and concluded that aspect ratio is a very important parameter in heat transfer analysis. But in the literature there is no available experimental data about the influence of experimental enclosure aspect ratios on thermo-magnetic convection. Considering that Authors have access to a superconducting magnet (up to 10T) and that efficient heat exchange corresponds to lower costs, Authors took on the challenge of testing the effect of the enclosure AR on thermo-magnetic convection and heat transfer. Obtained results can be used as a first step in development of cooling technologies utilizing magnetic field influence on the heat transfer.

Experimental set-up

The experimental apparatus is shown in Fig.1. and was composed of five elements: two copper plates (one for the cooled top, second one for the heated bottom), a rectangular cavity made from Plexiglas, and cooling and heating chambers. The rectangular cavity, of dimensions height d=64mm, width a=32mm, had six holes, where six T-type thermocouples was inserted. The bottom copper plate was heated with nichrome wire connected to a DC power supply. The electric voltage and current of the nichrome wire were measured with a multi-meter. Top plate was cooled by cold water running from a thermostat. Temperature of heated and cooled copper plates was measured with six T-type thermocouples inserted into small holes in each plate. The experimental apparatus was positioned in the superconducting helium free magnet shown in Fig. 2. (HF10-100VHT-B, *Sumito Heavy Industries,* Ltd. Japan), which can generate magnetic induction up to 10 T. The position of the enclosure along the magnet axis was chosen in the upper half of the bore, where the gravitational and magnetization forces acted in the same direction, causing enhancement of the heat and mass transfer, shown in Fig. 3.

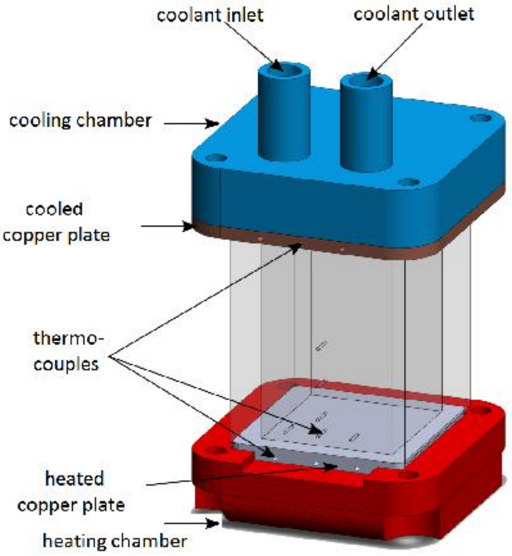


Fig. 1. Experimental enclosure
Source: Author's

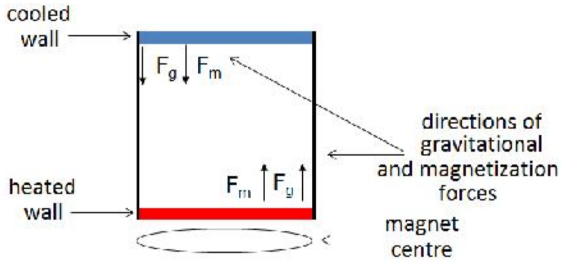


Fig. 3. Directions of gravitational and magnetization forces
Source: Author's

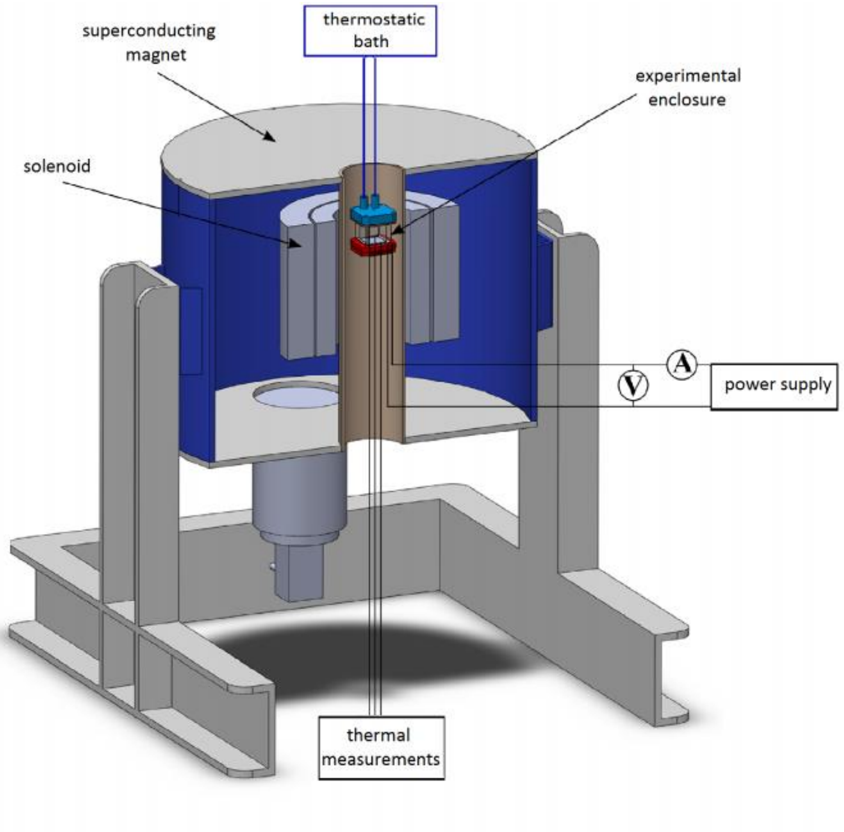


Fig. 2. Experimental setup and location of a rectangular enclosure in the magnet
Source: [5]

The enclosure was filled with 50% volume aqueous solution of glycerol with the addition of 0,8 mol/(kg of solution) gadolinium nitrate hexahydrate ($Gd(NO_3)_3 \cdot 6H_2O$) to make it paramagnetic. In literature there are research publications concerning the effect of a strong magnetic field on thermo-magnetic convection for systems which aspect ratio equal 1. The fluid for following studies was selected as observed in [5], which gave an opportunity to compare obtained results.

Necessary properties of the fluid were measured: viscosity using Ubbelohde viscometer, density with a pycnometer, magnetic susceptibility with magnetic susceptibility balance by Evan's method. Other properties were taken from [5]. All of the necessary properties are listed in Table 1.

Table 1. Properties of the working fluid at 298 K

Properties	Symbol	Value	Unit
Density	ρ	1418,1	kg/m^3
Dynamic viscosity	μ	$1{,}56 \cdot 10^{-2}$	$kg/m \cdot s$
Kinematic viscosity	ν	$1{,}10 \cdot 10^{-5}$	m^2/s
Thermal conductivity	λ	0,376	$W/m^2 \cdot K$
Thermal expansion coefficient	β	$4{,}13 \cdot 10^{-6}$	1/K
Thermal diffusivity	a	$7{,}55 \cdot 10^{-8}$	m^2/s
Heat capacity	c_p	$2{,}92 \cdot 10^3$	$J/kg \cdot K$
Mass magnetic susceptibility	χ_m	$2{,}58 \cdot 10^{-7}$	m^3/kg
Magnetic susceptibility	χ	$3{,}41 \cdot 10^{-4}$	-
Prandtl number	Pr	146	-

Source: Author's

Experimental procedure

Experimental procedures were started by estimating heat losses in the system. This was done by placing the enclosure, filled with water, at the predetermined position, but the vessel was rotated 180 degrees, so the cooled wall was at the bottom, and the heated one at the top. Such placement allowed to reach the conductive state in the system (stratification), with no fluid movement. After setting the temperature difference between top and bottom wall and waiting sufficiently long for the system to stabilize, linear temperature distribution was achieved and heating power was measured. Assuming a one-dimensional conductive heat flow in the fluid (with no fluid movement), the heat flux can be calculated from the Fourier's law. Thus, the difference between directly measured heat flux on the heated wall and heat flux calculated from Fourier's law is the heat loss in the system, which is presented in Fig. 4.

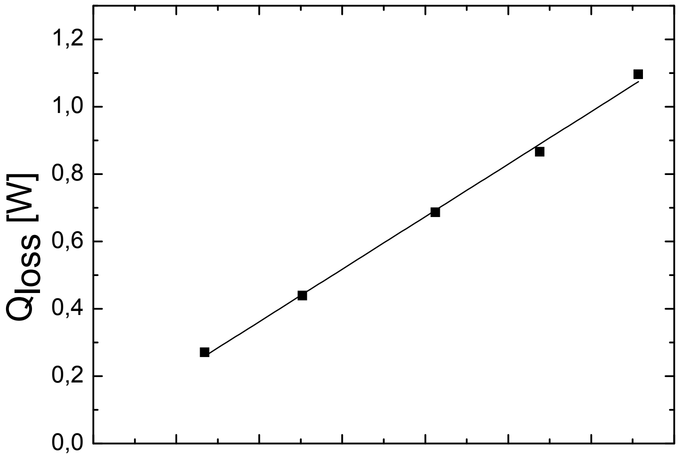


Fig. 4. Heat loss at several temperature differences
Source: Author's

Then main experiment was conducted. With enclosure filled with paramagnetic fluid and positioned with the bottom wall heated, the power supply was set to obtain chosen temperature difference between top and bottom walls (~ΔT=5K). The enclosure was left to acquire the stable state. After this was achieved, temperature, electric current and voltage were recorded. Then, magnetic field was applied to the system by stages of 1 T, from 1 up to 10 T. At each step, the electric current and voltage had to be corrected to keep constant temperature, and the system had to reach stable state. As previously, after thermal stabilization was obtained, temperature signal was recorded.

Flow structure analysis

In the analysis of turbulent transport mechanisms a very useful tool is a spectral analysis of a scalar field. With an assumption that the turbulence is homogenous, spectral functions can be calculated with the utilization of Fast Fourier Transform (FFT). In general, temperature spectral functions depend on the energy dissipation, thermal diffusivity, kinematic viscosity and temperature. But in some ranges, spectral function does not depend on the diffusion, and so does not rely on kinematic viscosity and thermal diffusivity. This range is called inertial-convective [16] and the spectral function has an inclination of wave number with -5/3 exponent. In cases when thermal diffusivity becomes more significant, the spectral function has an inclination of reverse wave number, and this range is called viscous-diffusive [16].

Heat transfer analysis

A criterion speaking of heat transfer in the system is a dimensionless Nusselt number, which can be written as follows:

$$Nu \,\mathrm{X} \frac{\dot{Q}_{net\_conv}}{\dot{Q}_{net\_cond}} \tag{1}$$

The net conduction (Q_{net_cond}) and net convection (Q_{net_conv}) heat fluxes were estimated by the method proposed by Churchill and Ozoe [17], which is based on following formulas:

$$\dot{Q}_{net\_cond} \,\mathrm{X} \dot{Q}_{cond} \,\mathrm{Z} \dot{Q}_{loss} \tag{2}$$

$$\dot{Q}_{net\_conv} \,\mathrm{X} \dot{Q}_{conv} \,\mathrm{Z} \dot{Q}_{loss} \tag{3}$$

As previously said, it was assumed that the heat loss depends only on the temperature of the heated wall. As a first step to estimate the Nusselt number, conduction measurements were made. The heat losses were estimated from:

$$\dot{Q}_{loss} \,\mathrm{X} \dot{Q}_{cond} \,\mathrm{Z} \dot{Q}_{Fourier's\_law} \tag{4}$$

where

$$\dot{Q}_{Fourier's\_law} \,\mathrm{X} a^{2} \,\mathrm{a}\, \zeta T / d \tag{5}$$

- d - enclosure height 0,064 [m];
- a – enclosure width 0,032 [m];
- λ – thermal conductivity of the fluid [W/m^2·K]
- ΔT – temperature difference between heated and cooled walls [K].

Heat flux was calculated for conduction area of 0,032m x 0,032m. The estimated heat loss was approximated linearly:

$$\dot{Q}_{loss}\ X0,0831\ \zeta T \qquad (6)$$

Applying equations 2, 4 and 5 to equation 1, Nusselt number can be written as:

$$Nu\ X\frac{\dot{Q}_{conv}\ Z\dot{Q}_{loss}}{d\,ª\zeta T} \qquad (7)$$

The convection heat flux (Q_{conv}) is given by the product of current and voltage of the heater supply. The results of determined Nusselt number are presented in Fig. 5.

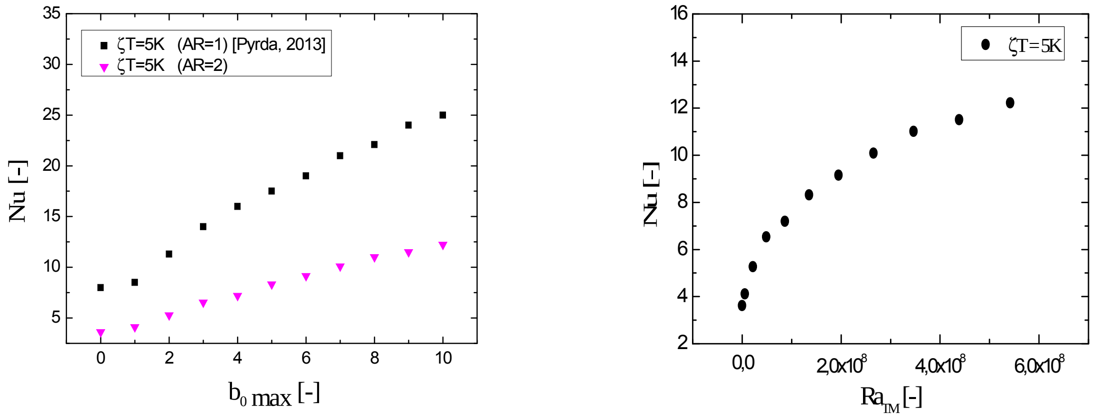


Fig. 5. The Nusselt number versus a) the magnetic induction, b) thermo-magnetic Rayleigh number
Source: Author's, [5]

Results and discussion

The results of heat transfer analysis are presented in Fig. 5. a). The Nusselt number versus thermo-magnetic Rayleigh number is shown in Fig.5.b). Thermo-magnetic Rayleigh number is defined as follows:

$$Ra_{TM}\ XRa_T\ \Gamma\,Ra_M \qquad (8)$$

where:

- Ra_T is thermal Rayleigh number:

$$Ra\ X\frac{g\ \ (\mathrm{T}_h Z T_c)\mathrm{d}^3}{a\neg} \qquad (9)$$

- Ra_M is magnetic Rayleigh number:

$$Ra_M\ X(1\Gamma\frac{1}{T_0})(\frac{g¥\ \ (\mathrm{T}_H Z T_C)\mathrm{d}^3}{2a\neg}) \qquad (10)$$

- where γ is magnetization number:

$$¥\ X\frac{\mathrm{i}\ |b_0|^2_{\max}}{°«_m g d} \qquad (11)$$

and: g – gravitation acceleration, β – thermal expansion coefficient, μ_m – vacuum magnetic permeability, ν – kinematic viscosity, ρ – density, χ – magnetic susceptibility, d – characteristic dimension, a – thermal diffusivity, T_H – temperature at the heated wall, T_C – temperature at the cooled wall, T_0 – reference temperature, b_0 – magnetic induction.

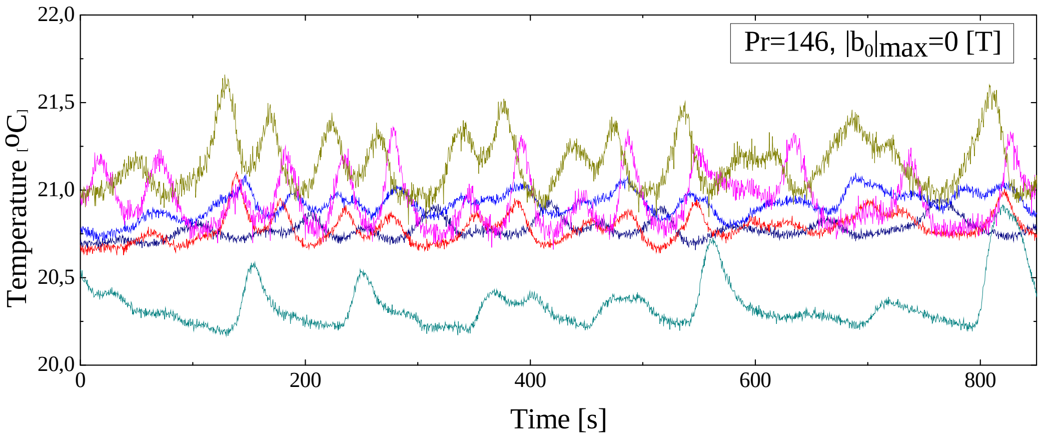
Obtained results are for the enclosure with aspect ratio equal two. The Nusselt number, at the natural convection case (without magnetic induction) was about ~3,6 for $Ra_{TM}=4\cdot10^4$. Changing the value of magnetic induction from 1 T, up to 10 T caused an increase of Nusselt number to 12,23 at 10T for $Ra_{TM}=5{,}4\cdot10^8$. Comparing those results with data available in literature for the same fluid but cubical enclosure with aspect ratio one, it can be seen that for the higher enclosure, heat transfer has smaller values. In the system with AR=2, total increase od Nusselt number, with magnetic induction from 0 to 10T, was about 340%, while in the enclosure with AR=1, total increase of Nusselt number was over 420%. It can be easily explained with the characteristic dimension, which plays a major role in the Nusselt number formula - because of a longer distance between heated and cooled walls, the rate of heat transfer is smaller.

Results of temperature signal analysis are presented in Fig. 6. Spectral analysis was conducted for signals from two thermocouples, located in bottom corners of the experimental enclosure. Fig.6. a), d) and g) presents temperature changes during 15-minute measurement. In the natural convection case (b_0=0 T) and in the case of magnetic induction b_0=3 T temperature slowly fluctuates, with relatively high amplitude, while in the case of 9T temperature fluctuations have much lower amplitude. It can be concluded that magnetic field applied to the system acts to fasten the fluid flow. In higher values of magnetic induction temperature field is more uniform.

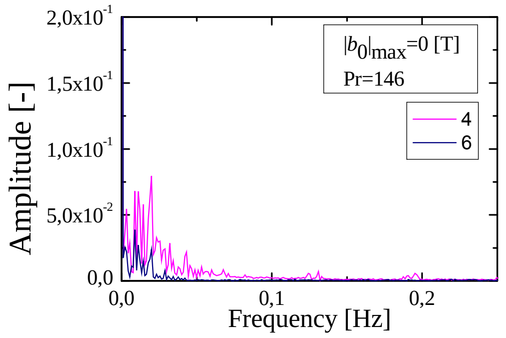
Fig. 6. b), e) and h) presents amplitude versus frequency, where characteristic peaks can be seen. For convective steady flow such peaks could be an evidence of vertical structure rotating in the enclosure with specified frequency. Because there is no particular frequency repeating in all cases, this can indicates that there were many vortexes in the fluid flow.

Fig. 6. c), f) and i). presents power spectrum as MSA (mean square amplitude) versus frequency in logarithmic scale. Blue and black lines represents slopes of wave number powers -5/3 and -1. In the case of natural convection it can be seen that black line fits the power spectrum of one thermocouple. This indicates that the flow was in inertial-convective regime. Increasing magnetic induction changed the power spectrum characteristics, as shown in Fig.6. f) and i). Spectral analysis of the signal in magnetic field equal 9 T shows quite good match to -1 slope, which is viscous-diffusive regime. This speaks of the fact, that magnetic field changes the order of the flow.

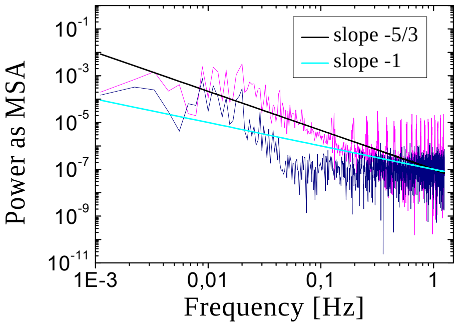
a)



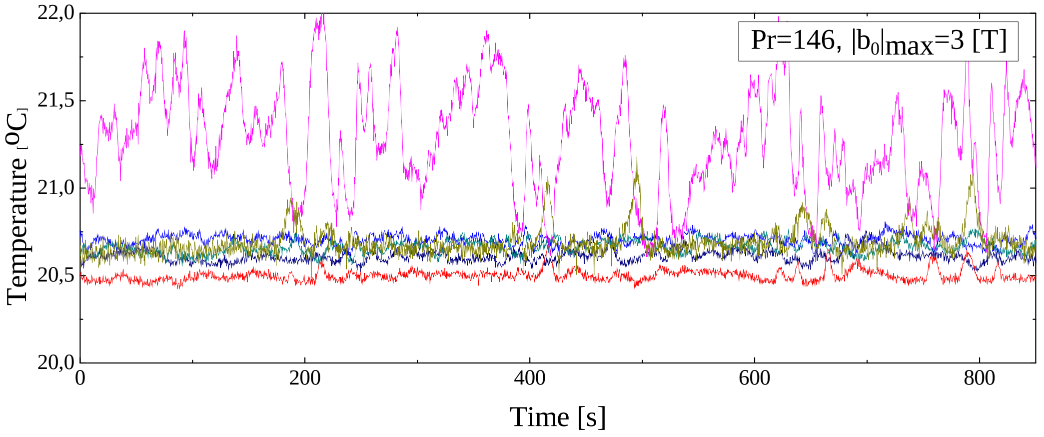
b)


Amplitude [-]
2,0x10^{-1}
1,5x10^{-1}
1,0x10^{-1}
5,0x10^{-2}
0,0
0,0
0,1
0,2
Frequency [Hz]
|b_0|max=0 [T]
Pr=146
4
6

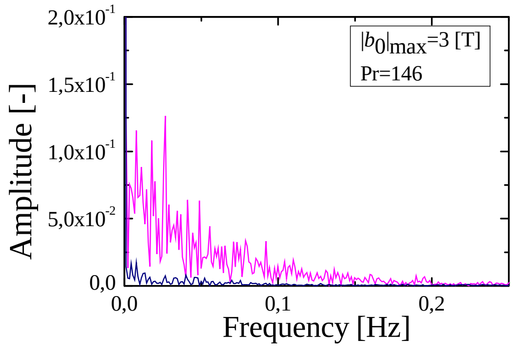
c)


Power as MSA
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
1E-3
0,01
0,1
1
Frequency [Hz]
slope -5/3
slope -1

d)


Temperature [^{o}C]
22,0
21,5
21,0
20,5
20,0
0
200
400
600
800
Time [s]
Pr=146, |b_0|max=3 [T]

e)


Amplitude [-]
2,0x10^{-1}
1,5x10^{-1}
1,0x10^{-1}
5,0x10^{-2}
0,0
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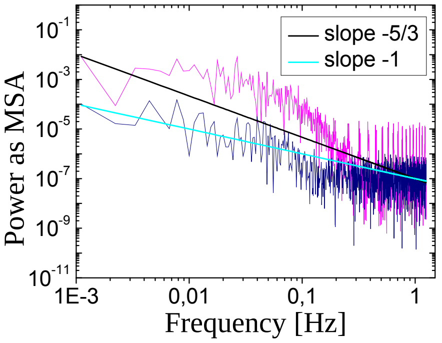
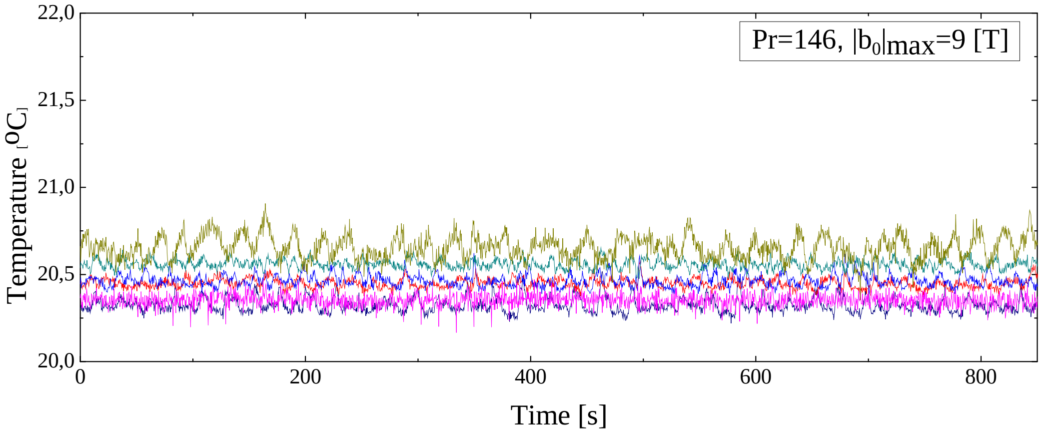
0,2
Frequency [Hz]
|b_0|max=3 [T]
Pr=146

f)


Power as MSA
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
1E-3
0,01
0,1
1
Frequency [Hz]
slope -5/3
slope -1

g)


Temperature [^{o}C]
22,0
21,5
21,0
20,5
20,0
0
200
400
600
800
Time [s]
Pr=146, |b_0|max=9 [T]

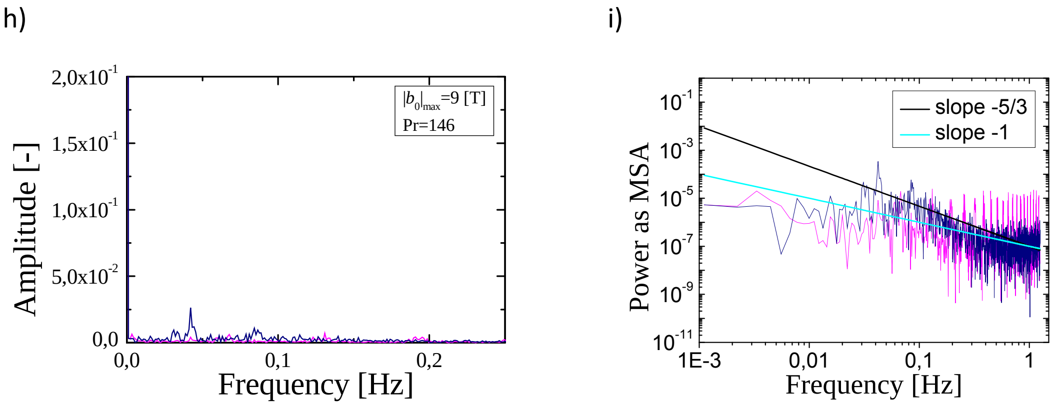


Fig. 6 a), d), g) temperature versus time series fot b_0=0,3,9 T; b), e), h) amplitude versus frequency for b_0=0,3,9 T; c) ,f), i) power spectrum versus frequency for b_0=0,3,9 T.
Source: Author's

Summary and conclusions

In this article the experimental analysis of the influence of a strong magnetic field on thermo-magnetic fluid convection was presented. Estimation of heat transfer and characteristic of fluid flow was able due to obtained temperature signal. Performed analysis leads to following conclusions:

- magnetic field strongly enhance heat transfer,
- use of magnetic field leads to enhancement of heat transfer over 300%,
- experimental enclosure height has a great influence on heat exchange in the system,
- enclosures with higher aspect ratios are characterized by smaller Nusselt numbers than enclosures with smaller aspect ratios;
- magnetic field heavily influence character of a fluid flow,
- Fast Fourier analysis is a helpful tool to characterize the fluid flow structure,
- positive reaction of the analyzed system to the magnetic field in the field of heat transfer shows a great potential in heat transfer area.

Performed studies have fundamental character, which means that the main aim is to acquire knowledge of the process mechanism, but on the basis of obtained results and conclusions, thermo-magnetic convection could be successfully used in modern cooling systems, resulting in improved heat exchange (heat dissipation), thus reducing some of the costs. In future studies Authors will determine the influence of external magnetic field on natural convection in systems with AR=0,5 and an analysis of systems, where thermally active walls are side walls.

Acknowledgements

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