

EXPERIMENTAL THERMO-MAGNETIC CONVECTION ANALYSIS IN TALL RECTANGULAR ENCLOSURE

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Abstract. Rectangular enclosure with aspect ratio (AR=height/width) 2 was investigated in experimental thermo-magnetic convection analysis. Experimental enclosure was placed inside superconducting magnet in Rayleigh-Bénard configuration, in position, where magnetic field gradient was enhancing natural convection. Two types of paramagnetic fluid behaviour were identified at different magnetic induction values. It was possible by utilization of Fast Fourier Transform of recorded temperature signals inside experimental enclosure. Presented results shown augmented heat transfer in rectangular enclosure at high magnetic field gradient up to 300%. Transition zone of fluid behaviour for presented experimental setup was observed from $Ra_{TM}=4 \cdot 10^7$ to $Ra_{TM}=1.3 \cdot 10^8$.

1. Introduction

Control of non-electrically conducting fluid flow in closed system is crucial in many industrial applications, such as heat exchangers, magnetic mixers, chemical reactors etc. Thermo-magnetic convection is new tool addressed for those applications, which combine both thermal and magnetic convection phenomena. Mutual configuration of gravitational and magnetic forces as result could enhance or suppress convection of working fluid in chosen application.

First thermo-magnetic convection experiment with paramagnetic fluid, presented by Braithwaite et al. [1], shown new approach in heat transfer enhancement. In later studies of thermo-magnetic convection, most of scientific interest was devoted to investigation of different geometries [2], flow visualization techniques [3] and dimensionless parameters description [4]. Recent studies were strongly connected with transition from laminar to turbulent flow regimes which could be obtained by application of high gradient magnetic field (up to 900 [T²/m], for the magnetic field induction in the centre of superconducting magnet bore $|b_0|_{max}=10$ [T] in contrast to 200 [T²/m], for magnetic field induction of $|b_0|_{max}=5$ [T] in previous studies) i. e.: Transients and turbulence pockets in thermal convection of paramagnetic fluid subjected to strong magnetic field gradients [5], Oscillatory states in thermal convection of a paramagnetic fluid in a cubical enclosure subjected to a magnetic field gradient [6], Numerical and Experimental Study of Rayleigh-Bénard-Kelvin Convection [7].

The goal of presented investigation was an analysis of paramagnetic fluid in experimental enclosure with AR 2 in Rayleigh-Bénard configuration. Fluid behaviour was investigated with utilization of Fast Fourier Transform method applied to thermocouple signals, which were place inside rectangular enclosure side wall.

2. Experiment



2.1. Experimental setup

Experimental setup, presented on Figure 1(left) consisted of: experimental enclosure (AR 2), superconducting magnet generating strong magnetic field, a thermo-stating bath, a power supply and a data acquisition system. Experimental enclosure centre was placed 0.095 [m] above centre of superconducting magnet. In that position, maximum gradient of magnetic field is present and enhance natural convection due to its orientation and chosen fluid type. Schematic diagram of superconducting magnet is shown in Figure 1(right). To calculate magnetic field distribution and its gradient, besides real dimensions of system presented on Figure 1(right), current density in internal and external coil should be taken into account, which was equal to $140.9 \cdot 10^{-6}$ [A/m²] and $167.3 \cdot 10^{-6}$ [A/m²] respectively at maximum value of magnetic field inside centre of magnet: $|b_0|_{\max}=10$ [T].

Dimensions of experimental enclosure were: 0.064 [m] height and 0.032 [m] x 0.032 [m] in base. It was placed inside magnet opening in Rayleigh-Bénard configuration, where lower horizontal wall was electrically heated, while the upper one was cooled with thermo-stated water - Figure 2.

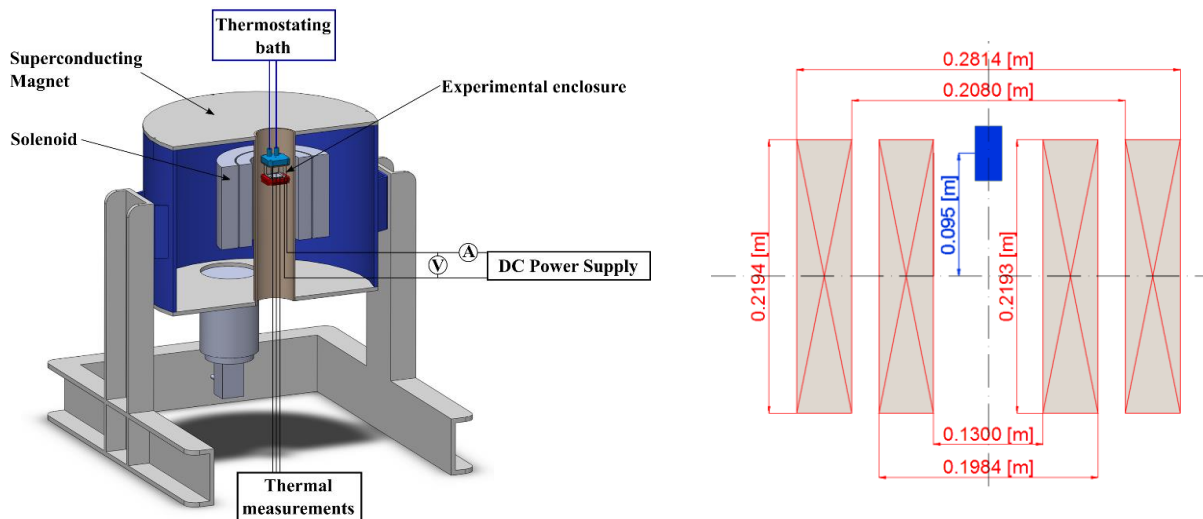


Figure 1. Experimental setup and location of the experimental enclosure (left). Schematic view of superconducting magnet solenoid with marked position of the enclosure (right).

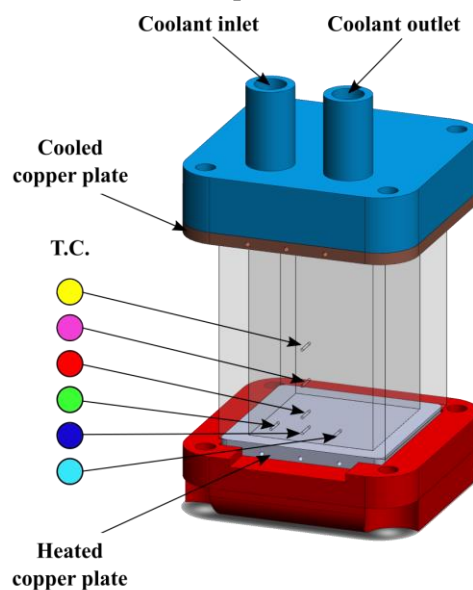


Figure 2. Experimental enclosure with AR 2 ($H=0.064$ [m] in height, $L=D=0.032$ [m] in base) with marked positions of thermocouples inside one wall.

Temperature of both walls was controlled with six thermocouples. Six other thermocouples were inserted into the enclosure walls 0.006 [m] deep, to measure temperature of the fluid. Their positions are presented on Figure 2 along with predestined colours which are used in results analysis further down. Thermocouple signals recorded during experiments were used in Fast Fourier Transform (FFT) analysis, which allow to identify type of the flow and change of fluid behaviour.

2.2. Experimental fluid

As a working fluid for experimental studies 50% volume aqueous solution of glycerol with 0.8 [mol/(kg of solution)] concentration of gadolinium nitrate hexahydrate ($\text{Gd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$) was chosen. All important, for presented studies, properties of the fluid were measured experimentally and are listed in Table 1.

Table 1. Properties of the working fluid at 298 K.

Property	Symbol	Value	Unit
Heat capacity	c_p	$2.92 \cdot 10^3$	[J/kg·K]
Thermal diffusivity	α	$7.55 \cdot 10^{-8}$	[m ² /s]
Thermal expansion coefficient	β	$4.13 \cdot 10^{-6}$	[1/K]
Dynamic viscosity	μ	$1.56 \cdot 10^{-2}$	[kg/m·s]
Thermal conductivity	λ	0.376	[W/m·K]
Kinematic viscosity	ν	$1.10 \cdot 10^{-5}$	[m ² /s]
Density	ρ	1418.1	[kg/m ³]
Mass magnetic susceptibility	χ_m	$2.58 \cdot 10^{-7}$	[m ³ /kg]

Due to the narrow temperature range studied, it could be assumed that almost all needed properties were constant, except viscosity. Therefore the dependence of viscosity on the temperature was checked experimentally and approximated function could be written as follows:

$$\mu_0 = 2.078 \cdot 10^{-5} \theta^2 - 1.678 \cdot 10^{-3} \theta + 4.451 \cdot 10^{-2} \quad (1)$$

2.3. Experimental course

The main aim of this paper was to identify fluid behaviour under a strong magnetic field gradient and analyse its influence on the heat transfer. Thermal measurements were used to obtain both stated aims. The experiment was divided into two steps. First step was thermal measurements with increasing magnetic induction for temperature difference between heated and cooled walls equal to 3, 5 and 11 [K]. Signal of thermocouples inserted into the rectangular enclosure was then analysed with FFT. The second step was connected with the energy balance and estimation of heat loss to the environment.

To archive that, the conduction experiment was carried out with reversely placed thermally active horizontal walls of experimental enclosure at investigated position. At first a specific temperature difference between horizontal walls was selected and then after thermal stabilization the heating power was measured, which together with theoretical heat flux obtained from Fourier's law allowed estimation of heat loss:

$$Q_{\text{loss}} = Q_{\text{cond}} - Q_{\text{theor_cond}} \quad (2)$$

$$Q_{\text{theor_cond}} = \frac{D^2 \lambda (\theta_h - \theta_c)}{H} \quad (3)$$

where: θ_h , θ_c – are temperature of hot and cold walls respectively, D – enclosure basis side 0.032 [m], H – enclosure height 0.064 [m].

Heat loss was calculated according to eq. (2) and could be linearly approximated for various heating rates ($\Delta\theta = \theta_h - \theta_c = 2.5 \div 15$ [K], where temperature of cold wall was kept at ambient temperature inside magnet), according to:

$$Q_{\text{loss}} = 0.0831 \Delta\theta \quad (4)$$

2.4. Dimensionless numbers

The thermo-magnetic convection can be characterized by a group of non-dimensional parameters such as Nusselt, Prandtl, thermal and magnetic Rayleigh and magnetization numbers.

Nusselt number was calculated as a ratio between the net convective heat transfer rate and the net pure conduction contribution with applied method invented by Ozoe and Churchill [8] to estimate net heat fluxes:

$$Nu = \frac{Q_{\text{net_conv}}}{Q_{\text{net_cond}}} = \frac{Q_{\text{conv}} - Q_{\text{loss}}}{Q_{\text{cond}} - Q_{\text{loss}}} \quad (5)$$

Assuming that convection heat flux was equal to heater heat flux ($Q_{\text{net_conv}} = Q_{\text{heater}}$) and applying eq. (2) and (3) to eq. (5) it could be rewritten in following form:

$$Nu = \frac{Q_{\text{heater}} - Q_{\text{loss}}}{Q_{\text{theor_cond}}} = \frac{IU - Q_{\text{loss}}}{\frac{D^2 \lambda (\theta_h - \theta_c)}{H}} \quad (6)$$

The Prandtl number definition was:

$$Pr = \frac{\nu}{\alpha} \quad (7)$$

The thermal Rayleigh number was defined as:

$$Ra_T = \frac{\beta g \Delta \theta H^3}{\nu \alpha} \quad (8)$$

where β is the thermal expansion coefficient, \mathbf{g} is the gravitational vector, $\Delta \theta$ is the temperature difference between horizontal thermally active walls, H is the enclosure height ($H=0.064$ [m]), ν is the kinematic viscosity coefficient and α is the thermal diffusivity.

The magnetic Rayleigh number was defined as:

$$Ra_M = \left(1 + \frac{1}{\beta \theta_0}\right) \left(\frac{\gamma \beta g \Delta \theta H^3}{2 \nu \alpha}\right) \quad (9)$$

The magnetization number:

$$\gamma = \frac{\chi_m |b_0|_{\text{max}}^2}{\mu_0 g H} \quad (10)$$

where: $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ [H/m].

The thermo-magnetic Rayleigh number was defined as:

$$Ra_{\text{TM}} = Ra_T + Ra_M = \frac{\beta g \Delta \theta H^3}{\nu \alpha} + \left(1 + \frac{1}{\beta \theta_0}\right) \left(\frac{\gamma \beta g \Delta \theta H^3}{2 \nu \alpha}\right) \quad (11)$$

3. Results

Temperature time series of investigated fluid for $\Delta \theta = 3, 5$ and 11 [K] cases at chosen $|b_0|_{\text{max}}$ are presented in Figures 3-5(left) and the Fast Fourier Transform (FFT) analysis was conducted to calculate spectral functions of a scalar field. Scalar functions of temperature depend on energy dissipation, thermal diffusivity, viscosity and temperature. According to [9] in some ranges, spectral functions do not depend on the diffusion, and therefore do not rely on viscosity and diffusivity. This range is characterised by a spectral function with an inclination of wave number with $-5/3$ exponent and is known as inertial-convective. In cases when thermal diffusivity is more significant, spectral functions have an inclination of reverse wave number and this range is called viscous-diffusive [9]. Figures 3-5(right) present power spectrum as TISA (time interval square amplitude) versus frequency.

Presented temperature-time series show transition in fluid behaviour. For $\Delta \theta = 3$ [K] transition from laminar to turbulent regime appears between $|b_0|_{\text{max}} = 5$ and 6 [T], and for $\Delta \theta = 5$ and 11 [K] between

$|b_0|_{\max}=4$ and 5 [T] and $|b_0|_{\max}=2$ and 3 [T] respectively. Power spectrum analysis for $\Delta\theta=3$ [K] case shows radical change in fluid behaviour. For natural convection case, flow appears to be between inertial-convective and viscous-diffusive ranges. For $|b_0|_{\max}=5$ [T] spectral functions have a good match to -1 slope, indicating that flow is in viscous-diffusive regime, but one thermocouple, placed in the down left side of the experimental enclosure, shows different behaviour and its spectral function has an inclination of -5/3 slope. After transition to turbulent regime, no matches to exponent lines can be found and that type of a flat power spectrum is characteristic for a steady state turbulent flow. For $\Delta\theta=5$ [K] and $|b_0|_{\max}=0$ [T] case spectral function has a sharp inclination, indicating that flow is unsteady. Transition to turbulent regime appears for this case between $|b_0|_{\max}=4$ and 5 [T]. For $|b_0|_{\max}=4$ [T] good match to -5/3 slope can be observed, while after transition character of the flow changes and spectral function has flat power spectrum, as for previous case. For $\Delta\theta=11$ [K] case spectral analysis indicates that for $|b_0|_{\max}=0$ [T] for low frequencies, flow is in viscous-diffusive regime and for slightly higher frequencies flow is in inertial-convective regime. Then spectral function flattens, indicating that for a certain range of magnetic induction flow is steady state, but further increasing magnetic induction over that range again changes character of the flow and match to -1 slope can be observed.

Results indicating transition behaviour were marked with red color on Nusselt number versus thermo-magnetic Rayleigh number diagram - Figure 6. Note that marked pairs represent before and after transition points.

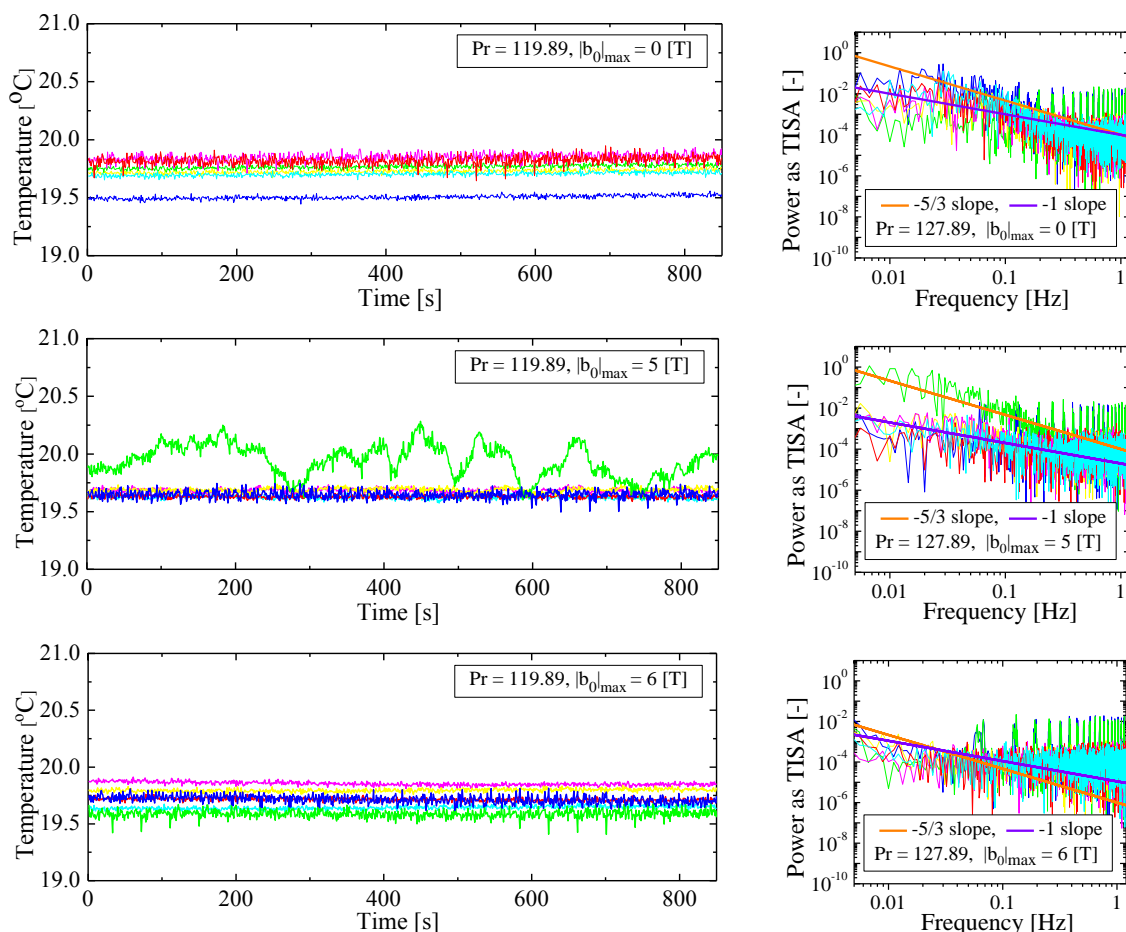


Figure 3. Example of fluid behaviour transition with applied strong magnetic field: temperature time series (left) and power spectrum vs. frequency diagram (right) for $\Delta\theta=3$ [K] case .

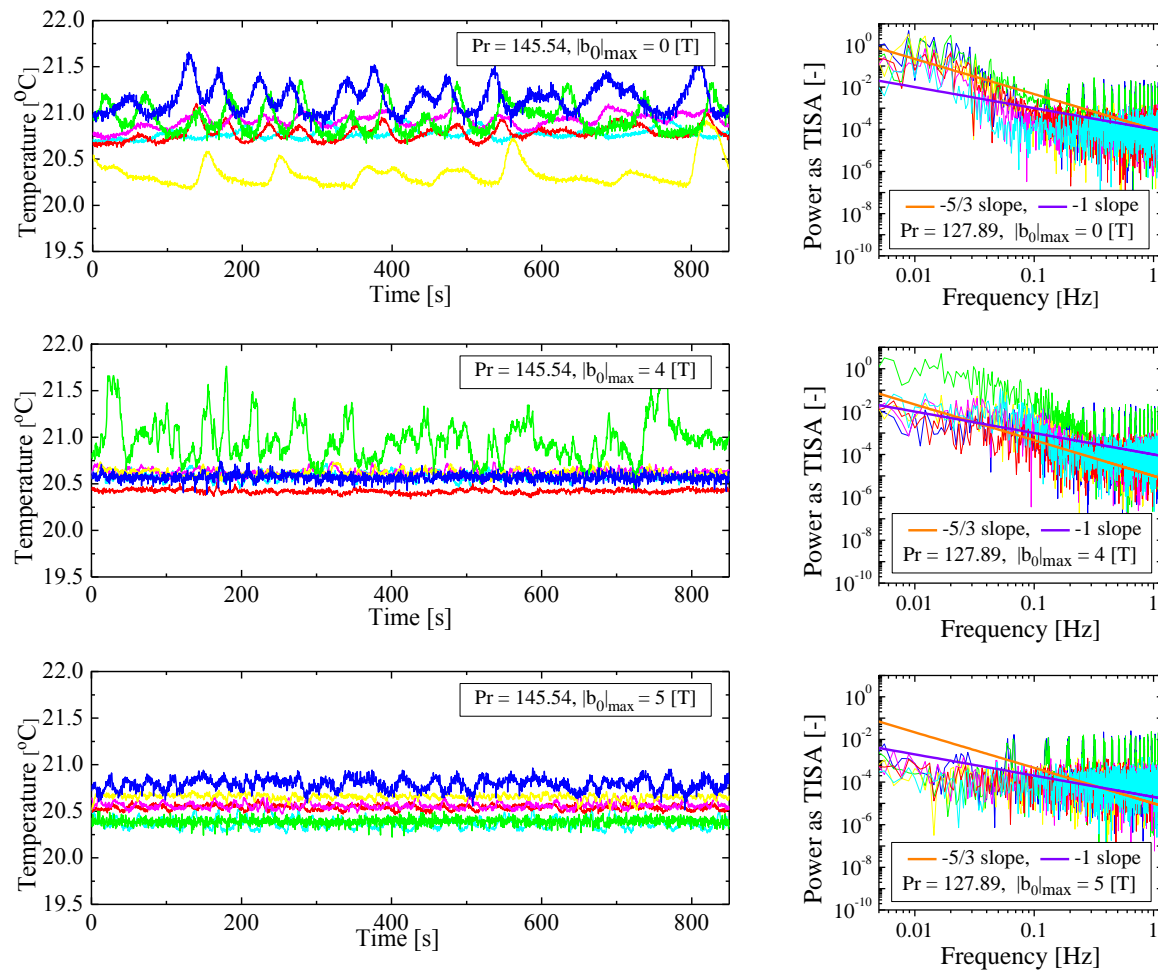
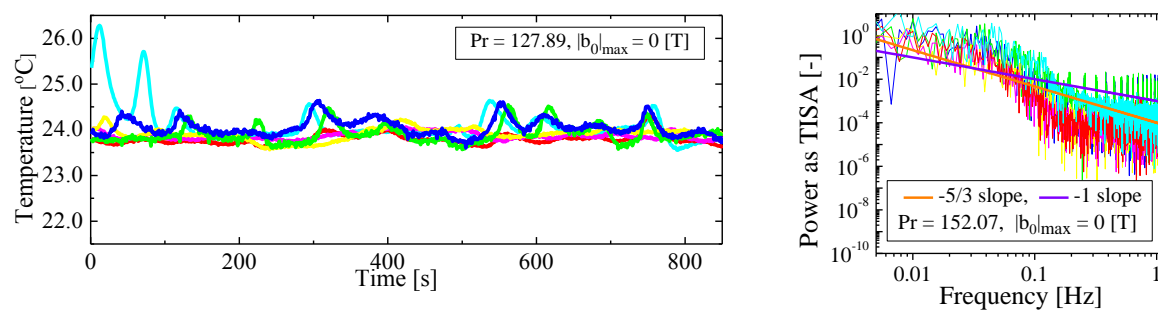


Figure 4. Example of fluid behaviour transition with applied strong magnetic field: temperature time series (left) and power spectrum vs. frequency (right) for $\Delta\theta=5$ [K] case.



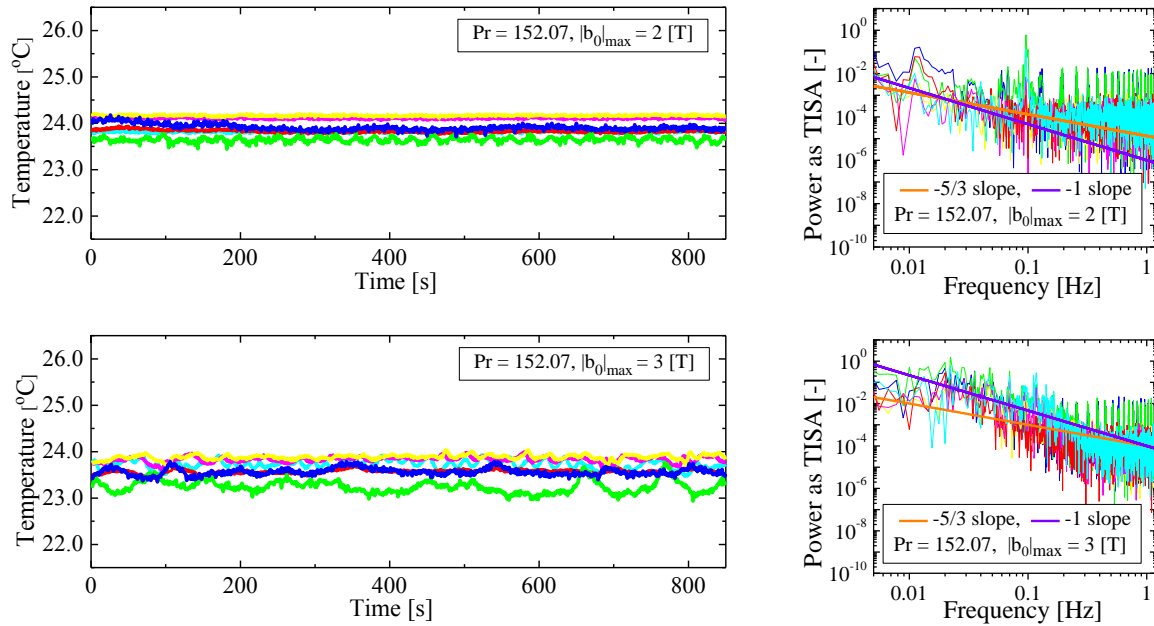


Figure 5. Example of fluid behaviour transition with applied strong magnetic field: temperature time series (left) and power spectrum vs. frequency (right) for $\Delta\theta=11$ [K] case.

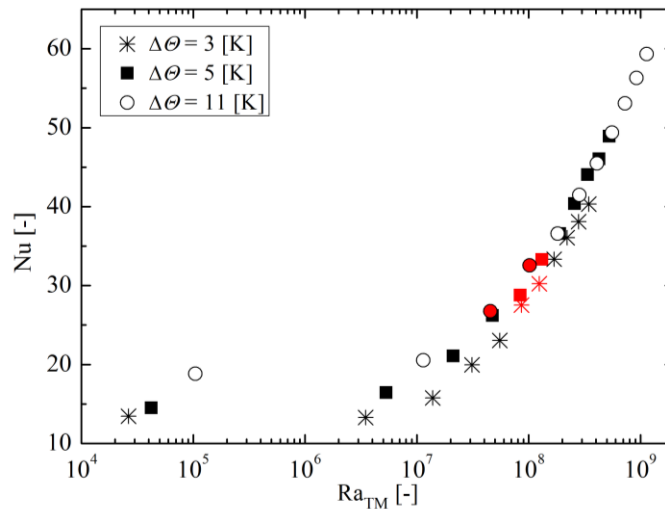


Figure 6. Transition points of fluid behaviour presented on Nu vs Ra_{TM} diagram.

4. Summary

Experimental analysis of thermo-magnetic convection was presented. An influence of Rayleigh number and magnetic field strength were examined. Due to the application of steady magnetic field at chosen temperature difference two flow behaviour were identified. With an application of Fast Fourier Transform and spectral analysis it was possible to determine the characteristic regime for the flow. The FFT analysis clearly indicates changes of fluid behaviour, what was shown in the form of power of TISA vs. frequency diagrams, based on temperature time series recorded from thermocouples. Identification of characteristic frequencies distribution in the case of 3, 5 and 11 [K] temperature differences allowed calculation of transition point for presented experimental setup which was from

$Ra_{TM}=4 \cdot 10^8$ to $Ra_{TM}=1.2 \cdot 10^8$. Heat transfer was significantly augmented with applied magnetic field. The heat exchange increased more than 300% in comparison with natural convection. All gathered data might be used in validation of numerical codes.

5. Acknowledgements

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