Intensification of heat transfer with an application of strong magnetic gradients

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Abstract. Experimental analysis of a strong magnetic field influence on heat transfer by paramagnetic fluid was conducted. A rectangular enclosure, filled with working fluid, was placed inside superconducting magnet's working section in Rayleigh-Bénard configuration and three temperature differences between heated and cooled walls ΔT= 3, 5, 11 [°C] were applied. On the basis of performed measurements heat transfer analysis in the form of Nusselt number, conduction and convection heat fluxes calculations was conducted. Obtained results demonstrated that Nusselt number strongly depends on the temperature difference between thermally active walls as well as on the magnetic induction applied to the system. An application of external high magnetic field from 0 [T] to 10 [T] caused an increase of the heat transfer rate – about 250% for ΔT = 3 [°C] and over 340% for ΔT = 5, 11 and 20 [°C] and can be successfully implemented to heat transfer intensification for paramagnetic fluids.

1 Introduction

Buoyancy-driven natural convection control in closed system is crucial in many applications, such as: heat exchangers, chemical reactors, space industry or non-gravitational state research.

All surrounding substances may be divided into three basic types, depending on magnetic properties: ferromagnetic, diamagnetic and paramagnetic. While ferromagnetics are strongly attracted towards magnetic field (i.e. iron volume susceptibility = $2 \cdot 10^5$), paramagnetics are poorly attracted by magnetic field source (i. e. oxygene volume susceptibility = $3 \cdot 10^{-8}$), and diamagnetics are weakly repelled by it (i.e. water volume susceptibility = $-9 \cdot 10^{-6}$).

To influence a fluid flow with paramagnetic or diamagnetic properties, a high magnetic field gradient should be applied. Then, depending on mutual configuration of magnetic and gravitational forces, different results could be achieved.

First published results with a paramagnetic fluid convection enhancement and suppression was presented by Braithwaite [1]. Tagawa [2] developed a model equation for thermo-magnetic convection. Bednarz [3] studied thermo-magnetic convection in configuration with one side wall heated and the opposite one cooled. Pyrda et al. investigated heat transfer enhancement in cubical enclosure [4] and developed non-dimensional analysis of paramagnetic fluid in Rayleigh-Bénard configuration [5]. Kenjeres et al. investigated oscillatory states in thermal convection of a paramagnetic fluid in a cubical enclosure subjected to a magnetic field gradient [6] and turbulence pockets in thermal convection of paramagnetic fluid subjected to strong magnetic field gradients [7]. His group performed numerical and experimental study of Rayleigh–Bénard–Kelvin Convection [8].

In present paper authors will focus on heat transfer enhancement with utilization of thermo-magnetic convection of paramagnetic fluid.

2 Experimental setup

2.1 Experimental apparatus

Apparatus used to performed experimental analysis of thermo-magnetic convection is shown in Figure 1. It consisted of an experimental enclosure placed in the bore of a superconducting magnet (HF10-100VHT-B, *Sumito Heavy Industries*, Ltd. Japan), thermostating bath with constant temperature flow, a heater control system, and a data acquisition system connected to a personal computer. The experimental enclosure of dimensions 0.032 x 0.032 [m] in base and 0.016 [m] in height is presented in Figure 2.

Experimental enclosure, heated from one horizontal wall and cooled from the opposite one, consisted of following elements: cooling chamber filled with cold water (18[°C]) pumped by thermo-stated bath washing over a top copper plate, cavity made from plexiglass and heating chamber, where bottom copper plate was heated by nichrome wire connected to a DC power supply to maintain constant temperature (21,23,29,38 [°C]). Six T-type thermocouples, inserted into small holes in bottom and top copper plates constantly measured temperature of thermally active walls. Another five T-type thermocouples, inserted into small holes in front wall of

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plexiglass enclosure, measured temperature of working fluid during experiments.

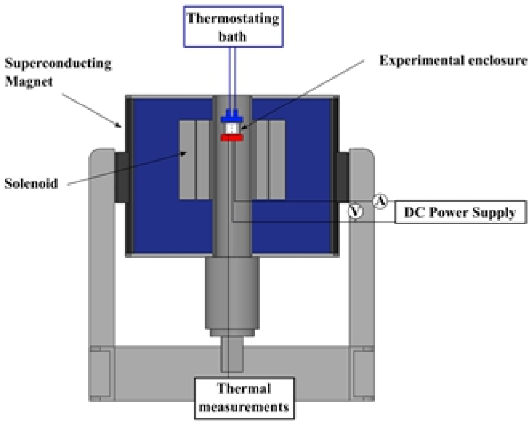

Figure 1. Schematic view of experimental apparatus.

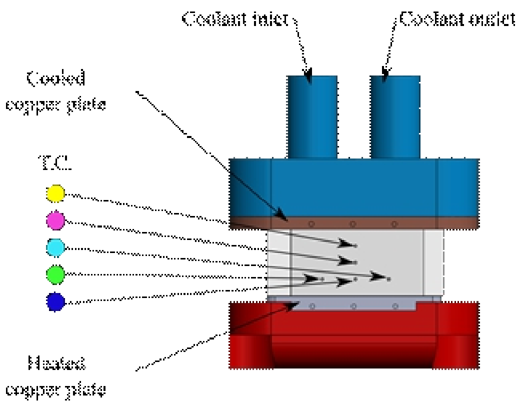

Figure 2. Schematic view of experimental enclosure with marked positions of thermocouples.

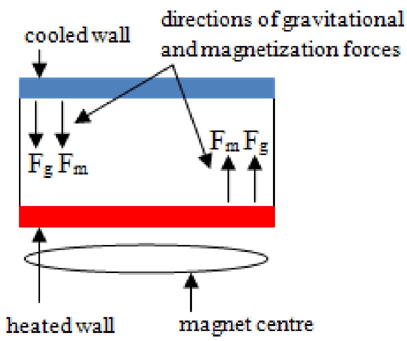

Figure 3. Directions of gravitational and magnetization forces.

Measuring vessel was placed in the upper half of the superconducting magnet, where gravitational and magnetic forces acted in the same direction, causing enhancement of convective flow, as shown in Figure 3. This position is correlated to the location of a maximal value of grad $\mathbf{b_0}$, where $\mathbf{b_0}$ stand for magnetic induction, and it was 0.095 [m] from the magnet's top.

2.2 Working fluid

As a working fluid, 50% volume glycerol aqueous solution with an addition of 0.8 mol/(kg of solution) gadolinium nitrate hexahydrate $Gd(NO_3)_3 \cdot 6H_2O$ to make it paramagnetic, was chosen. Properties of the working fluid are listed in Table 1.

Table 1. Properties of the working fluid.

Property	Sym.	Value	Unit
Density	ρ	1411	[kg/m³]
Kinematic viscosity	ν	$9.25 \cdot 10^{-6}$	[m²/s]
Dynamic viscosity	μ	$1.30 \cdot 10^{-2}$	[kg/m·s]
Heat capacity	c_p	$2.92 \cdot 10^{3}$	[J/kg·K]
Thermal diffusivity	α	$9.13 \cdot 10^{-8}$	[m²/s]
Thermal expansion coefficient	β	$1.21 \cdot 10^{-5}$	[1/K]
Thermal conductivity	λ	0.376	[W/m·K]
Mass magnetic susceptibility	χ_m	$2.39 \cdot 10^{-7}$	[m³/kg]

2.3 Experimental procedure

Experimental procedure consisted of two steps: an analysis of a conduction state and analysis of a thermo-magnetic convection. In the first step, the enclosure filled with water was placed in the magnet in a position, where the bottom horizontal wall was cooled, and the opposite one was heated (reverse Rayleigh-Bénard configuration). Temperature on a bottom wall was set to constant temperature of 18 [°C], the same as an ambient temperature in the magnet working section, and temperature on the top wall was sequentially: 21, 23, 26, 29, 32, 34 and 38 [°C]. After linear temperature distribution was achieved, heating power was measured. Assuming one-dimensional conductive heat flow, the heat flux can be calculated from Fourier's law of conduction, and therefore the difference between directly measured heat flux and the heat flux calculated from Fourier's law is the heat loss from the experimental enclosure.

The next step was connected with analysis of a thermo-magnetic convection. Experimental enclosure, filled with working fluid, was rotated 180 degrees to Rayleigh-Bénard configuration, with bottom wall heated and the opposite one cooled. The power supply was set to obtain chosen temperature difference between thermally active walls and the setup was left to obtain a stable state. Then temperature, electrical current and voltage were recorded and magnetic field was applied to the system by stages of 1 [T].

3 Heat transfer analysis

Temperature signals recorded during experimental analysis allowed investigation on a heat transfer rate, which was established by calculation of dimensionless parameter called Nusselt number. This criterion, speaking of a heat transfer in analysed system, can be written as follows:

$$\mathrm{Nu} = \frac{Q_{net\_conv}}{Q_{net\_cond}} \qquad (1)$$

The net convection (Q_{net_conv}) and net conduction (Q_{net_cond}) heat fluxes were estimated accrording to method proposed in [9]:

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

$$Q_{\text{net\_conv}} = Q_{\text{conv}} - Q_{\text{loss}} \quad (3)$$

Assuming that the heat loss depends only on the temperature of the heated wall, conduction measurements were made and heat losses were estimated from :

$$Q_{\text{loss}} = Q_{\text{cond}} - Q_{\text{Fourier's\_law}} \quad (4)$$

where:

$$Q_{\text{Fourier's\_law}} = \frac{a^2 \lambda \Delta T}{d} \quad (5)$$

d - enclosure height – 0.016 [m]; a – enclosure width 0.032 [m]; λ – thermal conductivity of the fluid [W/m·K]; ΔT – temperature difference between heated and cooled walls [K].

The heat flux was calculated for the conduction area of a base of the measuring enclosure 0.032 [m] x 0.032 [m]. The calculated heat losses were approximated linearly:

$$Q_{loss} = 0.0907 \cdot \Delta T \quad (6)$$

Heat losses dependency on temperature differences between thermally active wall is presented in Figure 4.

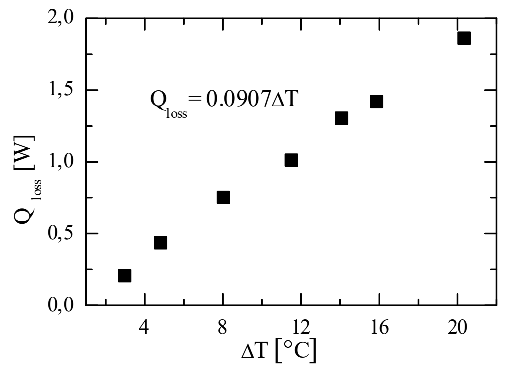

Figure 4. Heat losses in the measurement vessel versus temperature differences.

By applying equations (2),(4) and (5) to (1) expression for Nusselt number can be expressed as follows:

$$\text{Nu} = \frac{Q_{\text{conv}} - Q_{\text{loss}}}{\frac{a^2 \lambda \Delta T}{d}} \quad (7)$$

The results of heat transfer analysis are presented in Figure 5 - 7.

4 Results and discussion

Figure 6 presents results of heat transfer analysis as a Nusselt number calculation versus magnetic induction in the center of the magnet. Nusselt number significantly escalates with an increase of magnetic induction. For natural convection cases, without magnetic induction applied to the system, Nusselt number values start from 3.46, 2.95, 3.62 and 4.51 for ΔT=3, 5, 11 and 20 [°C] respectively.

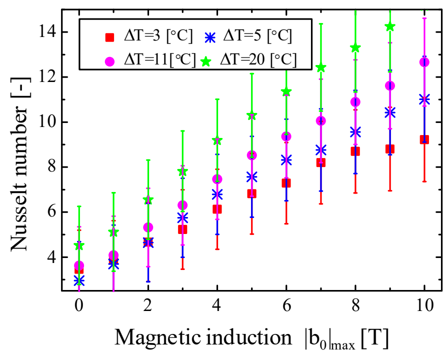

Figure 5. Nusselt number versus magnetic induction in the centre of the magnet $|b_0|_{max}$.

Such fluctuations of Nusselt number values are probably related to the fact that the working section of the magnet could not be tightly insulated and ambient temperature of the laboratory (measurements were performed in winter months and temperature in the room was about 15.6-17.3[°C]) had a significant impact on heat transfer in natural convection. In [4] Authors report Nusselt number values for natural convection in a cubical enclosure (of dimensions 0.032x0.032x0.32 [m]) to be ~7.5 for ΔT=5 [°C] and ~10 for ΔT=11 [°C], therefore a higher experimental geometry is characterized by greater heat transfer. An application of magnetic induction to the system and increasing its value to $|b_0|_{max}$= 10 [T] causes heat transfer growth by 260% for ΔT=3 [°C] and over 340% for ΔT=5, 11 and 20 [°C] cases, which is similar to increasement reported in [4].

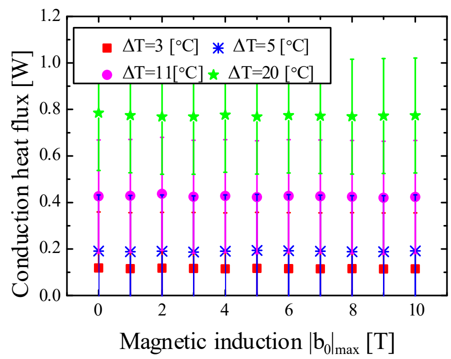

Figure 6. The conduction heat flux versus the magnetic induction in the centre of the magnet.

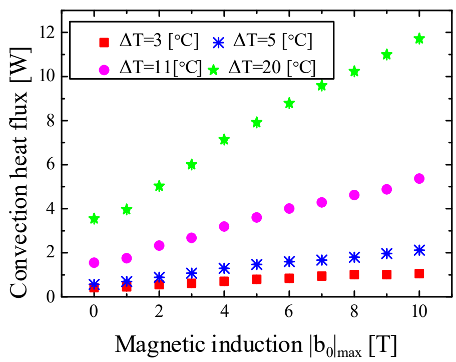

Figure 7. The convection heat flux versus the magnetic induction in the centre of the magnet.

According to equation (1) Nusselt number is a ratio of a convective heat flux to a conduction heat flux in the analysed system. Figures 6 and 7 presents results of conduction and convection fluxes calculations as a function of magnetic induction.

The conduction heat flux is the higher the grater the temperature difference and does not change significantly with magnetic induction increase. For $\Delta T = 3$ [°C] Q_{cond} value oscillates around 0.11 [W] while for $\Delta T = 20$ [°C] it is about seven times bigger and approximately equals 0.77 [W]. For all cases convective heat fluxes are significantly higher than Q_{cond}. For $|b_0|_{max} = 0$ [T] Q_{conv} are 0.41, 0.56, 1.54 and 3.54 [W] for $\Delta T = 3, 5, 11$ and 20 [°C] respectively. Application of external magnetic field results in a major increase in convective heat flux. For $\Delta T = 3$ [°C] and maximal magnetic induction in the center of the magnet convective heat flux rises over about 250% in comparison to natural convection case. For higher temperature differences this increase is even bigger and equals over 330%.

5 Summary

In this paper experimental analysis of thermo-magnetic convection of paramagnetic fluid was conducted. Four temperature differences between heated bottom wall and the opposite one cooled were applied and an influence of magnetic field induction on experimental fluid from 0 [T] to 10 [T] was tested. Performed analysis of signals obtained from thermocouples placed in the experimental enclosure enabled calculation of heat transfer indicator in the form of a Nusselt number and conduction and convection heat fluxes. Obtained results led to the following conclusions: (a) the Nusselt number strongly depends on temperature difference between thermally active walls, as well as on magnetic induction in the system; (b) an application of external magnetic field from 0 [T] to 10 [T] causes an increase of the heat transfer rate – about 250% for $\Delta T = 3$ [°C] and over 340% for $\Delta T =$ 5, 11 and 20 [°C]; (c) conduction heat flux increase with higher temperature differences, but does not depend on magnetic induction; (d) convective heat flux strongly depends on magnetic induction in the center of the magnet and the increase in its rate with magnetic induction up to 10 [T] is over 250% for every temperature difference; (e) external magnetic field can be successfully implemented to heat transfer intensification for paramagnetic fluids.

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