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RAYLEIGH-BÉNARD CONVECTION IN A VERTICAL MAGNETIC FIELD AT LOW PRANDTL NUMBER

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Abstract: The present work shows the experimental realisation of three-dimensional magnetoconvection studies at Rayleigh numbers between 10^6 and $6 \cdot 10^7$ and Hartmann numbers up to 1000 in a Rayleigh-Bénard convection cell. The fluid in the cell is the GaInSn metal alloy with a low Prandtl number of 0.029. The flow is investigated using thermocouples and ultrasound-Doppler-velocimetry. The change of the Nusselt number with increasing Hartmann number is studied and presented. Experimental results are compared to other experiments and simulations.

Keywords: liquid metal, low Prandtl number, Rayleigh-Bénard magnetoconvection, vertical magnetic Field

1. Introduction Experimental studies of Rayleigh-Benard convection in molten metals are a recognized and proven tool to shed light on crucial mechanisms within our planet, our sun, and other stars. It helps us to investigate and to understand the primary origin of our earth's magnetic field, one of the main reasons why our planet is inhabitable. Moreover, liquid metal convection has a high economic relevance. Liquid metal flow control by applying magnetic fields can contribute to better product quality and can lower the energy consumption in high power industries like melting and casting of steel, titanium and aluminium [2].

Even though today it is possible to simulate flows, as already done in [3,4], these calculations are associated with high computational power usage even if only a few seconds or minutes of flow need to be simulated. This leaves experimental studies using laboratory setups as the only possible option for studies of the long-term behaviour of the flow movement.

Several studies have investigated the heat transport and the large scale flow structure e.g. [5,6,7,8] by determining the dependency of the Nusselt number Nu on the Rayleigh number Ra (see below for definitions). Fewer studies address the dependence of the flow on Ra, in particular the dynamics of the large scale circulation (LSC) and turbulent substructures [8]. This is also due to the fact that the concerning low Prandtl number fluids are opaque which prevents the use of highly developed and easily applicable optical imaging techniques like particle image velocimetry and Lagrangian particle tracking.

The purpose of the presented experimental study is an in-depth analysis of flow substructures in Rayleigh-Bénard magnetoconvection by utilizing temperature measurements and ultrasound Doppler velocimetry (UDV).

2. Setup Experiments were performed in a cylindrical container with the inner diameter $D = 2R = 180$ mm and the aspect ratio $\Gamma = D/H = 1$ where H is the height. At the bottom the cylinder is closed by a copper plate. The cell is heated by an electrical heating plate attached to the bottom copper plate and cooled by water circulating through a heat exchanger embedded in a copper plate closing the top of the cell. The cylindrical sidewalls consist of polyether ether ketone (PEEK). The cylindrical sidewalls consist of Polyether Ether Ketone (PEEK). The cell is filled with the liquid metal alloy GaInSn with the Prandtl number $\mathrm{Pr} = 0.029$.

The sensor placement is shown in Figure 1. The temperature sensors amount to a total of 19 thermocouples. Four are placed in the top and bottom plate each, 4 mm away from the GaInSn. The mean temperatures of these sensors are used to control the heating and cooling facilities and to calculate the bulk temperature which was held constant at 35 °C for each measurement. Eleven sensors are positioned in a semi-circle around the middle of the cylinder in steps of 18° and are in direct contact with the GaInSn alloy. To measure the radial velocities, eight UDV sensors are located at three different heights in the sidewall of the cell. Counting from the bottom boundary surface between copper and the alloy, these measurement planes "Bot", "Mid" and "Top" are located at heights of 10, 90 and 170 mm. At each height, two sensors with an angle of $\pi/2$ between them are named "1" and "3". Additionally, the "Top" and "Bot" level each have a sensor number "2" which is placed in between sensors "1" and "3". Two further UDV sensors are placed in the top plate at radial positions $r/R = 0$ and $r/R = 0.8$ to measure the vertical velocity along their beamline.

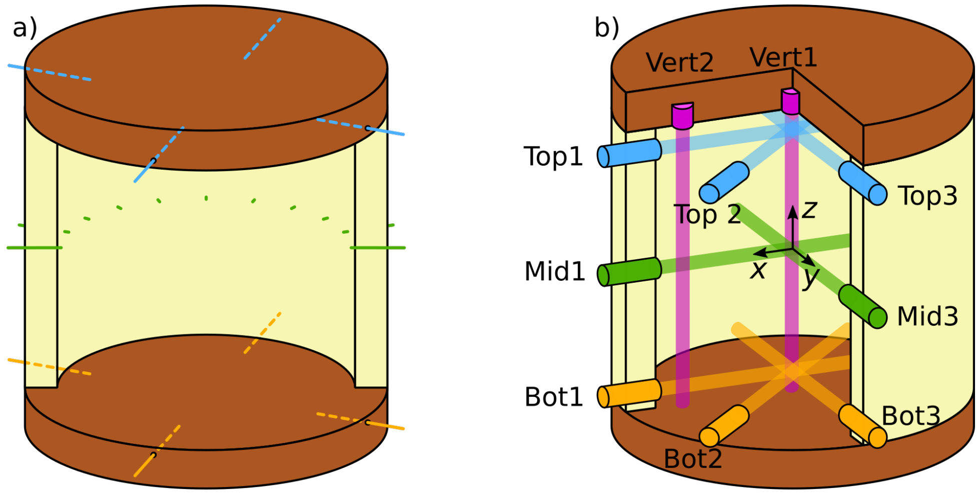

Figure 1: Schematical setup of the convection cell showing the thermocouple sensor placements (a) and the UDV sensor placement (b).

The Nusselt number is calculated by normalizing the global heat flux $\dot{Q}$ by the purely conductive heat flux $\dot{Q}_{cond} = \lambda A \Delta T/H$ over the height H between heating and cooling plate and through the horizontal cross section A of the convection cell. $\dot{Q}$ is determined by measuring the temperature difference $\Delta T_{water} = T_{out} - T_{in}$ between the in- and out-going cooling water of the heat exchanger in the top plate. Taking into account the volume flux $\dot{V}$ of the water, measured with a turbine flow sensor, the global heatflux can be calculated as

$$\dot{Q}_{cool} = c_{p,water} \cdot \rho_{water} \cdot \dot{V} \cdot, \Delta T_{water} \tag{1}$$

with $c_{p,water}$ and ρ_{water} as the specific heat capacity and the density of water at the mean temperature $T_{mean,water} = (T_{in} + T_{out})/2$, derived from [9].

3. Results In the absence of a magnetic field, the dependence of the Nusselt number Nu_0 on the Ra number is

$$\mathrm{Nu}_0(\mathrm{Ra}) \simeq ((0.10 \pm 0.02) \cdot \mathrm{Ra}^{0.28 \pm 0.01}. \tag{2}$$

This scaling is obtained by a power law regression of our measurements, as shown in Figure 2 a). It agrees very well with the curve obtained in direct numerical simulations published by Scheel et al. [4] thus excluding severe inaccuracies of the measurements and validating the setup.

Figure 2 b) shows the dependece of the convective part of the heat transport on the applied vertical magnetic field B_z, respective the Hartmann number $\mathrm{Ha} = B_z \cdot H\sqrt{\sigma/(\nu \cdot \rho)}$. Here σ, ν and ρ are the electrical conductivity, the kinematic viscosity and the density of GaInSn calculated at the mean fluid temperature [1]. The measurements depicted are normalized by $\mathrm{Nu}_0 - 1$, the convective part of the Nusselt number at $\mathrm{Ha} = 0$. If the Hartmann number is divided by $\sqrt{\mathrm{Ra}}$, the results collapse onto a single line for all Rayleigh numbers. Our measurements show a good agreement with the values of Cioni et al. and King et al. [5, 6, 7] and an almost perfect agreement with the simulated results of Liu et al. [3].

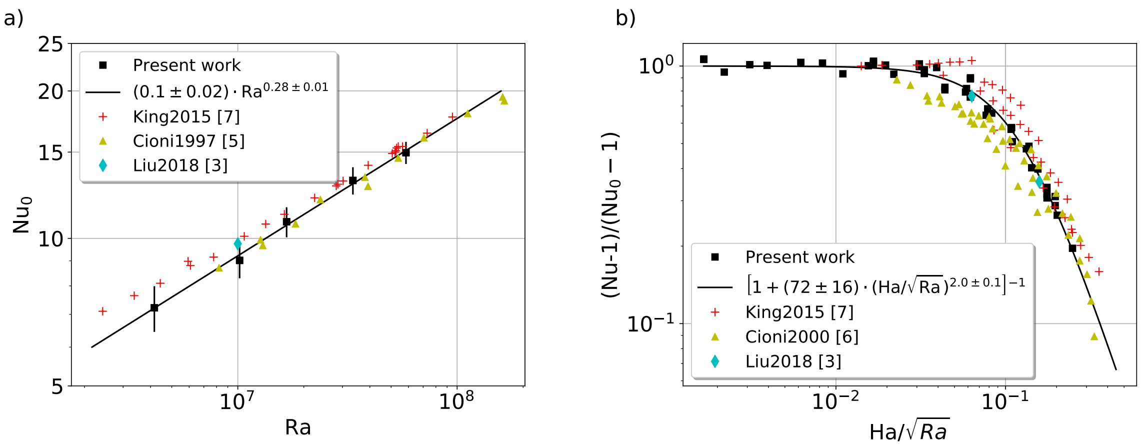

Figure 2: a) Nusselt number Nu_0 in absence of a magnetic field over Rayleigh number Ra. b) Convective part of the Nusselt number $(\mathrm{Nu}-1)$ under the influence of the vertical magnetic field normalized by the convective part $\mathrm{Nu}_0 - 1$ at $\mathrm{Ha} = 0$. The data in Cioni2000 [6] was normalized with data from [5].

As shown in Figure 3, the decrease in convective heat transport is caused by the growing magnetic field, influencing the flow by means of a Lorentz force. For Ha→ 0 the flow consists of a LSC with one circulation roll. This is shown in Figure 3 a) and b). The measured flow at the top is mainly directed towards the Sensor "Top1". At the bottom, the flow is going in the opposite direction, away from the sensor "Bot1". Figure 3 c) and d) show the change in the flow-structure caused by a vertical magnetic field. The flow velocity is strongly lowered and the cool downwelling flow is pushed to the sidewalls. This results in a hot flow rising in the middle of the cell, creating a toroidal cell-like structure. Also shown in Figure 3 is a rotating main-flow slowly moving in range of the sensors. Increasing the magnetic field causes a further suppression of the flow, resulting in the drop of the convective heat transport in Figure 2 b).

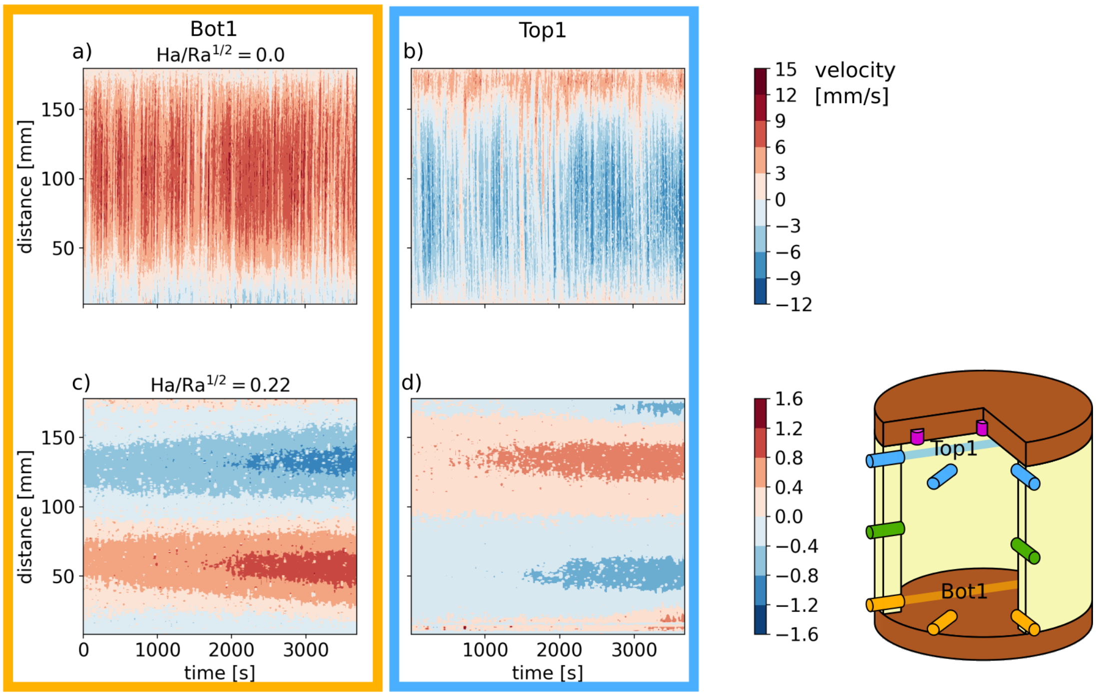

Figure 3: UDV measurements of the flow velocity in the convection cell without (a,b) and with (c,d) an applied vertical magnetic field. The vertical Axis is the distance from the sensor and the colorbar represents velocity in beam direction of the sensor probes. Positive velocities (red) are flows away from the respective sensor and negative values (blue) are flows towards the sensor.

4. Conclusion and Outlook Our measurements show, how a strong vertical magnetic field influences a liquid metal convection flow. The flow intensity and therefore also the heat transport decreases with increasing magnetic field strength. Our measurements are in good agreement with existing experimental and numerical studies. In addition to previous experiments, our setup allows the direct measurement of the velocity field and the internal flow structure using multiple UDV sensors. This reveals the breakdown of the well-known LSC flow structure of turbulent convection once the Hartmann number is increased.

Future studies will focus on a more detailed characterization of the large scale flow in the (Ra,Ha)-phasespace. Additionally, investigation of the global momentum transport and changes in the statistics of small-scale velocity fluctuations are planned.

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