Rayleigh-Bénard convection in molten salt at elevated temperatures

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ABSTRACT

The velocity field of turbulent Rayleigh-Bénard convection is analyzed by means of 2D2C particle image velocimetry (PIV). In order to investigate the influence of thermal radiation to the global heat flux hot molten salt with temperatures between 160 °C and 250 °C is used as working fluid. We report on the construction of the convection cell, the application of the PIV measurement technique and show first results of the velocity fields at two different Rayleigh numbers Ra = 1.7 x 10^7 and Ra = 1.3 x 10^8.

1. Introduction

Molten salts show a high potential for thermal energy storage systems and as heat transfer fluids (Otto et al. 2023). Typical temperatures of the transparent salts are in the range 200 - 400 °C. In this range the Prandtl number and the Planck number, characterizing the relative thickness of the momentum boundary layer w.r.t. to temperature boundary layer and the influence of radiation for the heat transfer, change significantly. For this reason, the flow behavior differs from low-temperature thermally driven flows. In addition, molten salts show an electrical conductivity that allows for magnetohydrodynamic flow control to influence the large-scale flow structures and thus heat transfer. For this reason, the present investigation aims to contribute to the fundamental understanding of Rayleigh-Bénard convection (RBC) when additionally affected by the combined effects of thermal radiation (Soucasse et al. 2020) and a magnetic field (Song et al. 2023; Li et al. 2024a). An experimental setup for the optical flow characterization using molten salt will be used. The experiments will be supported by numerical simulations.

Ordinary RBC (ORBC), i.e. the case when these additional effects are absent, refers to a special configuration in thermal convection where a horizontal fluid layer of height H is heated from below by a plate maintained at a constant temperature T_H and cooled from the top by a plate maintained at a constant temperature $T_C < T_H$. ORBC is considered to be a canonical configuration for studying convective heat transport phenomena in numerous natural and applied systems. Moreover, ORBC also serves as a classical example for a dynamical and dissipative system for which transition to turbulence, pattern selection and occurrence of large-scale circulations (LSC) are of fundamental interest. Turbulent RBC with a hot and electrically conducting working fluid (molten salt) can be considered as a simplified model for the heat flux in thermal energy storage systems and liquid metal batteries. In these applications, the turbulent heat flux is influenced by internal thermal radiation and externally applied or internally induced magnetic fields. In this case, besides the flow-driving control parameter Rayleigh number Ra, two additional dimensionless groups enter into the problem. These are the Planck number Pl as the ratio of heat conduction to heat radiation and the Hartmann number Ha as the ratio of electromagnetic force to friction force. The present study aims to determine the effects of these parameters on the LCS in the velocity and temperature field by conducting both model experiments and numerical simulations.

2. Experimental set-up and preliminary investigations

Early experiments for RBC in molten salts are discussed in the report of Hopfinger et al. (1979) and references therein. So far there are only few studies applying optical measurement techniques to molten salts. Sadoway and Szekely (1980) used LDV measurements in electromagnetically driven molten salts and Cramer et al. (2011) applied PIV to investigate the Marangoni flow on an open molten salt surface. The application of optical flow measurement techniques to a hot salt melt RBC requires a special design of the convection cell. There are high-temperature sealings necessary und the transparent side walls have to have a high optical quality. The salt melt of HITEC (53% KNO_3, 40% NaO_2, 7% $NaNO_3$) itself is transparent. One challenge for the measurements of the LSC investigation is the application of a suitable contactless optical measurement technique. In the present study we use 2D2C particle image velocity (PIV) with solid SiO_2 tracer particles. The spherical particles have a diameter of 10 μm and a density of 2 gcm^{-3} (same as salt melt).

In Fig. 1 the experimental set-up is introduced. The integral part is a RBC cell with a side length of 70 mm and an aspect ratio of unity. The cell is designed to withstand the required high temperatures and thus is completely made of quartz glass. The cooling and heating plates are made of an aluminum alloy which is chosen for its high thermal conductivity. This is important as slight changes in the boundary conditions (constant temperature or constant flux) will significantly alter the flow (Käufer et al. 2023). The temperature of the plates can be adjusted by pumping tempering oil though the plates and controlled with eight thermocouples connected to a data logger (AGILENT).

The laser light sheet is generated by a cw line laser (Z-LASER) with 532 nm wavelength and 40 mW power. A M-LITE 2M CCD-camera from LaVision GmbH with a NIKON Nikko objective (35 mm, 1:1,14) records the images of the tracer particles in the light sheet. Image rate (single frame) and exposition time are 40 Hz and 7 ms, respectively.

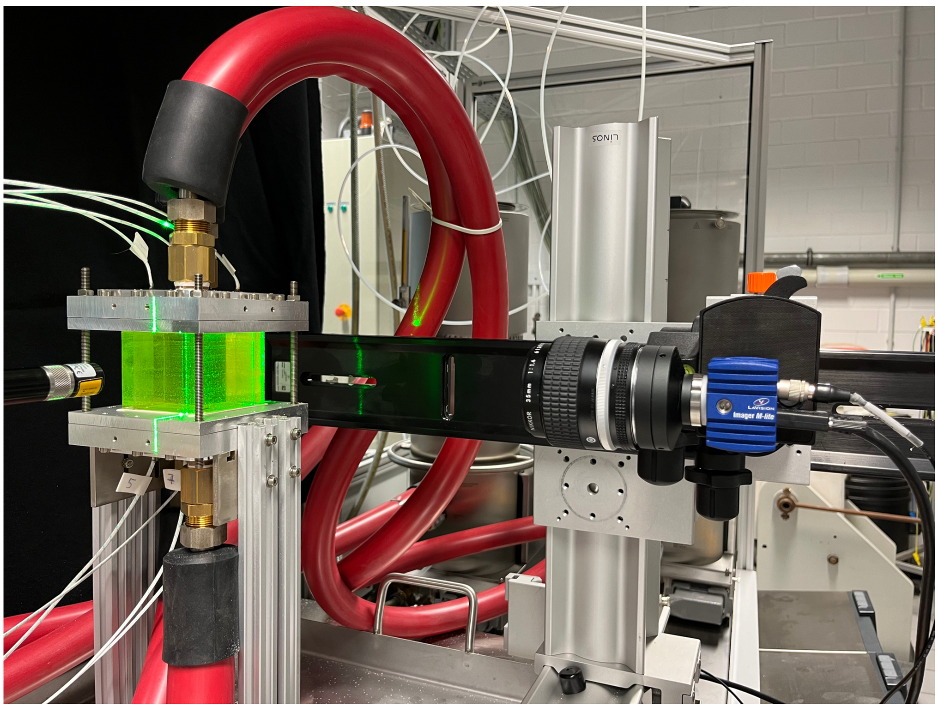
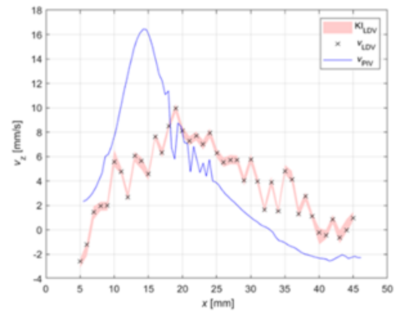


Figure. 1 Final experimental set-up with convection cell (green), laser light sheet (left) and PIV camera (right).

Figure. 2 Quartz glass cuvette on an electrical heating plate with HITEC molten salt and HGS particles for preliminary tests.



In order to select a suitable contactless velocity measurement technique both PIV and laser Doppler velocimetry (LDV) was tested in a simplified convection cell with a free surface using hollow glass spheres (HGS) as tracer particles (Fig. 2) (see also Li et al., 2024b).

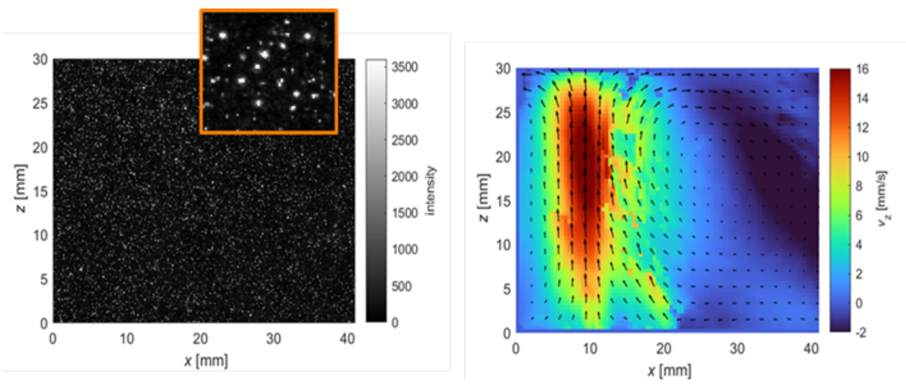
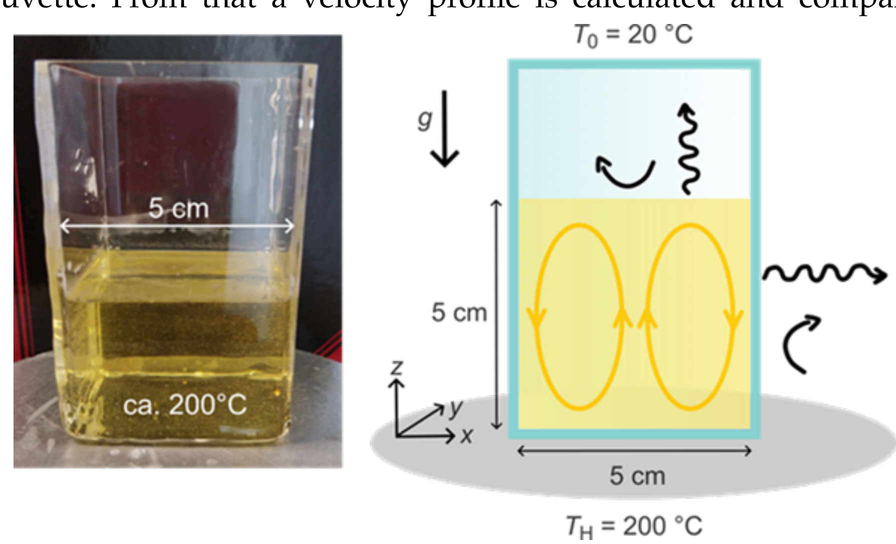


Figure. 3 Raw image after subtraction of the averaged minimum when exposed by a pulsed laser (left). PIV velocity field: Cross-correlation with multi-pass FFT and sum-of-correlation (right).

Figure 4 Instantaneous PIV and time-averaged LDV velocity profile.

Fig. 3 shows an instantaneous PIV raw image after background subtraction and the resulting velocity vector plot in the center plane of the cuvette. From that a velocity profile is calculated and compared with the time-



averaged LDV profile in the same plane (Fig. 4). Because these measurements have not been done at the same time, the profiles do not well collapse, but both velocity fields have in principle the same LSC. LDV is in principle applicable and has the benefit that only a small access for the laser is necessary and most of the cell may be insulated. However, the thickness of the quartz glass is not homogeneous, which results in small variations of the measurement volume position while scanning a line. Furthermore, the data are not instantaneous, i.e. it is not easily possible to evaluate the structure of the flow. Moreover, using LDV, the measurement duration is much longer for the same amount of data in comparison to PIV. After considering the limitations and benefits of both methods, the velocity field measurement with 2D2C PIV was favorized for further investigations (Li et al. 2024).

3. Results

Fig. 4 shows the time-averaged velocity vector field measured a vertical plane in the middle of the RBC cell for two different Ra. Every 4th vector is shown and the background colour corresponds to the velocity magnitude. The cooling plate temperature was set to 170 °C and the heating plate temperature was varied between 180-250 °C. For temporal averaging, 500 images are taken for each run and analyzed with the PIV software DAVIS 10 from LaVision GmbH.

For the lower Ra number, a two role LSC configuration can be anticipated by the strong uprising jet in the middle of the field of view. This completely changes for the larger Ra number to a single roll orientated in diagonal direction, which is a typical configuration in an aspect ratio unity convection cell. Due to the applied high temperature difference of 80 K, the velocity magnitude increases up to 20 mm/s.

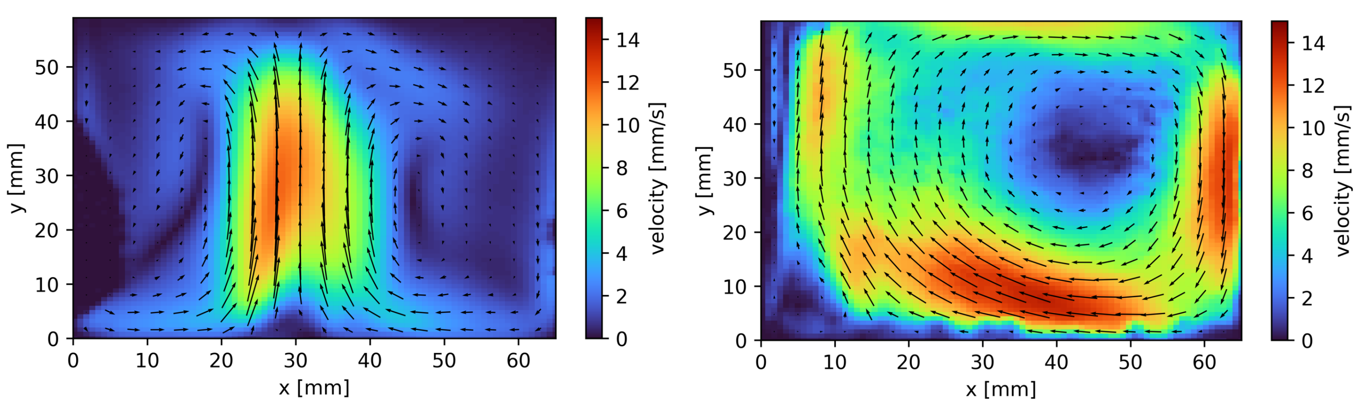


Figure. 4 Time-averaged velocity field from PIV measurements at Ra = 1.7×10^7 (left) and Ra = 1.3×10^8 projection of a LSC in a plane in the middle of the RBC cell.

4. Conclusion and outlook

It was demonstrated that PIV measurements of RBC in a convection cell filled with molten salt are possible. During the conference measurements for various Ra number will be shown and the different LSC will be discussed in detail. The high signal to noise ratio allows spatially very fine resolved instantaneous measurements. With this data also the reorientation of LSC during longer time spans can be studied. However, the quartz glass windows showed some kind of degradation of the transparency over time that has to be further analyzed. The setup of the cell showed no leakage, even running for several hours at 250 °C and allows for future long-term studies. When the molten salt freezes at room temperature, the cell can be disassembled and the salt can be taken out, grinded and used in the next experiment. However, special care has to be taken to further improve the boundary conditions since radiation and conduction towards the surrounding has to be minimized to not influence the flow.

Later, the finite difference scheme (Krasnov et al. 2011) will be adopted to conduct numerical simulation on RBC in a cavity under the combined effects of thermal radiation and magnetic field. Since Prandtl number has little influence in our investigation (Li et al. 2024a), in the simulations it is fixed as Pr = 7. Finally, the numerical results of the velocity and temperature field at different Rayleigh, Planck and Hartmann numbers will give important information about boundary conditions and measurement parameters for further investigations at temperatures up to 400 °C.

5. References

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