Wide field of view stereoscopic PIV measurements in a Rayleigh-Bénard cell

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Abstract

Turbulent flows show features on a large range of time and length scales which are difficult to access. Turbulent convection is an example of such a flow which is often encountered in nature and engineering. A simplified, yet fundamental model for that is the Rayleigh-Bénard Convection (RBC) case, where the fluid is confined in a box that is heated from below and cooled from above with adiabatic side walls and constant wall temperatures at the top and bottom plate. This flow is highly dependent on Rayleigh number and its complexity increases for higher Rayleigh numbers. Numerical studies of this flow are limited to short time realization of the flow due to the immense computational power consumption, while the experimental counterparts lack the accurate measurements of this flow for large Rayleigh numbers in large aspect ratio ($\boldsymbol{\Gamma} =$ width/height) RBCs. The latter is important due to the formation of turbulent superstructures in such systems that can be used as models for the atmospheric convection. Therefore, a facility, named SCALEX (Scaled Convective Airflow Laboratory Experiment), has been designed at the Technische Universität Ilmenau to fill the gap in the available long-time measurements of the large aspect ratio RBCs at high Rayleigh numbers. Therefore, current manuscript provides a description of the challenges faced in the experiments plus the current advancement of the measurements.

Introduction

Natural convection is involved in many geophysical and astrological phenomena. Thus, any advance in its understanding will expand our capabilities to predict or alter our surroundings. Meanwhile, the turbulent state of natural convection is a suitable case study to analyze turbulence from a fundamental point of view. A well-known idealized model of this flow is the Rayleigh-Bénard Convection (RBC) case. In RBCs the fluid is confined in a closed box where the bottom (heating) plate has a higher uniform temperature compared to the top (cooling) plate and the side walls are adiabatic. Initially, heat transfer is limited to conduction. As the temperature difference between the heating and cooling plates increases, the fluid in the vicinity of the cooling plate becomes denser and falls due to gravity and vice versa at the heating plate. This initiates convective heat and momentum transport in the fluid. The flow structure in RBC is dependent on the working fluid, the cell height, and the temperature difference between the top (cooling) and bottom (heating) plates. This is represented via a dimensionless number named as Rayleigh number (Ra) as follows:

$$Ra = \frac{\alpha \Delta T g h^3}{\upsilon \kappa} \tag{1}$$

In the denominator, α is the thermal expansion coefficient, ΔT is the temperature difference between the heating and cooling plate, g stands for the acceleration due to gravity, and h represents the cell height. In the numerator υ and κ are the kinematic viscosity and thermal diffusivity of the fluid, respectively. Thus, Ra is the ratio between the flow favoring effects (buoyancy) and flow hindering effects (friction). The onset of convection occurs at $Ra = 1708$ (critical Ra number). As Ra further increases, the flow becomes more chaotic and it shifts from simple convection roles to fully turbulent flow. Long-term analysis of this turbulent flow reveals so-called superstructures as the underlying skeleton of the turbulence. The number and structure of these superstructures depend also on the aspect ratio of the cell $\Gamma = l/h$ (I being the length of the cell). Large aspect ratio RBCs are more realistic models of natural convection and are richer in terms of the patterns of superstructures. Thus, investigating this type of flow has been a point of interest in recent years. Ideally, one aims at analyzing the large aspect ratio RBCs in large Ra numbers for long periods. The typical time scale in convection is the free-fall time $t_f = h/u_f$ (with free fall velocity being $u_f = \sqrt{\alpha \Delta T g h}$), and one needs to average the flow for about $100t_f$ to best visualize the superstructures. However, superstructures reorganize at around $1500t_f$. Thus, much longer time spans are required in order to study the dynamic behavior of the superstructures in a statistically meaningful way. Currently, numerical studies are limited to maximal simulation time of $250t_f$ and Rayleigh number of $Ra = 10^7$. Such simulations took several weeks on supercomputers and will take even longer if the Ra or the time span increases. Therefore, experimental studies are necessary to investigate RBCs at higher Rayleigh numbers for very long time spans.

Particle Image Velocimetry (PIV) can visualize superstructures via velocity measurements in the mid height of the cell. In PIV, the fluid is seeded with particles that are small enough to follow the flow faithfully. Then, consecutive images of the illuminated particles (via a laser sheet) are taken and compared to reveal the velocity field. It is therefore essential to have transparency through the heating or cooling plates and to have clearly distinguishable particle images. So far, few experimental attempts have been made to study RBC [Kästner et al. 2018]. Recently, Moller et al. [Moller et al. 2021, Moller et al. 2022] did experiments on RB convection in water for $Ra = 2 \times 10^5$ to 7×10^5 and the Prandtl number ($Pr = \upsilon/a$) of 7. However, Pandey et al. [Pandey et al. 2018] have recently numerically studied the effect of Prandtl number on RB flow, concluding that for similar Rayleigh numbers the flow structure significantly varies with Prandtl number variations. In conclusion, experimental measurement of the RBC in gas offers promising advantages in terms of studying the Prandtl number effect, creating a long-time measurement database, and investigating large Rayleigh numbers. In this regard, an experimental setup has been designed and developed at the Technische Universität Ilmenau to investigate RB convection in SF_6 and air over a wide range of pressures. As a result, it is possible to not only reach very high Rayleigh numbers up to $Ra = 10^9$, but also to vary Prandtl numbers between $0.7 \leq Pr \leq 1.3$, and to measure very long time spans for an RBC with an aspect ratio of 10. In the next section, we will discuss the challenges associated with the measurement setup.

Methods

The Rayleigh number depends on the temperature difference ΔT between the heating and cooling plates, the height h of the cell, and the flow properties. ΔT is limited to a few kelvins to comply with the Boussinesq approximation. Moreover, a large ΔT is not feasible due to technical reasons such as water cooling or heating, and because of the proximity of the heating and cooling plates. The height h is limited to small values because for a fixed aspect ratio Γ, any enlargement in h will result in a large length l of the cell as well, which prevents having highly resolved PIV measurements. Meanwhile, within the flow properties themselves, the thermal expansion coefficient α and kinematic viscosity υ do not vary significantly for moderate pressures. However, the thermal diffusivity κ is inversely related to the pressure. Thus, higher Rayleigh numbers are possible by elevating the flow pressure. Therefore, the convection cell was placed inside a pressure vessel named SCALEX (Scaled Convective Airflow Laboratory Experiment) at Technische Universität Ilmenau as schematically sketched in Figure 1 [Körner 2014]. SCALEX consists of a pressure vessel with a diameter of 980 mm that can provide pressures of up to 10 bar. Glass windows with a thickness of 40 mm distributed over the surface of the vessel provide optical access to its inside and thus allow optical measurements.

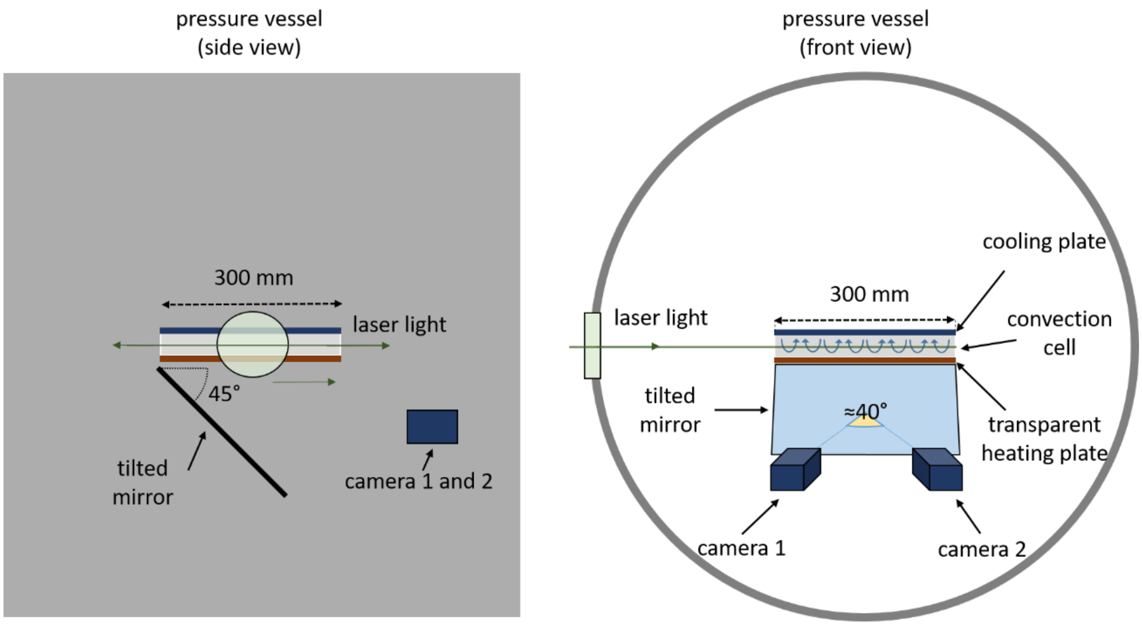

Fig. 1: A schematic sketch of SCALEX facility.

The Rayleigh-Bénard cell (RBC) has an aspect ratio $\Gamma = l/h$ of 10, and the cell height and length are 30 mm and 300 mm, respectively. Unlike numerical studies, setting adiabatic sidewalls and iso-thermal heating and cooling plates is quite challenging for experiments [Moller et al. 2022]. Meanwhile, the side walls and one of the heating or cooling plates must be transparent to shoot the laser into the cell and capture the images via cameras. In the current setup, the cooling plate consists of a nontransparent aluminum plate cooled by a recirculating cooler. The side walls are 4 mm thick Polycarbonate with thermal conductivity of only 0.2 W/mK. Thus, the side walls can be assumed almost adiabatic, especially in higher Rayleigh numbers. A transparent heating plate provides optical access to the cell. The heating plate is manufactured at the Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP Dresden. One side of the heating plate is coated with a thin layer of indium tin oxide (ITO, 150 nm) by plasma deposition. Then, the plate is heated via ohmic heating through direct electric conduction to the ITO layer via copper bands on both sides of the plate. Initially, two heating plate panes with a dimension of 500 × 500 × 4 mm^3 were stacked on top of each other to obtain uniform temperature distribution, and the RBC was positioned on a 300 x 300 mm^2 area of the heating plate [Cierpka et al. 2019]. However, this reduced the light transmission through the plate. Each heating pane has a light transmissivity of 0.68 only, which resulted in a total transmissivity of 0.4 for the heating plate. This had a negative effect on the signal-to-noise Ratio (SNR) of the particle images. Therefore, a single heating pane with a more uniform temperature distribution was manufactured so that one pane instead of two would be used. Figure 2 shows the temperature distribution captured by separate measurements using an infrared camera for the old and new heating plates with two and one panes, respectively. The average and standard deviation of the temperature distribution in the area of RBC over the heating plates are $28.63\ C^o$ and $0.36\ C^o$ for the new plate, and $28.53\ C^o$ and $0.25\ C^o$ for the old plate, respectively. In addition, the gradients from left to right and top to bottom are $0.60\ C^o$ and $1.03\ C^o$ for the new plate, and $0.99\ C^o$ and $0.98\ C^o$ for the old plate, respectively. Therefore, the temperature distribution is almost similar for the two plates thus the new heating plate has the advantage of more light transparency while holding the same degree of uniformity in its temperature distribution compared to its older pair.

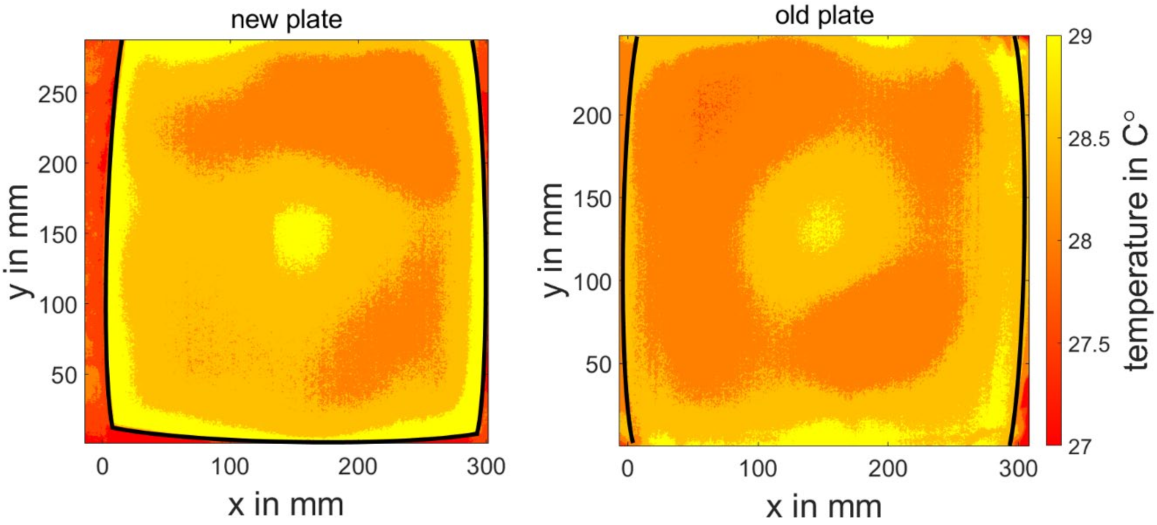

Fig. 2: Comparison of temperature distribution between the old and new heating plates with two and one panes, respectively.

The size of the seeding particles PIV is always compromise between having particles small enough to have a long sedimentation time and perfect advection of the flow, plus having bright enough particle images for PIV. The sedimentation velocity of the seeding particles u_s can be estimated as follows:

$$u_s = \frac{d_p^2(\rho_P - \rho_F)}{18\mu g}, \tag{2}$$

where d_p is the diameter of seeding particles, $(\rho_P - \rho_F)$ is the density difference between the fluid and tracer particles, μ is the dynamic viscosity, and g is the gravitational acceleration. For experiments in liquids, $(\rho_P - \rho_F)$ is often negligible and can be estimated to be zero. Thus, one can enlarge the seeding particle diameters to reach ideal particle images. However, the density difference term can not be neglected for the experiments in gases. Therefore, in order to have a reasonably low u_s, d_p must be chosen accordingly.

For the current study, small droplets of di(2-ethylhexyl) sebacate (DEHS) with $(d_p \approx 1\mu m)$ were generated using a vaporizer (PIVTEC GmbH). This results in a sedimentation velocity of approximately $u_s = 0.3\ \mu m/s$ for the worst case when air is in ambient pressure and thus lowest density for the experiments. However, the free-fall time is about 3.53×10^6 times higher compared to particles sedimentation time and can be neglected. In order to check the faithful tracing of the flow by the seeding particles, one should also calculate the Stokes number (St) as follow:

$$St = \frac{d_p \rho_P u_f}{18 \mu g} \tag{3}$$

Where u_f stands for free-fall velocity of the flow as defined in the introduction section. For our study, St is calculated to be less than 0.1, and thus particles are assumed to track the flow faithfully. In Figure 3 a schematic sketch of the entire seeding system which is placed inside the SCALEX is shown. The DEHS droplet generator generates the 1 μm particles which are directed to a settling chamber in order to settle down from their initial speed. It has been proven that the generator can create droplet particles at elevated pressures up to 9 bar as well. Then after the deposition of the particles, they are directed to the RBC via magnetic valves from six inlets. However, the injection of the particles disturbs the flow inside the RBC, so a waiting time of 15 minutes was required to neutralize this effect. The other important issue with seeding is that the particle intensity is reducing due to the evaporation of the particles [Cierpka et al. 2019]. For $p = 1$ bar the particle intensity is reduced to 80 percent of its initial value after 20 minutes. But, as the pressure increases to 2 bar, 80 percent of the initial particles are is still in the cell after 30 minutes. Thus, an increase in pressure reduces the speed at which particles are evaporating. Therefore, the evaporation of the particles limits the measurements to about 120 minutes in order to have reasonably acceptable particle image density in the PIV images. For further measurements, reseeding of the particles is necessary. However, 120 minutes correspond to about 24,000 free fall times for $Ra = 5 \times 10^5$ which is a reasonably long time span for the measurements.

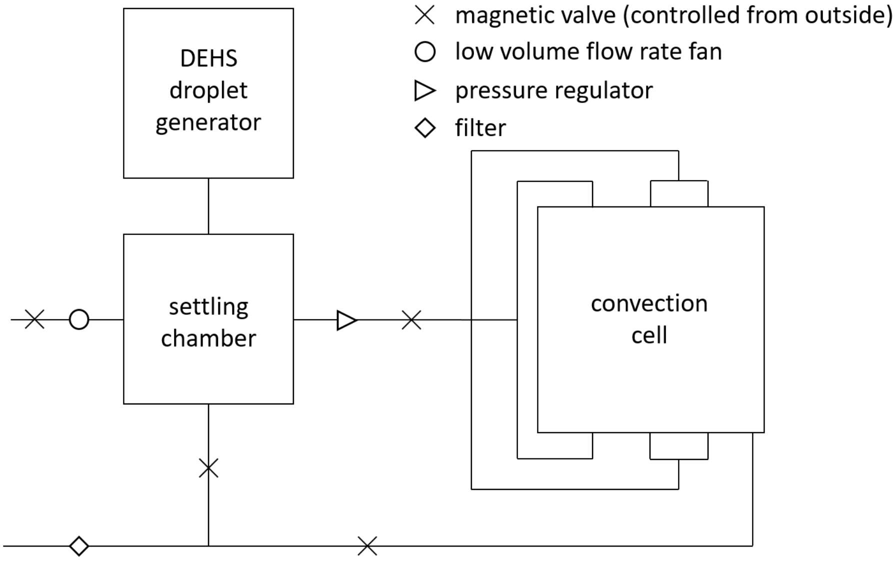

Fig. 3: A schematic of the seeding generation and distribution system.

The aim is to measure all three components of velocity in the illuminated volume of the cell at the mid-plane via stereoscopic PIV [Prasad 2000]. Therefore, as shown in Figure 1, two cameras (sCMOS by LaVision GmbH) with a 40 degree stereoscopic angle were placed inside the SCALEX. They are looking through a mirror tilted 45 degrees with respect to the heating plate due to space reasons. However, several challenges are in the way of acquiring acceptable PIV measurements in this setup. The first issue is the small signal-to-noise ratio (SNR) defined here as the ratio between the light intensity of the tracer particles and the background noise in the particle images. As already described in the previous section, particles need to be very small so that they can follow the flow faithfully, thus the low light intensity of the particles in the images is inevitable. However, the background noise can be reduced by careful adjustment of the experiments. In this regard, the thickness of the heating plate was reduced compared to the previous experiments as discussed in the previous section. This increased the light transmission through the plate from 0.4 to approximately 0.68. Furthermore, the concentration of the seeding particles should be in a level that is acceptable for the measurements but not too much, to prevent the thick fog of particles that will cause high background noise.

The next issue is the fact that in RB flow, the velocities are of the same order of magnitude in all directions. On the other hand, for the stereoscopic PIV, about 75 percent of the tracer particles should stay inside the illuminated volume. This is a problem due to the much smaller extension of the illuminated area in the out-of-plane direction by the laser light sheet, which will limit the time difference between the double frames to very small values. Given the fact that PIV measurements have an error of the order of 0.1 pixel [Raffel et al. 2018], this will increase the relative error in the measurements due to the small pixel displacements in the in-plane movements. One can increase the thickness of the laser light sheet to reach higher pixel displacements, however, this is also limited since increasing the laser thickness results in larger averaging of the flow in the out-of-plane direction. Nevertheless, it has been shown in the previous studies that a light sheet of 5 mm will not be problematic in terms of the validity of the PIV data [Cierpka et al. 2019]. Finally, in order to measure the out-of-plane velocity with high accuracy, the angle between the cameras should be high, ideally 90 degrees, so that they can see the out-of-plane movement with higher pixel displacement. However, this is an issue due to the limits faced with positioning the cameras in the SCALEX facility that forces to have 40 degree angle between two cameras.

Results

In the previous studies, successful PIV measurements in this setup that allow also the determination of higher order moments have been acquired in a Field Of View (FOV) of approximately $2h \times 3h$ [Valori 2022]. However, in order to characterize the flow field of RBC in different Rayleigh and Prandtl numbers, and to fully resolve the dynamics of the superstructures, measurements of the RBC for larger FOV, ideally $10h \times 10h$, is necessary. Thus, without moving the cameras further away from the cell, the focal length of the camera lenses was reduced from 100 mm to 50 mm to have a larger FOV of $5h \times 6h$. The initial PIV measurements have been started and up to this point, the results are promising. Figure 4 shows the initial results of the PIV measurements. Since the measurements have recently started, thus here only the PIV results of a single camera for the in-plane velocities are shown. However, this shows that the particle images are detectable by the PIV system and their displacements can be calculated with the current data.

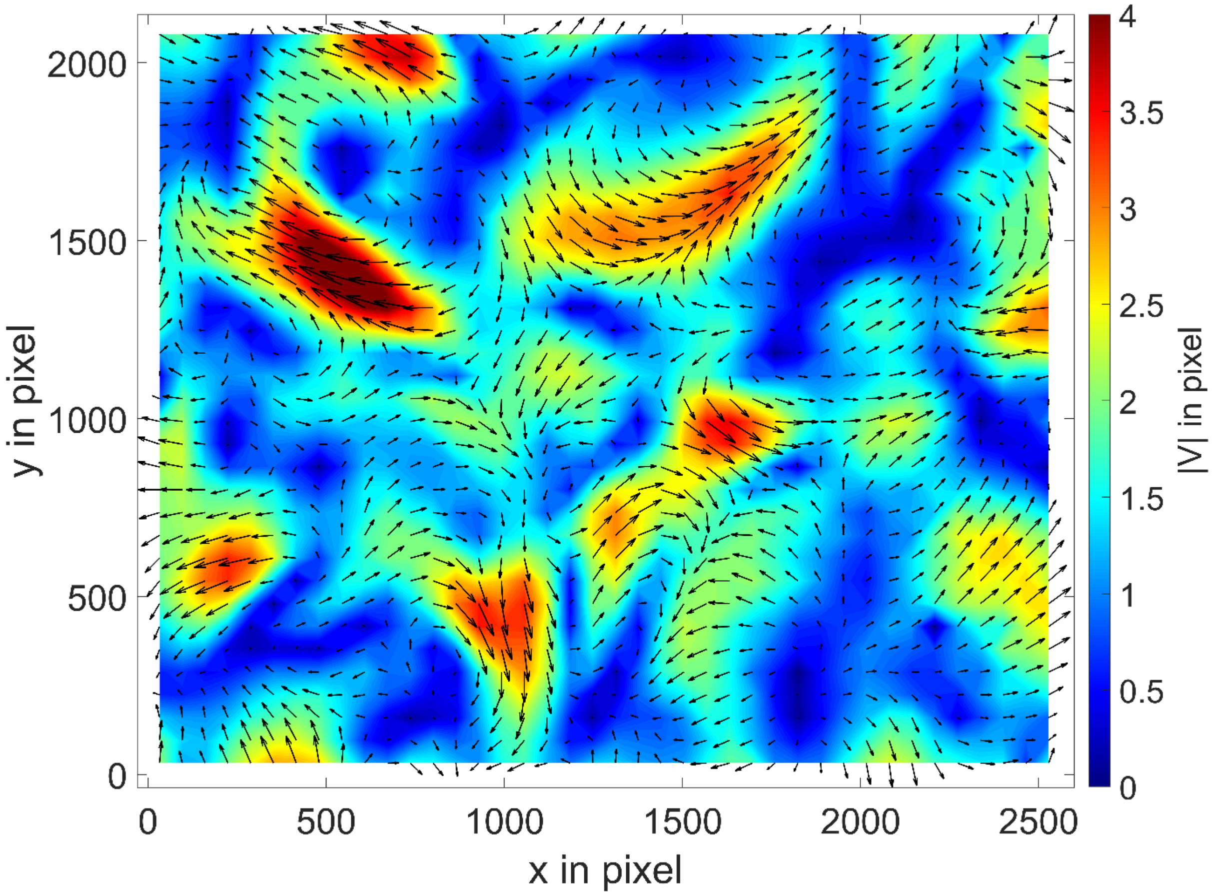

Fig. 4: The initial results of the PIV measurements for the in-plane movements of a single camera in a FOV of $5h \times 6h$. The absolute in-plane velocity is represented by the colors, while the arrows indicate the displacement directions.

Conclusion

The current state of the art for stereoscopic-PIV (SPIV) measurements of the Rayleigh-Bénard convection inside a pressure vessel (SCALEX) was discussed in detail. Several challenges are faced for the accurate measurement of all three components of the velocity field. The laser sheet thickness is limited to a maximum of 5 mm to prevent averaging of the flow in the out-of-plane direction while keeping enough particles in the illuminated area for reliable in-plane measurements. This results in a limited time difference between the frames of the SPIV to preserve the majority of the particles inside the illuminated volume for both frames. In addition, the relatively small space inside the pressure vessel limits the stereoscopic angle between the two cameras, which will further increase the uncertainty in the measurement of out-of-plane velocity. The seeding particles are very small ($d_p \approx 1$ µm), thus the signal-to-noise ratio of the particle images is low. Therefore, the thickness of the heating plate was reduced to its initial half to increase the light transmissivity from 0.4 to 0.68. Nevertheless, the promising advantages of characterization of Rayleigh-Bénard convection flow in a large FOV provide the motivation to tackle this problem despite the relatively complex experimental challenges in the way. In this regard, the recent measurements of the flow for FOV of $5h \times 6h$ show the possibility of the SPIV for large FOVs for this setup in the future. Therefore the next step is to find the maximum FOV in which the SPIV is possible. Then the aim will be to characterize the flow for different Rayleigh and Prandtl numbers and analyze the dynamics of the superstructures by long-time measurements.

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