Strömungsfeldvisualisierung von thermo-elektrodynamischer Konvektion mir einer kombinierten PIV- und Schattentechnik

Flow field visualisation of thermo-electrodynamic convection utilising a combined PIV and Shadowgraph technique.

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Key words: Thermo-Electrohydrodynamic convection, PIV, Shadowgraph technique

Abstract
Combined natural convection and thermo-electrohydrodynamic (TEHD) convection is studied experimentally in a differentially heated cylindrical annulus. The annulus is filled with a dielectric fluid where its density and electrical permittivity is sensitive to temperature and the later to an electric potential. Convection may than be induced in axial direction by terrestrial gravity and TEHD-convection in radial direction when applying an electrical field between the concentric inner and outer cylinder. To study both convection phenomena simultaneous PIV and shadowgraph measurements are conducted to understand the evolving temperature and flow fields. Results reveal similar convection patters as studied in microgravity of finite mode numbers evaluated by previous literature. The results suggest to further investigate such patterns to study the apparent increase in convection by the means to measure the heat transfer across the domain.

Introduction
Convective heat transfer plays an important role is may processes especially in cooling or heating applications. Therefore, it is essential to make such processes as efficient and effective to increase or suppress heat transport through boundaries or influence it by an active control. One possibility to achieve this is the use of dielectric fluids that possess the properties of a temperate dependent electrical permittivity variation. This property is used the present study to investigate convection based on a non-isothermal dielectric fluid in the presence of an inhomogeneous alternating electric field to induce thermo-electrohydrodynamic (TEHD) convection.
While heat exchangers play an important role in heat transfer applications for example to enhance or decrease heat rates, a differentially heated cylindrical annulus is studied and is one of the most common geometrical shapes compared to the plane cavity. To study the flow and temperature fields PIV and shadowgraph measurements are used simultaneously to get an indication of the complete thermodynamical process as previously studied by (Yoshikawa 2013 and Travnikov 2015) under microgravity convection. However, experiments are carried out in a terrestrial environment compared to many other microgravity investigations e.g. in parabolic flights (Meier et al. 2018, Meyer et al. 2019) or even on the International Space Station (Zaussinger et. al. 2019, Zaussinger et. al. 2020, Szabo et al. 2020, Haun et al. 2021).
To investigate the influence of TEHD-convection in the presence of gravity and to study the ability of heat transfer performance the fundamental convection patterns are studied and have to be visualized. The use of shadowgraph technique has proven to be a robust

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framework to investigate evolving and quasi-stationary convection cells within a differentially heated annulus (see, Meier et al. 2018, Meyer et al. 2019). In combination with the PIV technique simultaneous measurements can be achieved to be able to investigate evolving temperature fields together with their corresponding fluid velocity.

Experiment setup

The experiment cell a thermally heated annulus seen in Figure 1 (a) consists of two concentric cylinders with radius R_1 and R_2., respectively. The inner cylinder is maintained with temperature $T_1$and the outer with T_2 to apply a radial temperature difference of $T_1 = T_2 + \Delta T$ across both cylinders. The annulus is closed at the top and bottom to confine a dielectric fluid with properties given in (Table 1, Seelig et al. 2019).

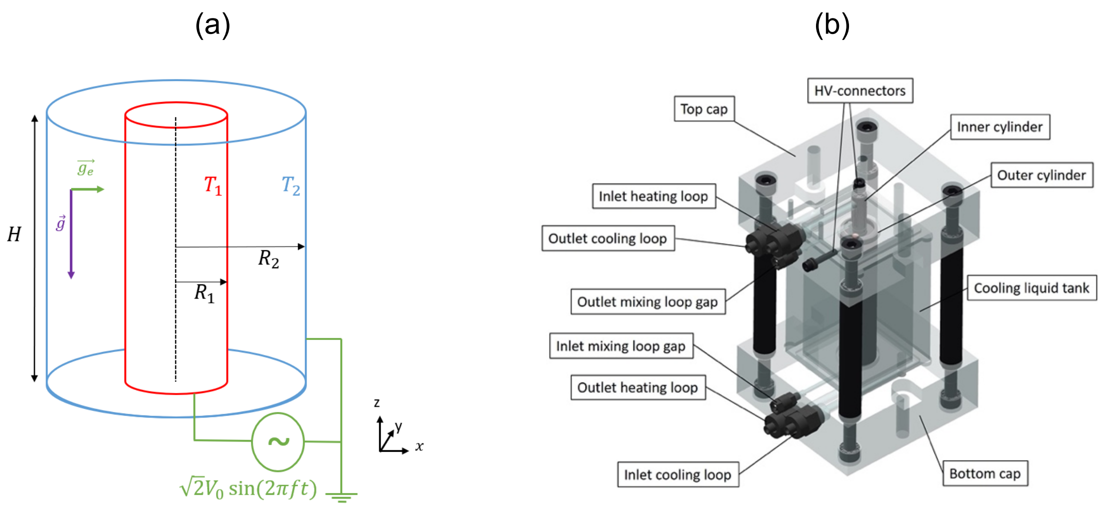

Figure 1: Layout of experiment cell in (a) and manufacture sketch in (b).

To induce TEHD-convection an alternating electric potential, $V(t) = V_p \sin 2\pi f t$, is applied at the inner cylinder whereas the outer is grounded. In addition to terrestrial gravity an electric gravity field is established in radial direction. All boundary conditions of the experiment cell are given for a vertical alignment with the geometrical properties and experimental parameter range in Table 1.

Table 1: Dimensions of cell and experimental parameter range (Meier et al. 2018)

Property	Symbol	Value	Dimension
Annulus inner radius	R_1	5	mm
Annulus outer radius	R_2	10	mm
Annulus height	H	100	mm
Aspect ratio	Γ	20	-
Radius ratio	η	0.5	-
Characteristic Length	$L = R_2 - R_1$	5	mm
Reference temperature	T_2	25	°C
Temperature range	ΔT	2-5	K
Peak voltage range	V_p	$\pm$10	kV
Voltage frequency	f	200	Hz

The manufactured experiment cell seen in Figure (b) is built accordingly to the theoretical specification. To thermally force the annulus, the outer cylinder is surrounded by a rectangular fluid containment that is connected to the cooling loop via the top and bottom cap. The same principle applies to the inner cylinder that is connected to the heating loop via the top and bottom cap and the electric connections which are also provided through both caps. To provide a good heat intake the inner cylinder is made out of aluminium alloy and the

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outer out of borosilicate glass coated with an electrical conducting transparent oxide (TOC) layer. This enables to see into the interior of the cavity to track suspended tracer particles for the PIV measurements. To control a set temperature difference both cooling and heating loop are monitored by 4-leads PT100 temperature sensors at each fluid loop's inlet and outlet. A more detailed description of the experiment cell is found in (Meier et al. 2018).

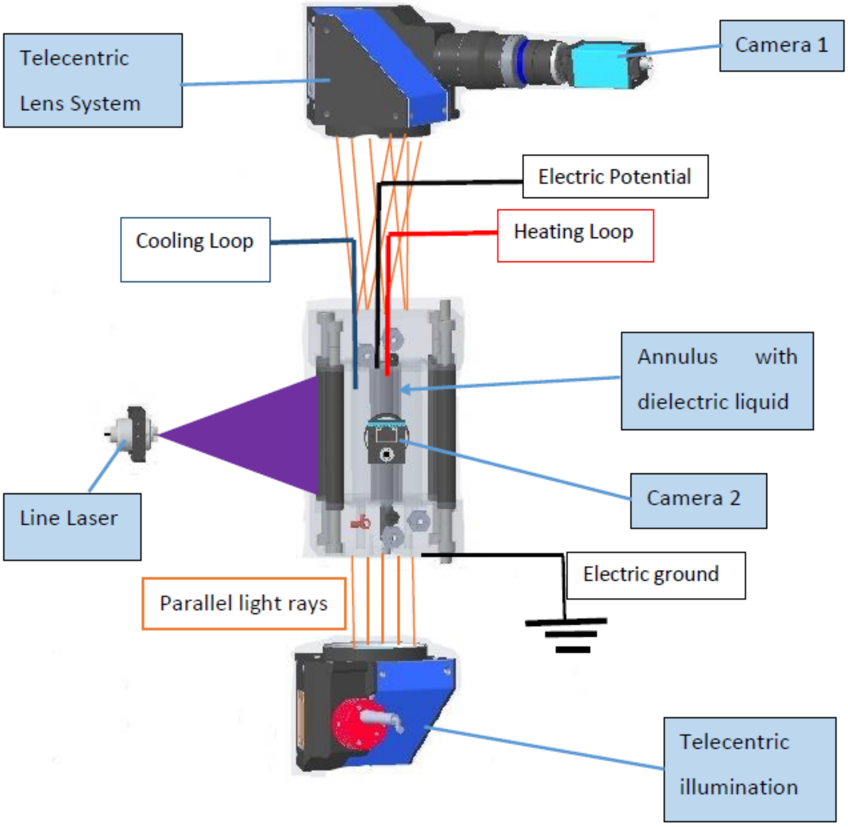

Figure 2: Sketch of simultaneous measurement of PIV and shadowgraph visualisation.

Simultaneous Shadowgraph and PIV measurement

In this section the PIV and shadowgraph technique are first introduced with their particular setup and is followed by providing how such a system can be combined to provide a measure of the evolving temperature and velocity field.

The shadowgraph technique is based on light refraction. In general, an illuminator emits columnar light rays that can be disturbed when they pass a fluid with density variations causing light refraction for example in a non-isothermal fluid as $n{\sim}\rho{\sim}T$ where n is the refractive index, ρ the fluid's density and T the temperature. The measurement principle follows the "*line-of-sight*" and is fact an integral quantity of through the individual path of each ray. Thus, a detector at the other side of the illuminator captures only a 2-diemnsional (2D) projection of the 3D field.

The PIV technique is based on observing tracer particles suspended in the working fluid that travel through space and time. These particles can be observed and corelated to calculate the fluid's velocity by recorded consecutive images. The present experiment utilises this technique by using a constant laser beam to illuminate tracer particles which are recorded by a camera manufactured by Imagine Source DFK33GX174 having a CEMOS Pregius sensor and a resolution of 1,920x1,200. The laser LLM-100-650 is manufactured by MediaLAS and emits a laser beam with a wavelength of 655~nm. In front of the laser's aperture a 110° lens is mounted to produce a homogenous laser sheet providing a radial plane to illuminate the tracer particles within the annulus at a width of 1.4~mm.

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There are two major reasons why a simultaneous recoding of refractive index and PIV are in use. First, one can provide corresponding shadowgraph and PIV images measurements that do not alter between consecutive repeated experiments, for example to do one or the other measurement separately before or after one another. This enables to record bifurcations and understand more complex flow fields that may alter in time and intensity.
The second reason is the physical relevance itself. While (Yoshikawa 2013 and Travnikov 2015) report on mode numbers from 4 to 6 that may establish in a differentially heated cylindrical annulus with a radial force field under microgravity conditions, the structures of the helicoidal nature or columnar cells within the system need to be captured experimentally. Thus, using an approach to visualise a line-of-sight measurement via shadowgraph systems may not reveal such structures but provide a deeper insight when comparing the results with PIV measurements.
A sketch of the simultaneous setup is depicted in Figure 2. The experiment cell is aligned together with the telecentric system where the illuminator is placed above the top cap with the telecentric detector and mounted camera on below the bottom cap. The PIV measurement is conducted parallel to the telecentric detector and is able to record tracer particles that are illuminated by a laser mounted perpendicular to the PIV-recording plane. Utilising this setup enable to measure the refractive index gradient that provides an indication of the temperature distribution in the line of sight and the fluid's velocity by a PIV-measurement.

Image post-processing

The shadowgraph images are post-processed with MATLAB where all non-essential parts are masked and only the cylindrical gap is evaluated. The masking is based on a triangulation where the centre of the gap is defined by three points placed on the outer cylindrical boundary. The RGB values are than converted into a grey scale expressed via a grey level, (GL), and plotted in heat scaled map.
The PIV images, to determine the fluid's velocity, are post-processed according to the same principle as was discussed in (Seelig et al. 2019) where the MatPIV 1.6 toolbox (Sveen 2004) was used. The field of view was calibrated and mapped from a pixel to mm coordinate-system with a resolution vof 16 px/mm. An irrogation windows of size 32x128, 16x64 and 8x32 was used to calculate the fluid's velocity by the algorithms embedded in as a toolbox in MATLAB.

Results and discussion

In this section we first present recorded shadowgraph images followed by simultaneous PIV measurements. A time resolved analysis is also given to provide an indication of thermal pattern development classified as observed mode numbers.
Figure 3 presents a set of shadowgraph images providing an indication of the temperature distribution via the refractive index after an equilibration period of about 20 min. At low electric potential only, the base flow is present and is defined with hot fluid rising at the inner cylinder towards the top and cold fluid descending at the outer cooled cylinder towards the bottom defining an overall large convection cell. Figure 3 (a, e, i) shows this base state of the shadowgraph images where no azimuthal mode numbers are observed indicating only natural convection referred the base flow. However, only a bright spot at the left-hand side of the cavity is observed and arise out of a non-uniform distribution of the incident light beam which was difficult to avoid. However, the flow is clearly disturbed when the peak voltage is increase to about 7 kVp where azimuthal mode numbers started to appear, see Figure 3 (b, f, j). These structures increase in intensity and mode number when the voltage is increase, see Figure 3 (c, g, k) and (d, h, l). The recorded shapes are similar of those reported in (Meier et al. 2018, Meyer et al. 2019, Szabo 2021) however are recorded at terrestrial gravity conditions such as those investigated by Seelig et al. 2019.
Figure 4 depicts the fluid velocity of the post processed PIV recordings for the case of $\Delta T = 5$ K and four different applied voltages ranging from 6 to 9 kVp. The simultaneous

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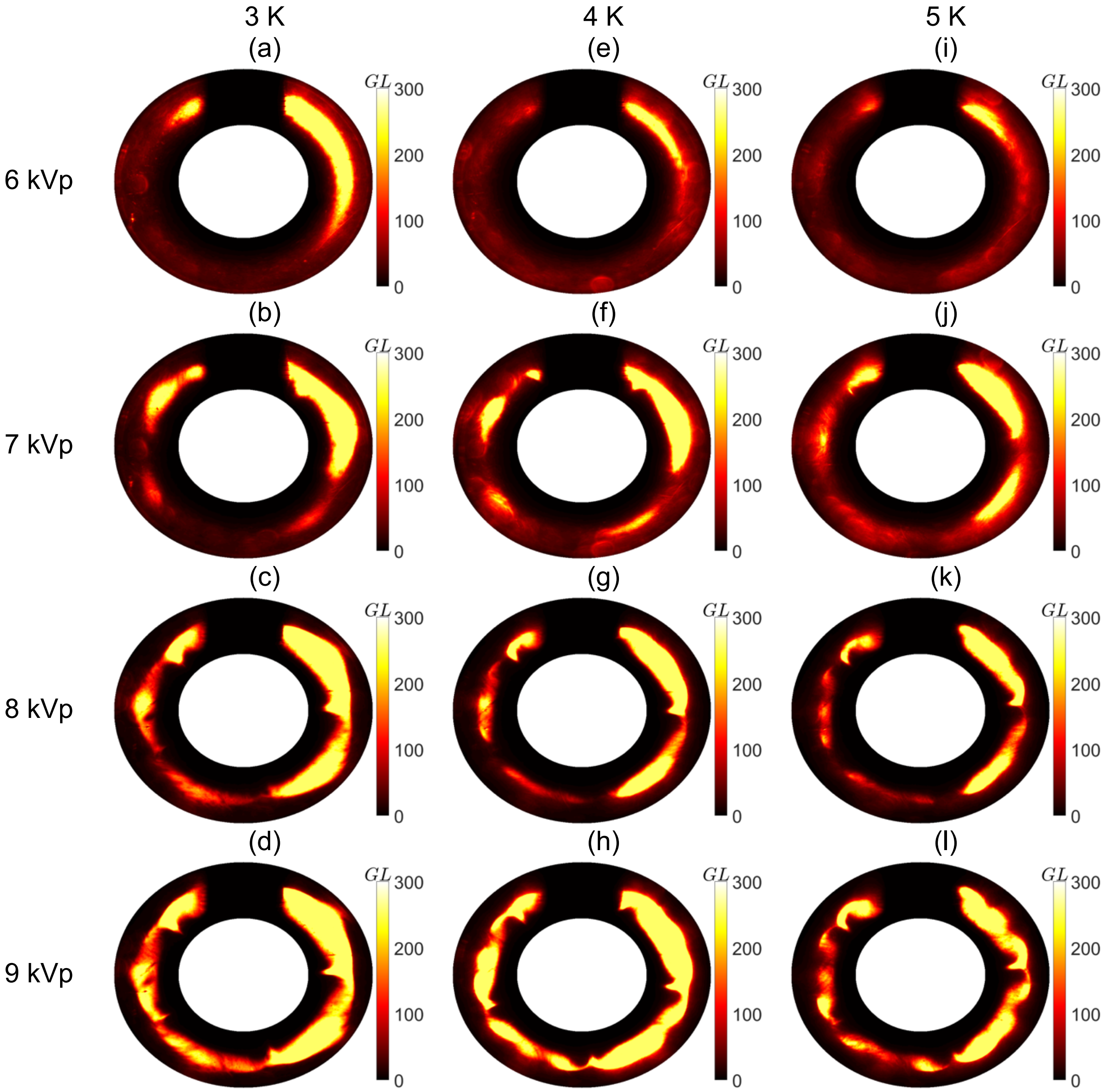

Figure 3: Shadowgraph images recorded at different electric peak potentials and applied temperature difference after a equilibration period of about 20 min that show a quasi-steady state developed mode structures.

recorded fluid velocity corresponds to the observed shadowgraph images and show no axial flow at small voltages as depicted in Figure 4 (a) where only natural convection is present indicating the typical structure of the base flow. With the increase in voltage radial flow fields become visible and show counter rotating convection cells between inner and outer cylinder indicating TEHD-convection. This of course is reflected in the shadowgraph images where azimuthal modes develop with increasing voltage.

A time resolved evolution of the induced radial TEHD-convection is given at the mid-gap for fluid velocity and at the azimuthal mid gap for the shadowgraph recordings in the upper and lower panel of Figure 5, respectively. With a temperate difference of 7 K and an applied voltage of 9 kVp a radial flow is observed at about 20 s after the electrical voltage is turned on. This indicates TEHD-convection in radial direction in the presence of the base flow. As shown by the PIV measurement the flow patterns appear to be radial at an axial height of about 20 to 80 mm of the cavity. This flow is also observed by the axial shadowgraph measurements in the lower panel of Figure 5 where azimuthal modes develop over time

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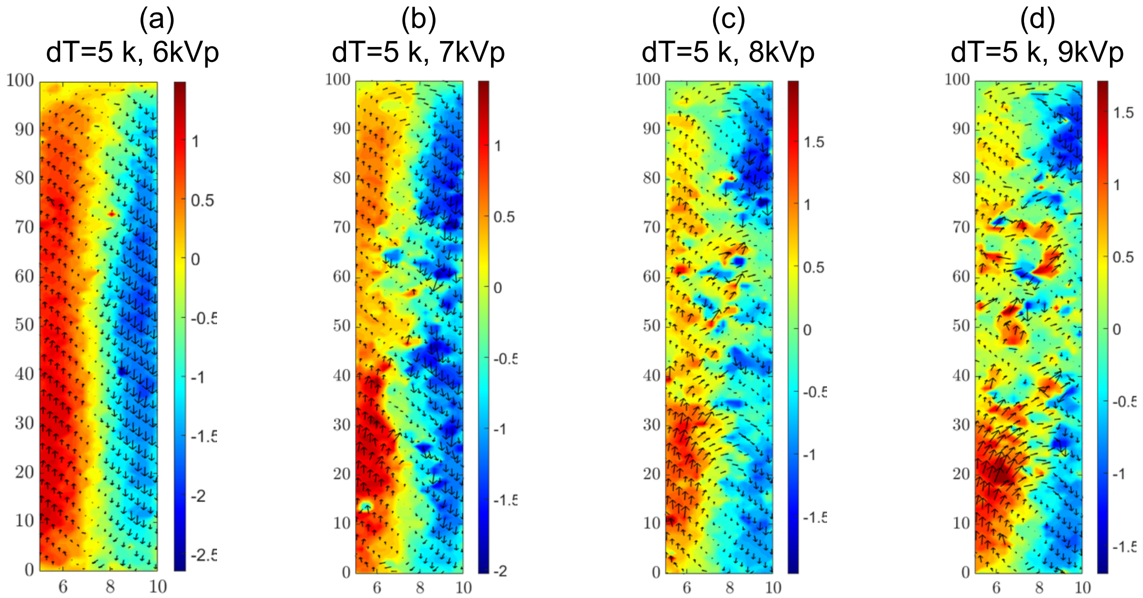

Figure 4: PIV measurements in the axial-azimuthal plane for $\Delta T = 5$ K at different peak voltages ranging from 6 to 9 kVp after an initial settling period of about 20 min. The velocity scale is in mm/s and the velocity magnitude multiplied by the sign of the vertical fluid velocity. Arrows indicate the flow direction.

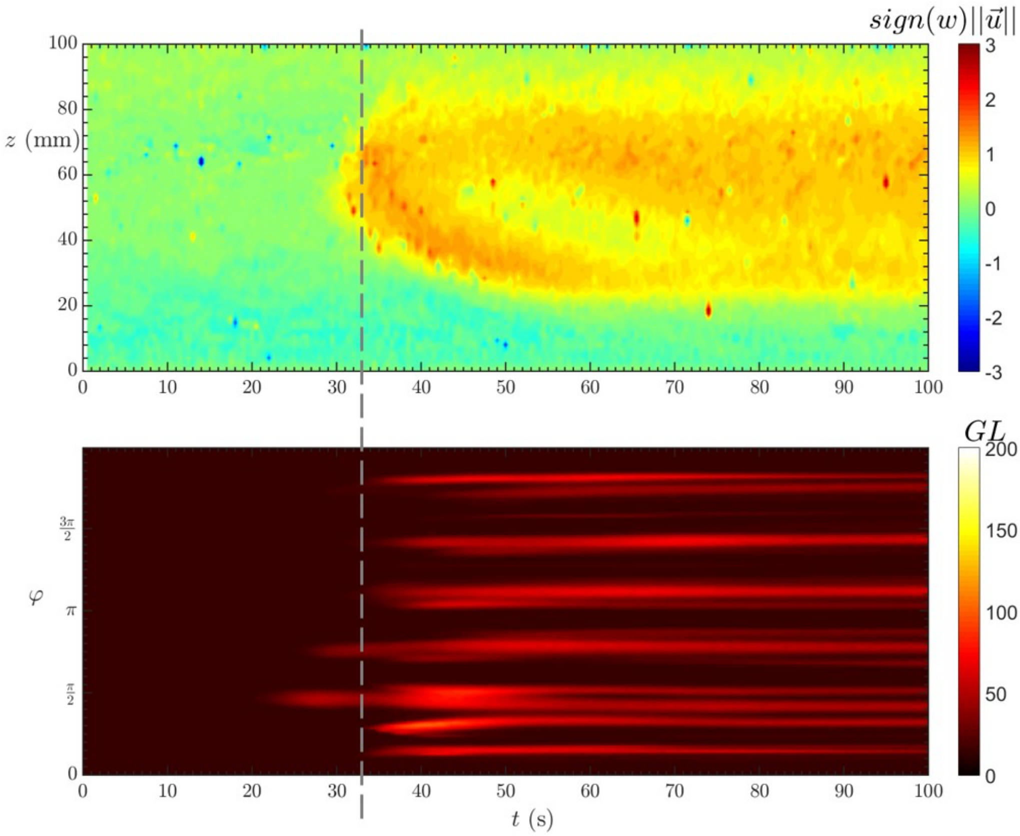

Figure 5: 7a) and b): Synchronized PIV (top; 7a)) and Shadowgraph (bottom; 7b)) space-time diagram. In both cases the selected radius is the mid-gap, ΔT=7K and Vp=9 kVp. Zoom on the first 100s. In both cases, the growth of the instability starts approximately at the same time, i.e. 20s after the high voltage is applied.

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indicating radial flow fields. It can be seen that both techniques record the simultaneous change in flow and temperature evolution to a quasi-steady state structure of fully developed radial convection cells, referred as TEHD-convection, in the presence of the axial base flow.

Conclusion

In this study simultaneous visualisation of combined natural and TEHD-convection was investigated by PIV and shadowgraph measurements. Both techniques showed to be a robust framework to analyse evolving flow patterns and temperature distribution inside a differentially heated cylindrical cavity. An electrical potential was applied between both cylinders to induce TEHD convection. Results showed that at about 7 kVp radial convection patterns develop that can be characterised by their mode number. It was further observed that the quasi-stationary mode number increased with electric potential. To investigate TEHD-convection without the arising base flow of natural convection further studies will be conducted during parabolic flight campaigns and the TEXUS sounding rocked project.

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