Summary

The main topic of this thesis is the influence of the dielectrophoretic (DEP) force on a thermal flow in a cylindrical annulus.

To perform these experiments an experimental setup was designed and constructed. Since it was used in parabolic flights certain safety standards and limitations had to be applied. Two different Experiment Boxes were build for different measurement methods. Inside these boxes are among other things the Experiment Cells, which consist of two concentric cylinders with a height of $H = 30mm$ or $H = 100mm$. The inner cylinder is heated and connected to the phase of a high-voltage amplifier. The outer cylinder is cooled and connected to ground. The gap is filled with silicone oil AK5, which is a dielectric fluid.

The temperature difference causes a thermal convection in axial direction. The DEP force invoked by the electric field creates a radial, inward-directed force. The combination of both forces creates a complex flow pattern in laboratory experiments. The experiment is also performed in a microgravity environment during parabolic flight campaigns to reduce the axial force to $< 0.1g$. The flow patterns which emerge during microgravity conditions can be different than in laboratory experiments with the same applied temperature gradient and voltage. These patterns are visualized using different methods such as Shadowgraph, Synthetic Schlieren and PIV. Additionally the convective heat transfer is determined and described using the Nusselt number $\mathcal{N}u$. The experimental data is compared to theoretical data from a linear stability analysis. The patterns predicted by the theory can also be found in the experiments. It is also possible to see a change in $\mathcal{N}u$ when the flow pattern changes.

1. Introduction

Electric fields created by direct current (d.c.) have been used in microfluidics and biology to e.g. sort cells or purify fluids by electrophoresis since a long time. However, the application of alternating current (a.c.) fields has not been researched as thoroughly. In this thesis I will present some results of experiments on the effect of an a.c. electric field on a thermal convection in a dielectric fluid.

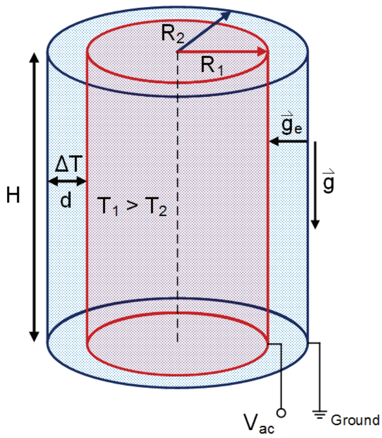

Figure 1.1.: A schematic of the experimental setup.

The experiments are performed in a cylindrical annulus (Fig. 1.1). The inner cylinder is heated, connected to the phase of a high-voltage amplifier and has the radius R_1. The outer cylinder is cooled, connected to electric ground and has the radius R_2. The gap with width $d = R_2 - R_1$ is filled with a dielectric fluid. The height of the cylinders are given by H. When a temperature difference $\Delta T = T_1 - T_2$ is applied, then a flow with an unicellular flow pattern (Fig. 1.2) is induced. This flow is driven by the temperature dependent density changes of the fluid and the natural gravity g. The permittivity of the fluid is also temperature dependent. It increases as the temperature of the fluid decreases. When an electric a.c. field is applied in addition to the temperature, then an electric gravity g_e acts on the force. It is in fact not a gravity like earth's gravity, but the effects can be compared. The permittivity increases when the temperature decreases. The fluid from the outer cylinder, which is cooled, will be pulled towards the inner cylinder (Pohl 1978). This is analogous to a density gradient and the gravity of the earth. Since the experiment is performed in a cylindrical annulus, the electric field is non-uniform and stronger near the inner cylinder. The combination of thermal and electric forces results in the thermo electrohydrodynamic force (TEHD). The experiment which we designed and build is able to achieve ΔT up to $20K$ and a peak voltage V_p up to $10kV$ at a frequency of up to $f = 500Hz$.

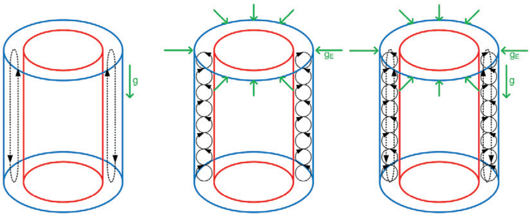

Figure 1.2.: The basic flow states inside the gap under different gravitational conditions (Dahley 2014). Left: Thermal convection with natural gravity. Middle: Thermal convection with applied artificial electric gravity g_e. Right: Superposition of both gravitational forces.

This flow is always superimposed by the natural convection in the laboratory. The natural gravity is stronger than the artificial electric gravity g_e (Eq. 3.5). Due to the curvature of the geometry the strength of g_e differs depending on the position in the gap (Fig. 1.4). It can be stronger than g directly at the inner cylinder, but is on average weaker. To isolate the effect of the radial oriented g_e, the experiments are performed in microgravity conditions during parabolic flights. Parabolic flights offer a comparably easy way to perform experiments in microgravity (μg). The experiment is mounted inside an aircraft and the pilots perform a special parabolic maneuver, which gives a phase of about $22s$ in μg ($g_z < 0.01g$). This time is very short compared to the time required that a stable temperature can establish, but it is enough time that new flow pattern can develop and stabilize (see Tbl. A.6).

This geometry was chosen because it resembles a triple pipe heat exchanger (Fig. 1.3). Hot fluid is pumped through the inner pipe. The cooling fluid is pumped through the outer pipe. The newly introduced middle pipe would contain the dielectric fluid. The heat transfer between the inner and outer pipe can then be regulated by changing the applied voltage. The experiments are performed in μg to get an understanding of the effect. Later this knowledge can be applied to design a setup to use in a $1g$ environment.

The experimental results are compared to a linear stability analysis (LSA)(Yoshikawa *et al.* 2013) and numerical simulations by Travnikov (Travnikov *et al.* 2015 and Olivier Crumeyrolle (not yet published). The LSA gives critical parameters for ΔT and V_p at which the flow changes the pattern in μg . There is also a LSA based on the same

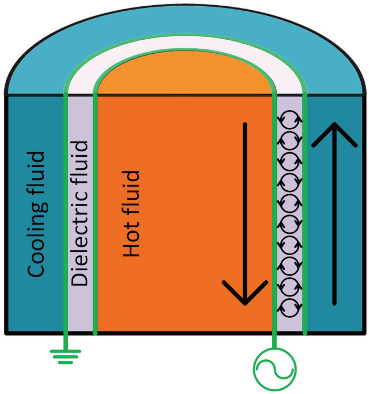

Figure 1.3.: A triple pipe heat exchanger where the TEHD force is used to control the convective heat transfer.

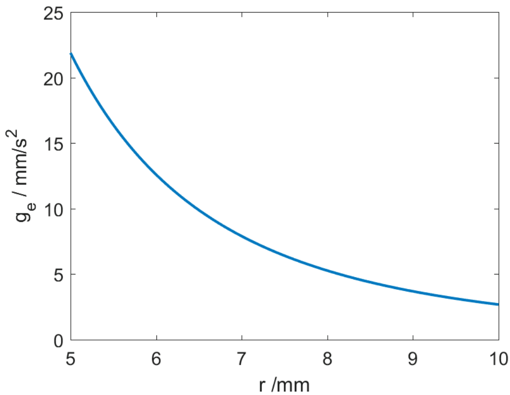

Figure 1.4.: The strength of the electric field inside the gap. The inner cylinder is at $r = 5mm$ and the outer at $r = 10mm$. The used parameters are $\Delta T = 10K$ and $V_p = 10kV$.

algorithm performed by Meyer, which gives the critical values for laboratory experiments including $g_z = 1g$ (Meyer 2017). The LSA assumes a cell of infinite length and applies the Boussinesq approximations for the density and permittivity. The simulations give a prediction how the 3D flow structure should look like in μg .

This effect gives a way to control a thermal convection. A gravitational force is required to create thermal convections. A possible application for TEHD is to create and control heat transfer in fluids in microgravity conditions. The gained knowledge can then be used to increase the efficiency of heat exchangers on earth (Bergles 1998; Futterer, Dahley, *et al.* 2016; Jongmanns, Meyer, *et al.* 2018; Laohalertdechaa *et al.* 2007; Marucho *et al.* 2013).

A first pre-study was performed by Norman Dahley (Dahley 2014) and Birgit Futterer (Futterer, Dahley, *et al.* 2016) at this department. I was able to use their experiences to continue to work on this topic. During the current project, we drastically improved the experimental setup to eliminate flashovers, modularized the setup to make it more variable, increase the reliability of the temperature gradients and measurements, and increased the quality of the visualization techniques. This allowed me to produces repeatable results with a higher quality, which are able to answer some of the open questions.

2. State of the art

Research on the DEP force has been performed by several groups since a long time, but it was mostly neglected in favor of the coulomb force. The coulomb force has applications in e.g. biology, where it is used to separate cells or molecules based on their charge. One of the first experiments involving the DEP force was done by Chandra and Smylie (Chandra *et al.* 1972). They used two concentric cylinders where the gap is filled with a silicone oil, one side is cooled and the other heated. An alternating electric field is applied to the two cylinders. The strength of the resulting DEP force is given as a dimensionless number, the electrical Rayleigh number. The temperatures were measured to calculate the Nusselt number, which is a measurement for convective heat transfer (Fig. 2.1). They also performed a linear stability analysis (LSA) to determine the critical parameters at which the heat transfer increases.

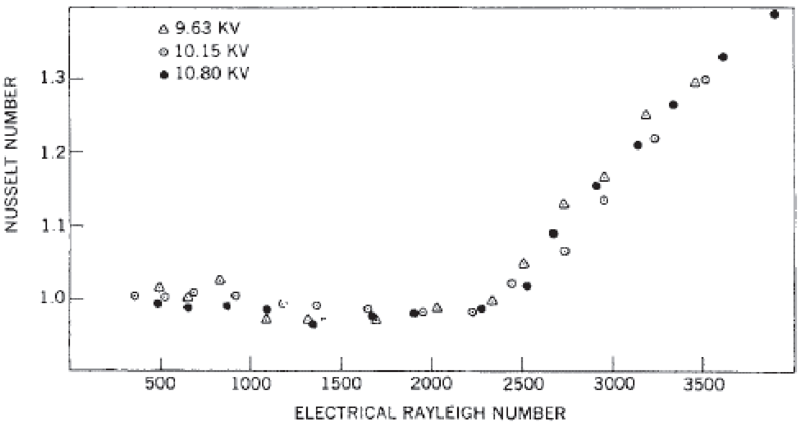

Figure 2.1.: Early experiment with applied electric field. The graph shows the critical Ra_e at which the convection, given by Nu, increases (Chandra *et al.* 1972).

The experimental results show that starting from an electric Rayleigh number of 2200± 100 the Nusselt number increases, which means that the heat transfer by convection increases because of the flow induced by the electric field. This agrees very well with their LSA, where the critical Rayleigh number is 2119.346. In their results, Nu first decreases slightly before is starts to increase. There is no explanation for this local minimum. The usage of DEP to increase heat transfer in fluid systems has also been suggested by others like Jones 1978, Laohalertdechaa *et al.* 2007, Futterer, Dahley, *et al.* 2016, and Allen *et al.* 1995.

A stability analysis (Bahloul *et al.* 2000) performed in a similar geometry, but without electrical field, aimed to determine the flow pattern within the gap along the height. The thermal buoyancy is characterized by the Grashof number, the diffusion properties of the fluid are defined by the Prandtl number and the geometry assumes a cylinder of infinite length with variable radius ratio η. They differentiate between two modes, a hydrodynamic (H.M.) and thermal mode (T.M.). The critical Grashof numbers for Prandtl numbers from 0 to 50 are given in Fig. 2.2. In the described thermal mode counter rotating vortices with their center at the center of the gap are established. This structure gradually changes to vortices with two rotation centers in the hydrodynamic mode.

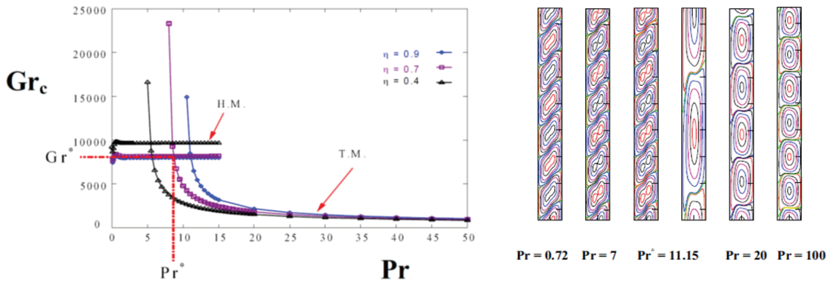

Figure 2.2.: Left: The point at Gr^* and Pr^* shows the parameters at which the mode changes between the hydrodynamic mode (H.M.) and thermal mode (T.M.) occurs. Right: Streamlines of the vortices (Bahloul *et al.* 2000).

The LSA is only concerned with the flow pattern, but not the resulting heat transfer. As different patterns have their specific effect on convective heat transfer, this information could indirectly be used to determine the heat transfer by convection. For example, a single, big convection cell has a lower convective heat transfer than several smaller cells.

Another approach looking at the effect of high voltage alternating electric fields on dielectric fluids was done by Sitte (Sitte 2004, Sitte and Rath 2003). Different methods were used. A first experiment was designed with a grounded electrode, which also emitted hot oil, and a plate to which the voltage was applied (Fig. 2.3, plate outside of image). The Shadowgraph method was used to visualize the jet. With increasing potential of the electric field the deflection angle of the jet increases, showing that the field has a direct influence on the fluid.

Some different parameters were tested by Takashima 1980. The temperature gradient was applied either by inward or outward heating and different radius ratios η were tested. For outward heating, the critical Ra_e decreased as η decreased. But for inward heating it was the other way around. The flow was more unstable for outward heating and can become completely stable for inward heating.

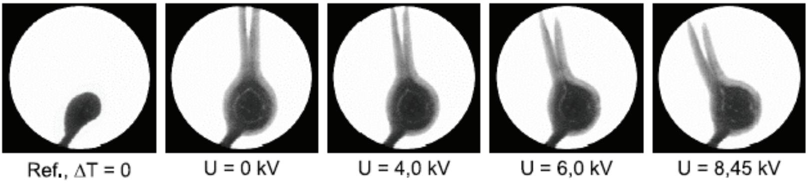

Figure 2.3.: Heated oil is emitted from an electrode. The angle of deflection increases with increasing electric potential (Sitte 2004).

Further Sitte did experiments in microgravity during a parabolic flight. For this experiments he used two concentric cylinders, similar to Chandra *et al.* 1972, where the gap is filled with a silicone oil. The gap is heated at one side and cooled on the other. The electric field is applied directly to the inner and outer cylinder. The Shadowgraph method is used as well to visualize the flow. There is no buoyancy flow in microgravity, since no external forces act on a fluid. However, when an electric a.c. field is applied to a fluid with stratified permittivity, a flow can be seen. The Shadowgraph images of Sitte give a first impression on how the structures inside the fluid changes (Fig. 2.4).

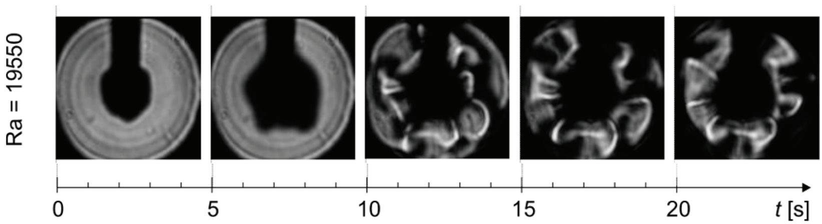

Figure 2.4.: The fluid inside the gap of two concentric cylinders is influenced with an electric field during a parabolic flight. The time line shows the development of the flow over one microgravity phase (Sitte 2004).

Quite recently a 3D numerical simulation (Travnikov *et al.* 2015) has been performed to compute the flow pattern in a cylindrical annulus of infinite length with applied temperature gradient and electric field. This simulation shows a pattern with slightly inclined columns from the bottom to the top of the gap (Fig. 2.5). The convective heat transfer was also determined and shows a greater increase than in a plane geometry.

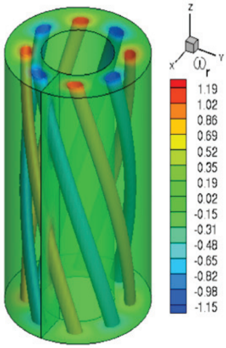

Figure 2.5.: A numerical simulation of the 3-dimensional flow assuming that the cell has infinite length with applied electric field and under microgravity conditions. $Ra_e = 1540, Pr = 100, \eta = 0.5$ (Travnikov *et al.* 2015).

A simulation of the development of the flow pattern in an experiment cell with $H = 30mm$, $\Gamma = 6$, $V_p = 10kV$ and $\Delta T = 10K$ has been performed by Olivier Crumeyrolle. He considered the same boundary conditions which are present during the parabolic flight. At the beginning of the μg phase (Fig. 2.6 left) there is still an unicellular convection pattern visible similar to the convection pattern in $1g$. At the middle of the μg phase this changes to a toroidal pattern, but also shows the onset of plumes in the lower part of the annulus. At the end of the μg phase, which is $22s$ after the μg phase started, there are only toroidal patterns at the upper and lower boundaries and plume structures otherwise.