1 Introduction

Research in microfluidics and mesofluidics focuses on fluid dynamics at small scales. These small scales offer the possibility of setting up physical effects, which are more efficiently at those ranges. With regard to industrial applications, especially of electro-hydrodynamic forces, e.g. small pumps and micro-dosing systems, cylindrical geometries come to the fore. Besides these small scaled applications is thermal flow control of interesting for containment in engineering, which often provides thermal insulation. Such interesting encapsulated set-up, e.g. is the cask for storage and transport of radioactive material (castor) containers. Another sample for such enclosures is a heat exchanger system. For this, an improvement of heat transfer via efficient enhancement is of general interest due to its benefits by low operational costs and due to sustainable usage of energy. From all available heat transfer enhancement techniques I want to focus here on the active method of applying electric fields, known as thermal electro-hydrodynamic TEHD driven heat transfer augmentation (Bergles, 1998; Marucho and Campo, 2013).

The project 'Convection in a Cylinder' (CiC) studies heat transfer enhancement for the case of two concentric, vertically aligned cylinders at small scales. The annular cavity is defined by the radii a and b, resulting in a gap width of $d = 5$ mm, and the length $L = 100$ mm, which lead to an aspect ratio of $\Gamma = L/d = 20$. The cylindrical gap is filled with a dielectric liquid, which viscosity is just few times higher than that of water. The inner cylinder is heated and the outer one is cooled.

When a dielectric fluid in an annulus is under common action of a radial temperature gradient and a radial alternating electric field, the variation of dielectric permittivity with temperature creates a radial stratification of the permittivity. This stratification, and the radial inhomogeneity of the electrical field, leads to the generation of a radial electric buoyancy force, which increases with increasing the applied high tension and/or with decreasing the annulus radii. An outstanding effect of this electric buoyancy force is an enhancement of heat transfer thanks to the convective flow pattern it creates Chandra and Smylie (1972), Takashima (1980), Smieszek et al. (2008).

However fundamental properties of the electro-hydrodynamic instabilities for cylindrical annulus have to be clarified, and further aspects arise due to the competition with natural convection. In Fig. 1.1 two cases of radial temperature gradient induced convection are distinguished. On the left side, the flow formation is resulting from natural gravity g, which is present in a laboratory. On the right side, a radial gravity g_E is set-up in micro-gravity μg conditions by means of an electric field, which will be discussed afterward. The set-up in a natural gravitational buoyancy field leads to a fluid movement in form of a single convective cell as expected, in which hot fluid is rising at the inner heated boundary and cold fluid is sinking at the outer cooled boundary. The top and bottom part

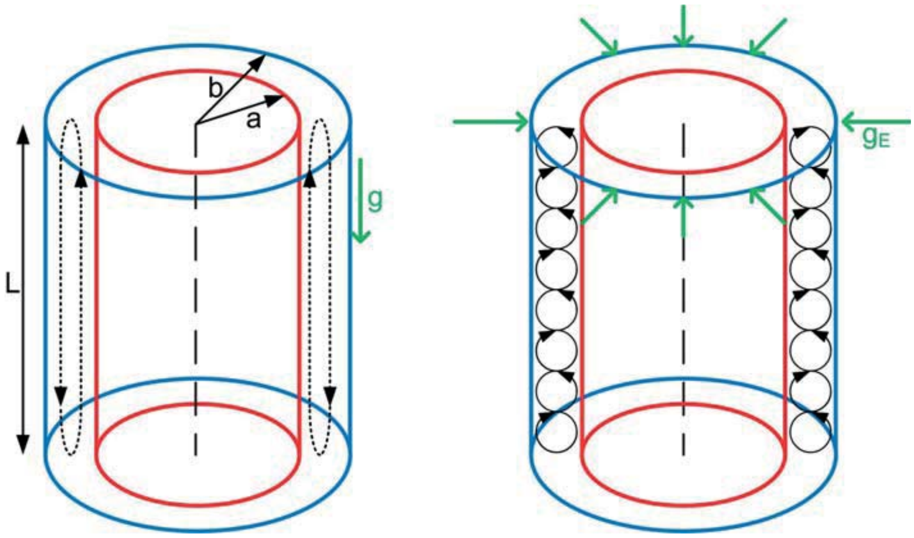

Figure 1.1: Schematic representation of the annular cavity with natural axial gravity g as first case and with radial gravity g_E as second case. The expected convective cell formation is plotted.

of the system shows horizontal movement, again in boundary layers. The strengthening of temperature gradient results into instabilities of that convective motion, as presented by means of a stability analysis and direct numerical simulation in Mutabazi and Bahloul (2002). The instabilities are characterized by small scaled convective cells.

The set-up of a pure radial gravity leads to much more complex patterns. An initial experimental and numerical study on the stability of thermal convection in such dielectric-insulating fluids were done by Chandra and Smylie (1972). They conclude, that it is feasible to overlay the axial natural gravity with a radial gravity, due to a high voltage field, and observed the onset of thermal convection with temperature and power measurement of the heat transfer. Takashima (1980) extended the work of Chandra and Smylie and solved numerically the linear stability problem. In both numerical studies, the flow system was considered to be infinite. However, the impact of the electrical field on the flow has not been fully clarified.

To filter out the pure electro-hydrodynamic effects, reduced gravity conditions are required. Parabolic flights give that opportunity, to investigate thermal convection and heat transfer in three different gravity conditions, see Fig. 1.2. Additionally to the 1g-laboratory situation, there are hyper-gravity ranges with an approximately double-g axial force field, i.e. 1.8g for about 20 seconds, and the micro-gravity μg range, which is very close to zero-g for a time-scale of 22 seconds.

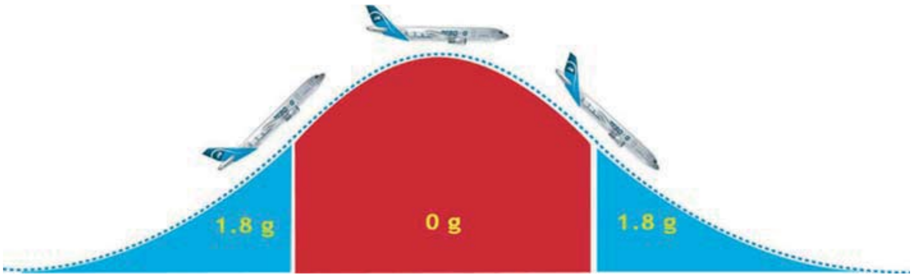

Figure 1.2: Natural gravity ranges in one parabola of a parabolic flight. Each parabolic flight consists of 31 parabolas. Courtesy of Novespace (2012)

With the goal to qualify that impact, Sitte and Rath (2003) set up an electrode experiment and, moreover Sitte et al. (2001b) and Sitte (2004) performed a parabolic flight experiment, in which they used a Schlieren-technique for fluid flow monitoring in the azimuthal plane, and only during the μg phase. In addition, their electrode experiment implicates the application of the dielectrophoretic force as flow control parameter in thermal convective effects, by controlling the onset of instabilities, due to g, with superposition of radial buoyancy, due to g_E.
From this it is possible to identify two open issues:

- effects of superposition of electric gravity with natural gravity
- extended studies of dielectrophoretic effect in microgravity

The arrangement of this work is as follows. First, I provide a short literature review in Sec. 2 identifying established results and open issues. In Sec. 3 I give a succeeding adequate background to the physical model of natural convection in the vertical annulus. Then I describe the experimental set-up involving flow visualization and heat transfer measurements in Sec. 5. There I also consider errors and quantification of uncertainty. The results are presented in Sec. 6 and in Sec. 7, I provide the outcome.

2 Preliminary work

This section focus on the review of literature, which describe the main topics of this work. Convection is known in a wide range of technical applications and in nature. This work points to the natural thermal convection, due to temperature-dependent fluid properties instead of technical applications (e.g. pumps, fans), where the thermal forced convection is often used. The impulse of such a natural convection are density gradients in gravitational buoyancy fields.

By assuming a stratification due to temperature gradients in non-rotating, Newtonian fluids due to buoyancy, it is possible to focus studies to natural convection. This is for delimitation of my work from the wide range of studies related Rayleigh-Bénard convection.

In this work I investigate two different constraints between temperature gradient and buoyancy force. One the one hand I have the natural convection with and without superposition of dielectric force, where the temperature gradient is inclined to the gravity. On the other hand I have the situation in parabolic flight, where the temperature gradient is parallel to the buoyancy force, which points to the topic of Rayleigh-Bénard convection. Etling (2008) subsumes the constraints between temperature gradient and direction of buoyancy under different categories, but he applies the behavior in the context of atmospheric flow and divides in barotropic and baroclinic behavior.

He describes the barotropic state as parallelism of isobars and isotherms in Cartesian space (z-space) and as horizontal isobars in pressure space (p-space). Therefor I want to anticipate the Rayleigh number Ra as dimensionless number associated with the heat transfer within a fluid. The onset of Rayleigh-Bénard convection, depends on a critical temperature gradient $\Delta T_{critical}$ and a critical Rayleigh number respectively. Below this onset, the barotropic state define the conductive flow in the fluid. In baroclinic state the isobars and the isotherms are inclined to each other in z-space. The discrepancy between the alignment of isobars and isotherms have to be balanced by the fluid and causes a convective flow immediately. The main topic of this work is to arranged right here.

The first part of the section discuss the studies related to the topic of natural convection. In contrast, the second part attends to the studies of thermal electro-hydrodynamic convection. At the end of this section, this work concentrates on the investigations, which discuss the superposition of thermal electro-hydrodynamic and natural convection, as an application of flow control.

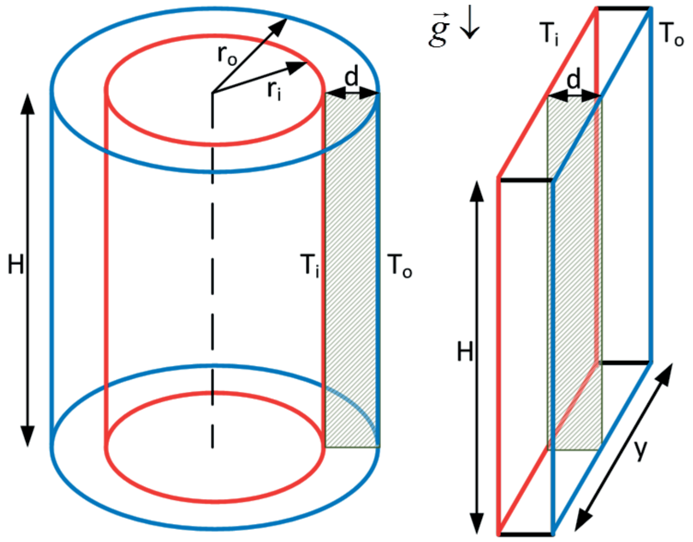

Figure 2.1: Schematic view of vertical aligned enclosures, in particular concentric cylinders (left) and a vertical slot (right) with a temperature gradient perpendicular to the gravity and adiabatic top and bottom boundaries. The radius ratio η for cylindrical enclosures is $\eta < 1$ and approximates to $\eta = 1$ for vertical slots.

2.1 Natural convection in vertical annuli

Natural convection is the flow motion that results from the interaction of gravity with density gradients within a fluid. The density differences may arise from temperature gradients or gradients in concentration or composition. This work deals with heat transfer combined with natural convection driven by temperature gradients in a Newtonian fluid in enclosures. In the large variety of enclosures, this work focus on vertical concentric cylinders.

In addition to the already introduced aspect ratio Γ, the dimensionless curvature

$$\beta = \frac{r_o - r_i}{r_i} \,, \tag{2.1}$$

describes the ratio of the gap width $d = r_o - r_i$ to the inner ratio r_i. The decreasing of the curvature leads to the geometry of the vertical slot. Figure 2.1 shows a schematic view on both enclosures with a two dimensional measurement plane. Many works dealt with natural convection in vertical slots in the past. The question suggest itself, when does the curvature influences the flow? My work investigates two curvatures with $\beta = 1.0$ and $\beta = 0.1$. This points to to question, can I assume the vertical slot with $\beta = 0.0$ as limiting case of convection in concentric enclosures. Tab. 2.1 specifies also the geometric parameters of the selected literature.

Table 2.1: Studies of natural convection in enclosures categorized by their dimensionless parameters and type of studies, e.g. experimental (exp.) or numerical (num.). The references (Ref.) are [1]: Elder (1965a), [2]: Elder (1965b), [3]: Lepiller et al. (2007), [4]: Ganguli et al. (2007), [5]: Venkata Reddy and Narasimham (2008).

Ref.	radius ratio η	aspect ratio Γ	Rayleigh number Ra	Prandtl number Pr	Grashof number Gr	Studies
[1]	1.0	1 – 60	$\leq 1.0 \cdot 10^5$	224 – 1000	$\leq 1.0 \cdot 10^2$	exp.
[2]	1.0	10 – 30	$\geq 1.0 \cdot 10^6$	7	$\geq 1.4 \cdot 10^6$	exp.
[3]	0.8	114.0	$9.7 \cdot 10^5$	3.5 – 7.5	$1.3 \cdot 10^4$	exp.
[4]	1.0	20	$\leq 1.0 \cdot 10^4$	0.7 – 7	$\leq 1.4 \cdot 10^3$	num.
[5]	0.1 – 0.5	1 – 15	$\leq 7.0 \cdot 10^7$	0.7	$10^6 - 10^8$	num.

Studies of natural convection heat transfer and fluid flow in enclosures has been studied very intense, because of its wide area of application in engineering. The most interesting applications are heating and cooling of buildings, solar collectors, insulation of double pane windows, cooling of nuclear reactor insulation, chemical vapor deposition, to name but a few.

A very recent literature review to natural convection in vertical slots is presented by Ganguli et al. (2007). They study numerically the genesis of formation of circulation cells due to thermal gradients for the range of the Prandtl number Pr, as the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity, between $0.71 \leq Pr \leq 7$. This includes namely the fluids mercury, air, water and silicone oil. They distinguish the results between experimental and analytical studies. In their own studies they capture the onset of multi-cellular flow patterns in a vertical slot for different Pr number and observe unsteady nature of cells and classify quasi-periodic behavior. For air and silicone oil, they find a good agreement with the experimental results reported in the literature. For mercury and silicone oil they point out, that the knowledge of pattern formation for low Pr numbers needs more discussion and further investigation.

Elder (1965a,b) studies the stability of fluid flow in vertical slots with viscous fluids (silicone oil and paraffin oil). He classify his studies in laminar (Elder, 1965a) and turbulent convective flow (Elder, 1965b). His apparatus has a larger height H than the width d and is sufficiently long in the third dimension y, comparable to Fig. 2.1, to assume a nearly two dimensional mean flow. The temperature difference ΔT is maintained by the two vertical side wall with different temperatures $T_i \neq T_o$. His studies contain three apparatus, the two slot experiments, where he can change the aspect ratio $\gamma = H/d$, by varying H

and the gap width d. The third apparatus is an concentric cylinder with fixed geometry and heated from within. The topic of his experiment focus on the interaction of boundary and shear forces in an experimentally 2D mean flow of paraffin and silicone oil with high Pr. In his case '2D' means, that he only take into account a middle part of a vertical box of $H = 0.80$ m and $d = 0.04$ m assuming that the boundary effects are negligible. An important finding is the 'cats-eye' pattern, shown in Fig. 2.2, and its modifications due to variation of the driving parameter Ra.

2.2 Thermo-Electro-Hydro-Dynamics (TEHD)

In a dielectric fluid, an inhomogeneous electrical field can be used to establish a buoyancy force, analogue to a gravity force (Landau and Lifshitz, 1984). This dielectrophoretic force is used in a broad variety of applications, e.g. as Pohl (1978). Jones (1995) showed, how to separate particles, to enhance the heat transfer through liquids or affect boiling processes (Snyder and Chung, 2000; Di Marco and Grassi, 2009). Jones (1979) introduce the definition of thermal-electro-hydrodynamics in his work. He studies the application of electro-hydrodynamics in related to thermal convection.

When I apply such an electric field E by a voltage potential V_{app} with $E = -\nabla V_{app}$, I consider the electric body force $F_E = F_C + F_{DEP} + F_{ES}$ formed by the electrophoretic (Coulomb) force F_C and the dielectric force F_D. This electric force is composed of the dielectrophoretic F_{DEP} and the electrostrictive force F_{ES} (Landau and Lifshitz, 1984). In general, I can neglect the gradient force F_{ES} as it has no contribution to the flow field (e.g. Yoshikawa et al. (2013a)). Applying direct current (d.c.) electric fields exert Coulomb forces F_C, whereas in alternating current (a.c.) electric fields of high frequency $f >> 1/\tau_e$, with τ_e as the charge relaxation time, the dielectrophoretic force F_{DEP} is dominant. Both forces enhance heat transfer, but F_C is more effective than F_{DEP} (Jones, 1979). Thus the electrophoretic force has been remained in focus up to now, e.g. very recently in Laohalertdechaa et al. (2007) and Marucho and Campo (2013). Researchers highlight the dielectrophoretic effect rather in the context of electrophoresis (Felten et al., 2008). In my work here, I study experimentally the heat transfer enhancement by the dielectrophoretic effect induced by application of an alternating current (a.c.) electric field superposing natural convection in the vertical annulus (Fig. 1.1).

In Tab. 2.2 is an overview of the geometric parameter of the following literature review to natural convection considered with superimposed a.c. electric fields.

An experimental set-up is designed by Smylie (1966) to investigate the fact that an electric field gradient induces a body force on dielectric liquids and that this force depends on the local temperature of the liquid. Fig. 2.3 shows the test facility of Smylie

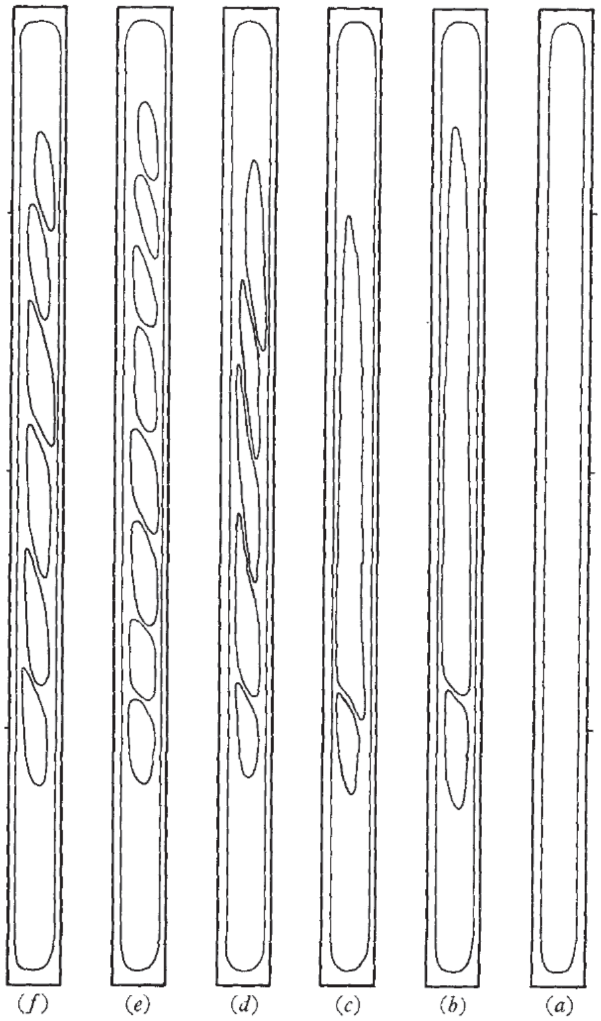

Figure 2.2: Streamlines of the flow with an aspect ratio $\Gamma = 19$ at increasing Ra: (a)$3.0 \cdot 10^5$, (b)$3.6 \cdot 10^5$, (c)$4.0 \cdot 10^5$, (d)$4.9 \cdot 10^5$, (e)$5.8 \cdot 10^5$, (f)$6.8 \cdot 10^5$; (Elder, 1965a, Fig. 9), reproduced with permission of Cambridge University Press.

Table 2.2: Overview to studies of Thermo-Electro-Hydro-Dynamics in cylinders in micro-gravity with type dimensionless Parameter and type of studies, experimental (exp.) or numerical (num.), some value were not mentioned and are marked as not available (*n.a.*). The references are [1]: Chandra and Smylie (1972), [2]: Takashima (1980), [3]: Bahloul et al. (2000), [4]: Sitte et al. (2001b), [5]: Malik et al. (2012).

Ref.	η	Γ	Ra	Pr	Gr	Studies
[1]	0.9	43.0	*n.a.*	*n.a.*	*n.a.*	exp.
						num.
[2]						num.
[3]	$0.4, 0.7, 0.9$	∞	$\leq 1.0 \cdot 10^6$	≤ 50	$\leq 2.0 \cdot 10^4$	num.
[4]	0.45	1.0	$1.9 \cdot 10^4$	35	$5.5 \cdot 10^2$	exp.
	0.29	1.0	$1.6 \cdot 10^4$	35	$4.7 \cdot 10^2$	exp.
[5]	$0.24 - 0.9$	$-$	≤ 8000	$1 - 200$	≤ 2000	num.

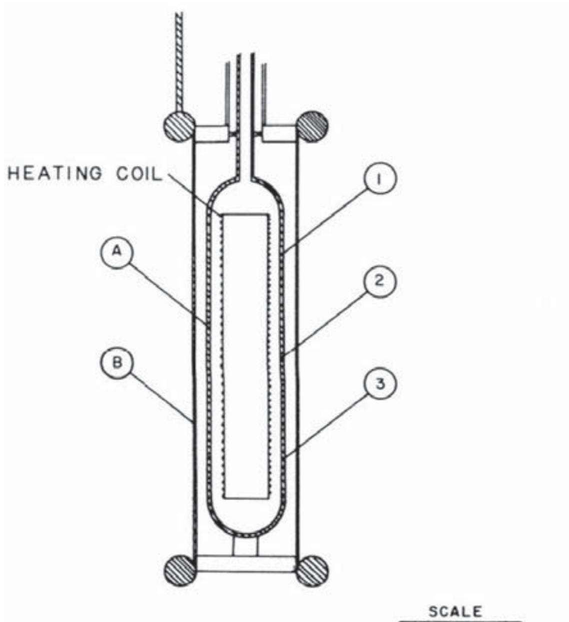

Figure 2.3: Vertical cross-section of the test facility of Smylie (1966, Fig. 1), reproduced with permission of Elsevier.