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Dielectrophoretic flow control of thermal convection in cylindrical geometries

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Contents

Nomenclature

Abbreviations and acronyms	
CiC	Convection in cylindrical annulus
coef	coefficient
CNES	National Centre for Space Studies (France)
DEP	dielectrophoretic
DLR	German Aerospace Center (Germany)
e.g.	for example *(lat. "exempli gratia")*
Eq	equation
ESA	European Space Agency (Europe)
Fig	figure
ISS	International Space Station
NASA	National Aeronautics and Space Administration (USA)
PFC	parabolic flight campaign
PIV	Particle Image Velocimetry
Ref	reference
Sec	section
Tab	table
TEHD	thermo-electro-hydrodynamics
therm	thermal

Formula symbol	
A_i	surface of the inner cylinder [m]
D	diameter [μm]
d	thickness, gap width [m]
E	electric field [V/m]
f	frequency [1/s]
F	force vector [N]
F_C	electrophoretic (Coulomb) force [N]
F_D	dielectric force [N]
F_{DEP}	dielectrophoretic force [N]
F_E	electric body force [N]
F_{ES}	electrostrictive force [N]
g	acceleration due to gravity [m/s^2]
g_E	electric gravity [m/s^2]
Gr	Grashof number $g\alpha\Delta T(r_o - r_i)^3/\nu^2$ [ ]

$Gr_{critical}$	critical Grashof number [ ]
H, L	cylinder height [m]
I_1, I_2	direct current amperemeter values [A]
n_i	refractive index
Nu	Nusselt number $Nu = \dot{q}_{conv}/\dot{q}_{cond}$ [ ]
Nu_i	inner Nusselt number $Nu_i = (\delta p_{real} \cdot P_{max})/([\lambda \cdot A_i \cdot \Delta T_{real}]/[r_i \cdot ln(r_o/r_i)])$ [ ]
P, P_{max}	heating power [W]
Pr	Prandtl number ν/κ [ ]
$\dot{q}_{cond}$	conductive heat transfer [W]
$\dot{q}_{conv}$	convective heat transfer [W]
Ra	Rayleigh number $g\alpha\Delta T(r_o - r_i)^3/\nu\kappa$ [ ]
$Ra_{critical}$	critical Rayleigh number [ ]
Ra_E	electric Rayleigh number $g_E\alpha_E\Delta T(r_o - r_i)^3/\nu\kappa$ [ ]
r	radius of inner ($_i$) and outer ($_o$) cylinder [m]
t	time [s]
T	temperature [K]
V_0	voltage at high-voltage generator [V]
V_{app}, V_{rms}	applied and root-means-square voltage, respectively [V]
v_i	phase velocity of the light [m/s]
x, y, z	orientation vectors in schematic sections

Greek symbols

α	thermal expansion coefficient [1/K]
α_E	coefficient of TEHD expansion [1/K]
β	curvature $(r_o - r_i)/r_i$ [ ]
δp_{real}	measured percentage of retrieved heating power[%]
ΔT	temperature difference [K]
ε	electric permittivity $\varepsilon = \varepsilon_r\varepsilon_0$ [As/(Vm)]
ε_0	electric constant $8.8541 \cdot 10^{12}$ [As/(Vm)]
ε_1	relative permittivity at a reference temperature $\varepsilon_1 = \varepsilon(T_{ref})$ [ ]
ε_r	relative permittivity [ ]
Γ	aspect ratio $\Gamma = H/(r_o - r_i)$ [ ]
η	radius ratio r_i/r_o [ ]
κ	thermal diffusivity [m^2/s]
λ	thermal conductivity [W/(m K)]

ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
τ_e	charge relaxation time [s]
τ_{visc}	viscous timescale $(r_o - r_i)^2/\nu$ [s]
τ_{therm}	thermal timescale $(r_o - r_i)^2/\kappa$ [s]
θ_i	angle of incidence (optics)

Subscripts

e	error
i, in	inner
o, out	outer
ref	reference
real	real and performance values
set	set and target values
syst, stat	systematic and statistical error

Mathematical operators

∂	derivative
∇	Nabla

Kurzfassung

Untersuchungen zur thermischen Konvektion in Zylinderspaltgeometrien erfassen eine Vielzahl von physikalischen und ingenieurtechnischen Problemstellungen. Der Fokus dieser Arbeit ist die experimentelle Untersuchung thermischer Konvektion im Zylinderspalt unter dem Einfluss eines elektrischen Hochspannungsfeldes. Ziel ist es, Möglichkeiten aufzuweisen, dass dadurch der Wärmetransport verbessert werden kann. Dieser Effekt kann beispielsweise für energie-effizientere Wärmetauscher genutzt werden. Dazu wurden zwei Experimentzellen aufgebaut, die einen beheizten Innenzylinder und einen gekühlten Außenzylinder haben. Die Temperaturdifferenz $\Delta T = T_i - T_o$ erzeugt eine thermische Konvektion im Untersuchungsraum zwischen beiden vertikal ausgerichteten Zylindern. Der Untersuchungsraum ist mit einer dielektrischen Flüssigkeit befüllt. Zur Erzeugung des Hochspannungsfeldes ist der Außenzylinder an eine Wechselspannung angeschlossen und der Innenzylinder ist geerdet. Die beiden Experimentzellen unterscheiden sich in ihrem Radienverhältnis η. Die Spaltweite und die Höhe des Untersuchungsraumes ist bei beiden Experimentenzellen gleich, ebenso das Aspektverhältnis Γ. Im Rahmen von drei Parabelflugkampagnen wurden verschiedene Weiterentwicklungen realisiert. Diese haben den Einsatz von Partikeln in einem elektrischen Hochspannungsfeld und eine vollständige Automation zu berücksichtigen. Auch eine Messeinrichtung zur Erfassung des Wärmetransportes wurde entwickelt und realisiert. Als maßgebliche Kenngrößen für das Experiment sind das Radienverhältnis η und das Aspektverhältnis Γ zur Beschreibung der Geometrie zu nennen. Die Eigenschaften der verwendeten Fluide werden in der Prandtl Zahl Pr zusammengefasst. Der Antrieb für die thermische Strömung wird mit der Rayleigh Zahl Ra beschrieben. Die Auswertung des Wärmetransportes erfolgt über die Nusselt Zahl Nu.

Die wissenschaftlichen Ergebnisse lassen sich in zwei Klassen unterteilen. Die erste Klasse (Laborexperiment) enthält die natürliche Konvektion in einem Zylinderspalt. Des weiteren enthält sie die Überlagerung der natürlichen Konvektion mit einem künstlichen Kraftfeld. Die Ergebnisse zeigen, dass eine stabile Konvektionszelle durch ein künstliches Kraftfeld gestört werden kann. Diese Störung induziert eine Verbesserung des Wärmetransportes. Die zweite Klasse (Parabelflugexperiment) beschreibt thermische Konvektion in einem ausschließlich radialen Auftriebsfeld unter Ausnutzung des dielektrophoretischen Effekts und ohne den Einfluss der natürlichen Gravitation. In den Beobachtungen wird deutlich, dass der elektrisch getriebene Auftrieb, eine Konvektion unter Mikrogravitationsbedingungen induziert. Die Strömung verbleibt auf Grund der kurzen Mikrogravitationsphase in einem transienten Zustand.

Die präsentierten Ergebnisse zeigen, dass die Wirkung des dielektrophoretischen Effektes genutzt werden kann, um den Wärmetransport zu erhöhen.

Abstract

Consider a fluid-filled cylindrical enclosure with an inner heated cylinder of radius r_i maintained at temperature T_i and an outer cooled cylinder of radius r_o maintained at temperature T_o. This vertical annulus is of height H with adiabatic top and bottom boundaries. The temperature difference $\Delta T = T_i - T_o$ induces natural convection in the gap width $d = r_o - r_i$ at infinitesimal small increments of ΔT. This base flow experiences transition to instabilities depending on the radius ratio $\eta = r_i/r_o$, aspect ratio $\Gamma = H/(r_o - r_i)$, physical properties of the fluids (weighted with the Prandtl number) and on the driving force (weighted with the Rayleigh number). In this present work, I study the dielectrophoretic effect as heat transfer augmentation force via the performance of an alternating current (a.c.) electric field superimposing natural convection in the vertical annulus experimentally. This procedure allows to introduce an electric Rayleigh number for the system. I can show clear distortions of the base flow via flow visualization and quantify heat transfer via heating power measurements resulting in a Nusselt number for the inner cylinder.

The experiment consists of two separately fully automated experiment cells, which differ only in their radius ratio. Since my first parabolic flight campaign, the experiment was refurbished and improved for three further campaigns. One of the main challenges is to observe the convective flow with tracer particles and laser light sheet illumination in an electrical high voltage field and to realize a heat transfer measurement system.

To give an short summary of the experimental result, I differ into two different cases. For the case of natural convection (in laboratory experiment), there exists a stable single convective cell over the whole Rayleigh number domain with increasing temperature difference between the inner and outer cylindrical boundaries. The superposition of both buoyancy forces indicates the disturbance of the single convective cell and therewith the onset of instabilities at very low Rayleigh numbers for the smaller radius ratio. For low values of the electrical Rayleigh number, the superposed electric field decrease the heat transfer, whereas for large values of electrical Rayleigh number I observe a clear increase of the Nusselt number.

For the case (in parabolic flight experiments) in microgravity environment, the observations show, that the electrically driven buoyancy induce convection. The flow remains in a transient state, due to the short time range of the microgravity phase. The observation can be proofed with the results of the heat transfer measurement via an increase of the Nusselt number.

The results of this work demonstrate, that the dielectrophoretic effect can be applied for thermo-electro-hydrodynamic flow control and enhancement of heat transfer applications on Earth.

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

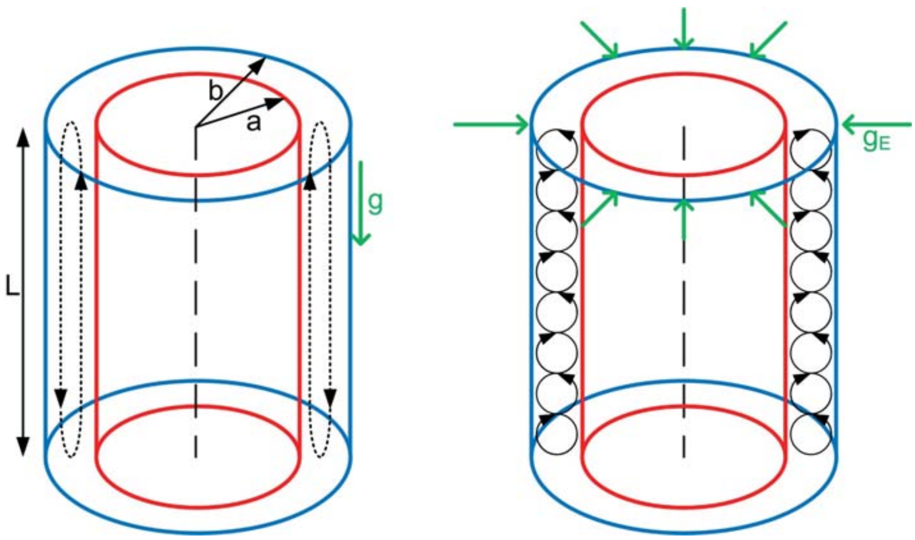

Figure 1.1: Schematic representation of the annular cavity with natural axial gravity g as first case and with radial gravity g_E as second case. The expected convective cell formation is plotted.

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.

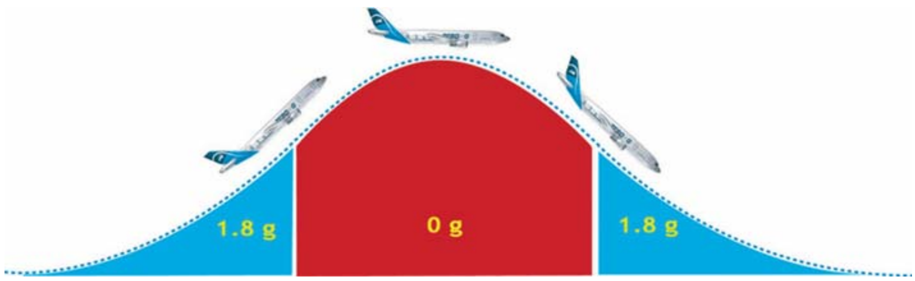

Figure 1.2: Natural gravity ranges in one parabola of a parabolic flight. Each parabolic flight consists of 31 parabolas. Courtesy of Novespace (2012)

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.

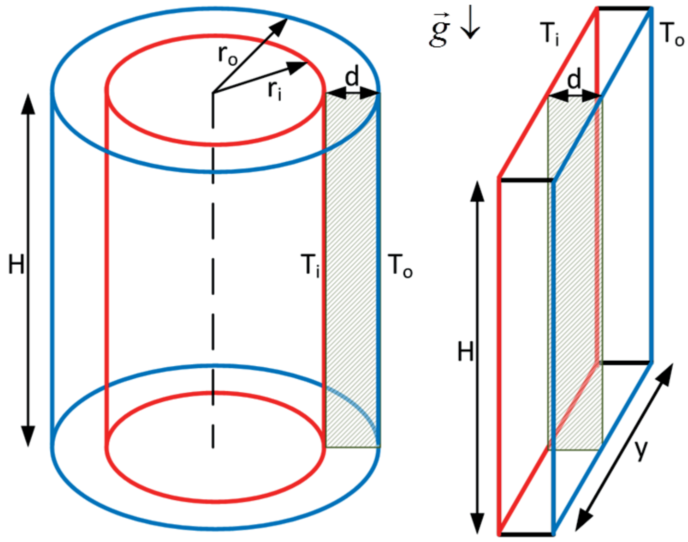

Figure 2.1: Schematic view of vertical aligned enclosures, in particular concentric cylinders (left) and a vertical slot (right) with a temperature gradient perpendicular to the gravity and adiabatic top and bottom boundaries. The radius ratio η for cylindrical enclosures is $\eta < 1$ and approximates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