Parabolic flight experiment “Convection in a Cylinder” – Convection patterns in varying buoyancy forces

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Abstract. Within the project “Convection in a Cylinder” (CiC) heat transfer enhancement is studied for the case of two concentric, vertically aligned cylinders. 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. This setup in a gravitational buoyancy field leads to a fluid movement in a single convective cell with hot fluid rising at the inner boundary and cold fluid sinking at the outer boundary. The top and bottom part of the system shows horizontal movement, again in boundary layers. The strengthening of temperature gradient induces instabilities of that convective motion. If we vary the buoyancy force by means of electro-hydrodynamic effects, the patterns of convection differ from those instabilities rising only from variation of the temperature gradient.

1. Introduction

Research in micro-fluidics 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. in heat exchangers, pumps and micro-dosing systems, cylindrical geometries come to the fore. Here we focus on the enhancement of heat transfer in an annular cavity, if an electro-hydrodynamic force field is set up in micro-gravity conditions. Parabolic flights give the opportunity to investigate thermal convection and heat transfer in three different gravity $g$ conditions. Additionally to the 1g-laboratory conditions, there are hyper-gravity ranges with an approximately double-$g$ axial force field with 1.8$g$ for about 20 seconds and the micro-gravity $\mu g$-range, which is very close to zero-$g$ for a timescale of 22 seconds, see Fig. 1.

This $\mu g$-range is used to investigate the influence of the synthetic buoyancy force field by establishing a high voltage potential between differentially heated inner and outer cylinders, filled with a dielectric insulating fluid. It acts comparable to thermal buoyancy forces induced by acceleration due to $g$. Sitte & Rath (2003) performed quantitative parabolic flight experiments without determining critical values, and finally, reported an azimuthally broken symmetry. With the accomplished experiment procedure, first scenarios are realized in order to weigh the different
Parabolic flight gives opportunity to investigate in different gravity conditions. There are two ranges of hyper-gravity (1.8g) and the micro-gravity-range (µg) in between. Image source: Novespace

influences of natural buoyancy, coming from $g$, and electro-hydrodynamic buoyancy, coming from synthetic force fields. First results of such scenarios are computed in numerical simulations by Smieszek et al. (2008).

They describe how such a system, show an increasing of heat transfer, even if still less thermal drive is set up. In µg-environment of a parabolic flight campaign, where buoyancy due to gravity does not exist, it is only that so called dielectrophoretic effect, which can be used to generate an electro-hydrodynamic buoyancy force field. Finally a dielectric thermally driven Rayleigh-Bénard convection will occur (Chandra & Smylie, 1972; Takashima, 1980).

Figure 1. Parabolic flight gives opportunity to investigate in different gravity conditions. There are two ranges of hyper-gravity (1.8g) and the micro-gravity-range (µg) in between. Image source: Novespace

Here we present thermal convection experiments in the vertical annulus for radial buoyancy forces with radial gravity during those parabolic flight with variation of the gravity. For this, we will first introduce the physical basics, followed by the description of the experiment setup. Then, our results refer to the thermal convection in the radial gravity and the comparison of the numerical simulation.

2. Physical basics

Specific experiment objective is the convection in an annular cavity with differentially heated inner and outer cylinders under the influence of the axial and radial buoyancy driven forces,
see Fig. 2. The description of buoyancy driven convection in Newtonian fluids is based on the equations of continuity, impulse and energy. With regard to low values for the coefficient of volume expansion \( \alpha \) we consider the Boussinesq-approximation, as shown by Chandrasekhar (1981)

\[
\rho = \rho_0[1 - \alpha(T - T_0)],
\]

where the index \( 0 \) marks the reference values for the used variables. In analogy to this buoyancy force, which is raised by density changes in natural gravity, there exists an electro-hydrodynamic buoyancy force, if the permittivity varies in dielectrophoretic force field:

\[
\epsilon = \epsilon_1[1 - \gamma(T - T_0)],
\]

with \( \epsilon_1 = \epsilon(T_0) \).

Here, the temperature-dependency of the dielectric permittivity \( \epsilon \) is described with \( \gamma \) as the thermal expansion coefficient, relating also with the following:

\[
\gamma = \alpha \frac{(\epsilon_r - 1)(\epsilon_r + 2)}{(3\epsilon_r)}
\]

with \( \epsilon_r \) as the relative permittivity of the fluid, as shown by Yavorskaya et al. (1984).

The synthetic radial force field is generated by applying an alternating high voltage up to 10kV between the inner and outer boundaries and the use of a dielectric liquid as experimental fluid, as shown by Hart et al. (1986). While in the laboratory the axial, natural gravity \( g \) superimpose the synthetic radial gravity \( g_E \), we consider to the micro-gravity environment, where the axial gravity tends to zero and offers the possibility to distinguish between both effects. Refer to Yavorskaya et al. (1984), Hart et al. (1986) and also Futterer et al. (2010), who introduced this technique in spherical applications in long-term \( \mu \)-gravity experiments on space flights and on the International Space Station. Sitte & Rath (2003) introduced the technique for cylindrical application in short-term \( \mu \)-gravity conditions on parabolic flights. All equations are scaled with the outer radius \( b \) for the length, the temperature difference \( \Delta T \) is defined by \( \Delta T = T_a - T_b \) with \( T_a > T_b \), where the indexes \( a \) and \( b \) refer to the inner and the outer base, respectively.

The non-dimensional equations for the velocity field \( U \) and temperature field \( T \) for thermal convection, with the influence of the radial buoyancy force field, is described by the continuity equation:

\[
\nabla \cdot U = 0,
\]

and by the Navier-Stokes-equation:

\[
\rho \left[ \frac{\partial U}{\partial t} + (U \cdot \nabla)U \right] = -\nabla p + \mu \nabla^2 U + \rho(T)g + \epsilon(T)g_E
\]

with the pressure \( p \) and the dynamic viscosity \( \mu \). The gravitational acceleration is marked with \( g \) and the electro-hydrodynamical acceleration, based on the dielectrophoretic acting, radial force field, with \( g_E \). The equation of energy conservation can be simplified to

\[
\frac{\partial T}{\partial t} + (U \cdot \nabla)T = \kappa \nabla^2 T
\]

by neglecting the viscous and electric dissipation terms. The thermal buoyancy forces are balanced with the Rayleigh number \( Ra \). For radial dielectrophoretic acting force field \( \alpha \) will
be replaced by the permittivity $\epsilon_r$ depending thermal expansion-coefficient $\gamma$ (see Eq. (3)). This leads to an electrical Rayleigh number $Ra_E$

$$Ra_E = \frac{\gamma g_E \Delta T (b - a)^3}{\nu \kappa}$$

(7)

with the radial acceleration $g_E$

$$g_E = \frac{\epsilon_0 \epsilon_r}{\rho(T)} \frac{1}{2} \left( \frac{V_{app}}{\ln(a/b)} \right)^2 \frac{1}{b^3},$$

(8)

which is induced by an alternating electrical field with the applied voltage $V_{app}$ as peak-to-peak value.

3. Experimental setup

The experiment consists of two separate cavities with different radius ratio $\eta = a/b$ for investigating convective flow in wide gaps with $\eta = 0.5$ and in small gaps with $\eta = 0.9$. The experiment cells are equal with a cavity length of $L = 100 mm$ and a cavity width of $d = 5 mm$, which leads to an aspect ratio $\Gamma = L/d = 20$, where $d$ is defined by $d = b - a$. Further geometrical parameters are given in Table 1.

| Parameter                  | A       | B       |
|----------------------------|---------|---------|
| radius inner cylinder      | $a \,[m]$ | $5.0 \cdot 10^{-3}$ | $4.7 \cdot 10^{-2}$ |
| radius outer cylinder      | $b \,[m]$ | $1.0 \cdot 10^{-2}$ | $5.2 \cdot 10^{-2}$ |
| length                     | $L \,[m]$ | $1.0 \cdot 10^{-1}$ | $1.0 \cdot 10^{-1}$ |
| radius ratio               | $\eta \,\left[\right]$ | 0.5     | 0.9      |
| aspect ratio               | $\Gamma \,\left[\right]$ | $2.0 \cdot 10^1$ | $2.0 \cdot 10^1$ |

Besides the geometrical parameters, we have parameters of the used working fluid, which are summarized in Table 2. Finally the physical properties are captured with the Prandtl number $Pr = \nu / \kappa = 64.64$.

The inner cylinder is heated and the outer cylinder is cooled, which leads to a thermal convective motion, based on the temperature gradient $\Delta T = 10 K$, see Fig. 2. The cavity is filled with silicone oil (Wacker AK5), containing additionally tracer particles, which follow the flow and do not align in the applied high voltage field. The observation of the flow is realized by an axial laser light sheet illumination. A camera is installed perpendicular to the laser illuminated plane, which enlightens the whole investigation gap from top to bottom for both experiments. A construction sketch for the alignment of the experiment is shown in Fig. 3. The analysis of the images is based on theories derived from real particle image velocity ($PIV$).

In $\mu g$-range we can observe the effect of radial buoyancy without disturbances due to natural gravity $g$, which is reduced to a negligible mean of $\pm 0.05 g$. One parabolic flight includes 31 parabolas, in which we increase $Ra_E$ with an increment of $\approx 610$. The high voltage is defined by the $Ra_E$, the $\Delta T$ and the parameter of geometry and fluid (see Tab. 1, 2).
Table 2. Fluid parameters of the working fluid Wacker AK5. The thermal expansion coefficient $\gamma$, applied in radial gravity in micro-gravity environment depends on the relative permittivity $\epsilon_r$ (see Eq. (3)).

| Parameter                        | Value       |
|----------------------------------|-------------|
| kinematic viscosity $\nu$ [$m^2/s$] | $5.00 \cdot 10^{-6}$ |
| density $\rho$ [$kg/m^3$]        | $9.20 \cdot 10^2$ |
| relative permittivity $\epsilon_r$ | $2.70$ |
| therm. diffusivity $\kappa$ [$m^2/s$] | $7.74 \cdot 10^{-8}$ |
| therm. expansion coeff. $\alpha$ [$1/K$] | $1.08 \cdot 10^{-3}$ |
| therm. expansion coeff. for relative permittivity $\gamma$ [$1/K$] | $1.07 \cdot 10^{-3}$ |

Figure 3. Alignment of both experiments in experiment container. Both experiments work independent to each other and fully automated during the parabolic flight. The experiment with radius ratio $\eta = 0.5$ is marked with “Exp. A”, $\eta = 0.9$ is marked with “Exp. B”, respectively.

4. Results

The convective flow of the natural gravity phase is stabilized in the hyper-gravity with $1.8g$. This effect resets the system to an initial state, which is equal for each set point of the parameter domain, see Fig. 4. With the beginning of the $\mu g$-range the convective flow stops immediately. Then, the convective flow is driven only by electrical acceleration $g_E$ and buoyancy is based on the temperature dependency of $\epsilon_r$.

Numerically simulated instabilities occur to the end of $\mu g$-range. First instabilities evolve near the top and bottom boundaries of the experiment. The numerical simulations in Fig. 4 show the temperature field for a fixed temperature gradient $\Delta T = 10K$ and an applied high voltage up to $V_{rms} = 10kV$ in the $\mu g$-range for both experiment cells. With the higher Rayleigh number ($Ra_E$) the instabilities propagate through the whole gap. At approximate $Ra = 3500$, which correlates to $V_{rms} = 5.7kV$ at $\Delta T = 10K$, we observe the transition from a large, single convective flow cell to a Rayleigh-Bénard flow in a cylindrical annulus with several small scale convective cells.
Figure 4. The parameter domain show selected numerical results at the onset of first instabilities at low $Ra_E$ and fully controlled flow patterns at higher $Ra_E$. The diagram also show the dependency of $Ra_E$ by the radios ratio $\eta$.

In the following we will describe examples of the experimental results for a low and for a high $Ra_E$. At low $Ra_E$ and very low buoyancy, respectively, the flow mostly 'freezes' as shown in the left side of Fig. 5. The image part a) shows the vector field of the velocities; the velocities tend to zero, which reduce the length of the vector to a dot. With increasing radius ratio, the effect of the freezing becomes more relevant, due to the radial buoyancy $Ra_E \sim g_E$ and $g_E \sim V_{app}^2$. Furthermore, as described in Eq. (8), $g_E$ depends by the cubic of the geometry with $g_E \sim b^{-3}$. This decreases $Ra_E$ for a radius ratio of $\eta = 0.9$ enormously. This let be aware that a technical application for flow control, due to the applying of the dielectrophoretic effect would be very sensitive.

It is also observable, if the $\mu g$-range starts and $g$ vanishes, the thermal convective flow stops directly. For small $Ra_E$, there seems to be some kind of stratification effects with the tracer particles. At higher $Ra_E$, this effect minimizes, due to stronger movement of the convection. A similar effect can be observed in natural gravity condition with very small $\Delta T$, when the density of the particles and the fluid varies a bit. In radial gravity it supervenes, that little differences in permittivity between fluid and particles lead to a similar effect. This effect could be applied to filter pressure-sensitive fluids and to separate fluids in mixtures. With higher $Ra_E$ these effects decrease, due to strength of the convective flow.

In Fig. 5 some kind of wavy movement in axial and radial direction for $\eta = 0.5$ at the top part in the vector field of experiment A can be observed. In experiment B, the vector field shows a small increasing of movement along the centerline of the investigation gap. The velocity field in axial (b) and radial (c) direction confirms this identification by comparison the left with the right part of Fig. 5. The amplified movement is a first indicator for the enhancement of heat transfer. The quantitative analyzes by assigning the power to the Nusselt number will follow.

The observation of the transition to more complex convective flow show promise to increase the timescale of $\mu g$ to more than the thermal diffusive time $\tau_{therm} = d^2/\kappa$. This would lead to investigations with non-transient kind of pattern formation.
Exp. A: $Ra_E = 3.2 \cdot 10^2$
Exp. B: $Ra_E = 1.2 \cdot 10^2$

Exp. A: $Ra_E = 9.3 \cdot 10^3$
Exp. B: $Ra_E = 3.1 \cdot 10^3$

Figure 5. Experimental images at a temperature gradient $\Delta T = 10K$ for low electrical Rayleigh numbers $Ra_E$ with an applied high voltage $V_{app} = 1.8kV$ and for high $Ra_E$ with $V_{app} = 9.8kV$. The frames show the temporal mean of a) vector field of the velocity, b) the axial velocity, c) the radial velocity and d) the vorticity of the flow. It shows that there is a drift of particles in radial direction at Exp. A with smaller radius ratio of $\eta = 0.5$. The inertial convective cell in Exp. B with $\eta = 0.9$ is mostly frozen. For higher $Ra_E$ a wavy movement of particles in radial and axial direction can be observed for $\eta = 0.5$. A very low movement can be observed along the centerline at $\eta = 0.9$.

These first results for the application of electrical fields, as parameter to control the convective flow, demonstrate the possibilities for an enhancement of heat transfer. Further technical applications like filters and distribution systems have to be mentioned.

5. Outlook

The combination of a radial temperature gradient and an alternating electrical force field has great impact on fluid flow patterns, which organize the heat transfer on convection. The presented results demonstrate, that a convective motion in the homogeneous fluid can be controlled by the dielectrophoretic effect.

Further planned studies with a variation of the Prandtl number will help to analyze the onset of instabilities in detail. Moreover the system shall be quantified with the focus on power measurement for assigning a Nusselt number.

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