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Investigations on thermal electro-hydrodynamic convection in a cylindrical gap

Martin Meier, Marcel Jongmanns, Christoph Egbers
Department of Aerodynamics and Fluid Mechanics
Brandenburg University of Technology (BTU) Cottbus - Senftenberg
LG 3A, Siemens-Halske-Ring 14
D-03046 Cottbus, Germany
Phone: +49-(0)355-69-4868
Fax: +49-(0)355-69-4891

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Abstract
The objective of our research is to describe a dielectrophoretic (DEP) force driven augmentation of heat transfer during natural convection in a vertical annulus. Therefore, we execute experiments on thermal convective flows in a microgravity environment with radial buoyancy induced by DEP forces, and additionally also the superposition of both buoyancy force fields. Understanding the heat transport mechanisms in a dielectric liquid confined between two concentric cylinders may lead to the improvement of heat exchangers.

Introduction

Within the project “CIC - Convection in Cylinders” we investigate the thermal convection in an annular cavity, with differentially heated inner and outer cylinders, under the influence of a centripetal electric force field. Our experiments focus on a dielectrophoretic (DEP) force driven augmentation of heat transfer during natural convection in a vertical annulus filled with a dielectric liquid. Figure 1 gives an overview on the expected flow behavior.

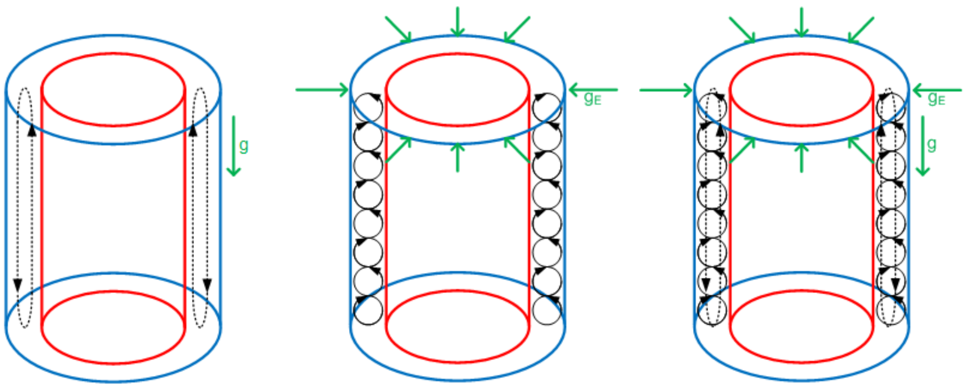


Fig. 1: Schematic representation of the annulus cavity with a radial temperature gradient and different directions of gravities. The schematics show the expected flow behaviour with axial gravity (left) in Earth’s gravity environment, DEP force induced radially acting electric gravity g_E in a microgravity environment (center), and the superposition of both gravities (right).

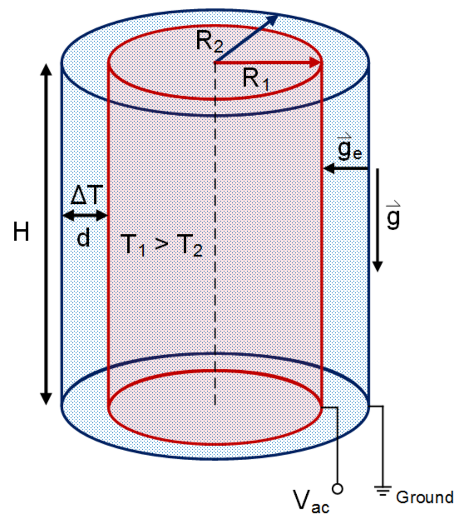
The superposition of both forces leads to different flow structures, e.g. columnar or helicoidal, depending mainly on the temperature gradient and the electrical field force. Therefore, we execute experiments on thermal convective flows in a microgravity environment with radial buoyancy induced by DEP forces, and additionally also the superposition of both buoyancy force fields in laboratory experiments.

A better understanding of the heat transport mechanisms inside a dielectric liquid confined between two concentric cylinders can deliver solutions for the improvement of the heat transport in technical applications. Examples are the optimization of heat exchangers or the improvement of boiler systems to maintain and enhance boiling processes in microgravity conditions (see Snyder and Chung 2000). The DEP force can be used to control the heat transport in cylindrical systems. The generation of convective motions by the dielectrophoretic force has been successfully tested in the GEOFLOW experiments that were performed in Fluid Science Laboratory of the International Space Station (see Futterer et al. 2015) where thermal convection patterns have been observed in a differentially rotating spherical shell submitted to a dielectrophoretic force.

Theory

Theoretical and experimental studies on the convective instability in a dielectric fluid between two coaxial cylinders were performed e. g. by Chandra and Smylie 1972, Takashima 1980, Stiles and Kagan 1993, Sitte and Rath 2003, Bahloul et al. 2000, Yoshikawa et al. 2013, Travnikov et al. 2015, Egbers et al. 2015, Futterer et al. 2015 and 2016 and Meyer et al., 2016.

A number of parameters are considered to describe the annulus cavity system with dielectric force field. Figure 2 shows the schematic layout for the cylindrical annulus experiments.



Properties of experiment liquids

AK5		AK0.65	
ν	$5\ 10^{-6}$	ν	$6.5\ 10^{-5}$
κ	$7.74\ 10^{-8}$	κ	$8.49\ 10^{-8}$
Pr	64.6	Pr	7.65
ε_r	2.7	ε_r	2.18

Figure 2: Experiment layout (schematically) and properties of experimental dielectric silicone oils (Wacker AK5 and AK0.65). The high ac-voltage (up to 10kV) is connected to the inner cylinder whereas the outer cylinder is connected to ground.

Geometrical parameters are the radius ratio $\eta = R_1/R_2$ and the aspect ratio $\Gamma = H/d$. Parameters to characterize the convection are the Prandtl number $Pr = \nu/\kappa$ and the Rayleigh number Ra. $\rho(T)$ is the temperature dependent fluid density, R_1 and R_2 are the radii of the inner and the outer cylinder, respectively, and $\mathbf{H}$ is the height of the system, $\mathbf{V_{rms}}$ is the effective voltage ($\mathbf{V_{rms}} = \frac{\mathbf{V_{peak}}}{\sqrt{2}}$).

The dielectric force $\mathbf{F_{DEP}}$ is defined as

$$F_{DEP} = -\frac{1}{2} E^2 \vec{\nabla}\varepsilon$$

Here, $\mathbf{E}$ is the electric field strength and $\boldsymbol{\varepsilon}$ is the temperature dependent fluid permittivity. Therefore, an electric Rayleigh number $\mathrm{Ra_E}$ can be defined with the kinematic viscosity $\boldsymbol{\nu}$, the thermal diffusivity $\boldsymbol{\kappa}$, the thermal coefficient of permittivity $\mathbf{e}$, the gap width $\mathbf{d} = \mathbf{R_2} - \mathbf{R_1}$ and the temperature difference $\boldsymbol{\Delta}\mathbf{T}$ between the heated inner and the cooled outer cylinder.

$$\mathrm{Ra} = \frac{\alpha \cdot \mathrm{g} \cdot \Delta\mathrm{T} \cdot \mathrm{d}^3}{\nu \cdot \kappa}$$

$$\mathrm{Ra_E} = \frac{\alpha \cdot \mathrm{g_E} \cdot \Delta\mathrm{T} \cdot \mathrm{d}^3}{\nu \cdot \kappa}$$

Since the artificial gravity $\mathbf{g_E}$, is a function of the radius $\mathbf{r}$, the values of the Rayleigh number hereafter refer to $\mathbf{Ra_E}(\mathbf{r} = \mathbf{R_2})$ at the outer cylinder.

$$g_E = \frac{e\varepsilon_0\varepsilon_r}{\alpha\rho}\left(\frac{V_{rms}}{ln\left(\frac{R_1}{R_2}\right)}\right)^2 \frac{1}{r^3} F$$

with

$$F = \frac{\gamma_E^2\left[1-\gamma_e\left(\frac{\Theta}{\Delta T}\right)+\frac{1}{log\eta}\right]}{[log(1-\gamma_e)]^2\left(1-\frac{\gamma_E\Theta}{\Delta T}\right)^3} \quad \text{and} \quad \gamma_E = e\Delta T \quad \text{and} \quad \Theta = \frac{\Delta T log\left(\frac{r}{R_2}\right)}{log\eta}$$

The alternating electric field ($\mathbf{V_{peak}} \leq$ 10kV) together with the temperature gradient gives rise to a dielectrophoretic force $\mathbf{F_{DEP}}$ induced by a gradient of permittivity. In a mono-phase dielectric liquid with a sufficiently high thermal coefficient of permittivity **e**, an applied temperature gradient generates convective flows. The dielectrophoretic force acts as an “artificial” buoyancy. The theoretical and numerical results for weightlessness condition show, for $\mathbf{Ra_E}$ larger than a critical value, that counter oriented stationary helices may occur in the annulus (Yoshikawa et al. 2013, Travnikov et al. 2015). In the simulations under terrestrial conditions, the gravity induced base flow (a mono-cellular convective flow) is only disturbed by the dielectrophoretic force, as the position and properties of upper and lower boundaries (end-caps) have a strong influence on the flow. Under parabolic flight conditions, any base flow possibly established prior to the microgravity phase will be damped during the microgravity phase, while the dielectrophoretic force influences the flow.

Experiments

Preliminary observations of the dielectrophoretic force effects in the cylindrical annulus were performed in parabolic flight experiments where non axisymmetric patterns were identified, see Egbers, Meier et al. 2015. As the microgravity phase in parabolic flight experiments last only 22 seconds, it is necessary to perform an exhaustive investigation of the different effects of the control parameters of the flow systems in order to isolate the real contribution of the dielectrophoretic effect compared to the Archimedean buoyancy.

The parameter field of our experiments with $\eta=0.5$, max. $\Delta T=15K$ and max. $V_{peak}=10kV$ is in a range of the thermal Rayleigh-numbers of up to $6\cdot10^4$ (for Pr=64.6) and $4.8\cdot10^5$ (for Pr=7.65). The corresponding electrical Rayleigh-numbers are in a range of up to $1.5\cdot10^4$ (for Pr=64.6) and $1\cdot10^5$ (for Pr=7.65).

Under laboratory conditions, thermal convection experiments are limited to the unidirectional gravity field of the earth. Other field geometries can be realized with the dielectrophoretic force. In analogy to large-scale geophysical flows, the thermal convection in a spherical shell under a central force field is investigated experimentally and numerically under microgravity in the "GeoFlow" experiment (Futterer et al. 2013). Different optical measurement methods are used to visualize and/or quantify the flow field inside the gap. Due to the electric high voltage field in the gap, non-invasive measurement methods should be used. For investigations in a wider parameter field, we designed a new modular experiment cell system (see figure 4) which will be used in our next PFC in October 2016.

The inner cylinder is heated by a heating fluid loop using silicone oil as fluid and connected to high voltage. The outer cylinder is connected to ground potential and is cooled by a cooling fluid loop, which also uses silicone oil. Inner and outer cylinder are made of Aluminium (AlMgSi0.5). The top and bottom caps are made of Polymethylmethacrylate (PMMA) to ensure thermal and electrical insulation. Temperatures of heating and cooling fluid loop are measured by thermocouples located in the in- and outlets outside the electric high voltage field. With this heating and cooling system it is possible to generate a temperature difference between the inner and outer cylinder of up to 10K. To visualize the flow pattern a Schlieren/ Shadowgraph method is used.

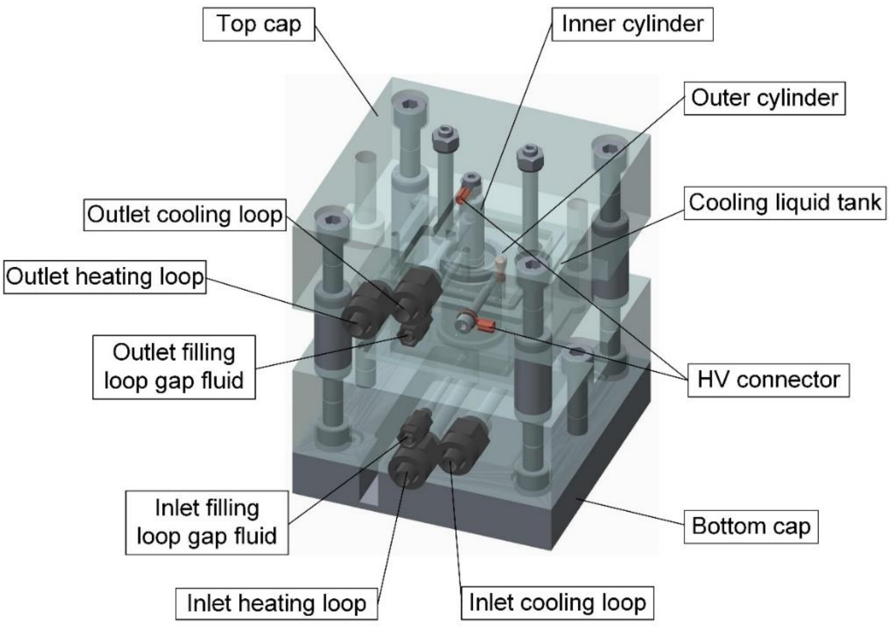


Fig. 4: Design of the new modular experiment cell. For our PFC-experiment in Oct. 2016, the radius of the inner cylinder is R1 = 5mm and that of the outer cylinder is R2 = 10mm, the gap width is d = 5 m and its height is H = 30mm. Thus, the radius ratio is η = 0.5 and the aspect ratio is Γ = 6.

The cell is illuminated from the bottom by a LED with approximate telecentric lighting. The light rays go through the liquid in the cell and are refracted because of density gradients inside the fluid. When the temperature changes, the density and the refractive index of the fluid change and the flow also changes. The image of the flow changes is captured with a camera, which is focused on the top of the cell. To enhance the contrast a false colour representation is used.

Parabolic Flight Experiments

In parabolic flights we have the opportunity to investigate thermal convection and heat transfer in three different gravity conditions. Additionally to the (normal) 1g-conditions, there are two hyper-gravity phases with 1.8g for about 20s and the µg-phase with about 22s during one parabola. One parabola has 5 succeeding phases of acceleration – 1g, 1.8g, µg, 1.8g and again 1g. Each scientific PFC has 3 flight days with about 30 parabolas per flight.

Up to now, 5 Parabolic Flight Campaigns (PFC) have been executed successfully by our group with varying aspect ratios, Prandtl and Rayleigh numbers of the CIC-experimental set-up, see Egbers et al. 2015 and Futterer et al. 2016. For the next two years we are preparing 2 PFC with our newly designed experimental set-up. For the CNES-PFC#125 in October 2016 our new designed experimental set-up contains two experiment cells, which differ in the used fluid. While Cell A contains Silicone oil Wacker AK5, Cell B contains Wacker AK0.65 (lower kinematic viscosity). Figure 4 shows the experimental set-up of our next parabolic flight campaign. While the microgravity time frame in parabolic flights is rather short (22s), we are also preparing a sounding rocket experiment (TEXUS-program). Onboard a TEXUS-rocket, a µg-time of about 360s can be achieved. Parabolic flights give the opportunity to investigate thermal convection and heat transfer in three different gravity g conditions.

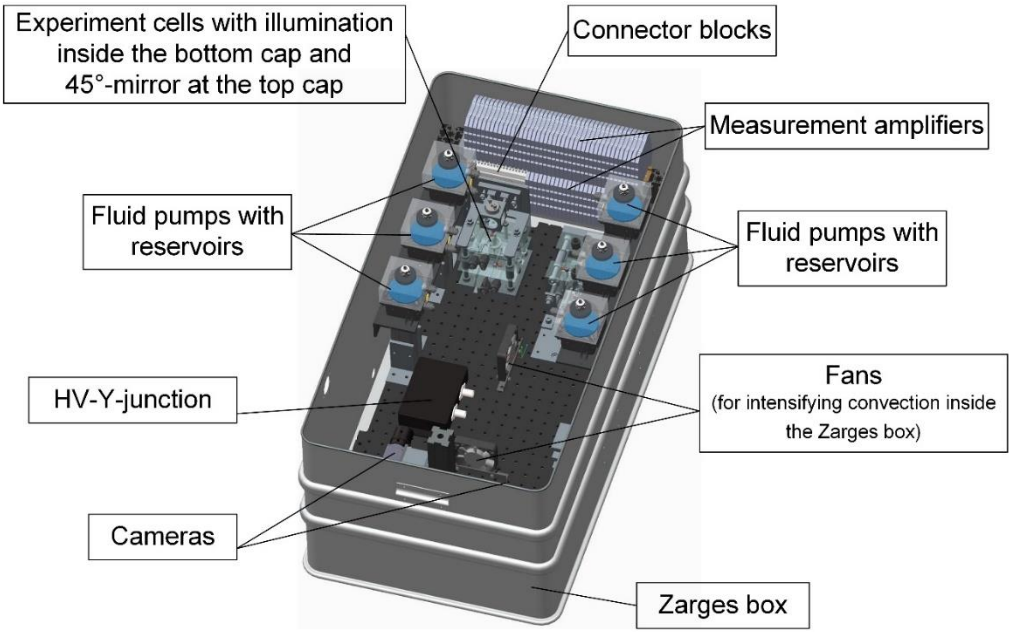


Figure 5: Sketch of the experimental set-up of PFC 2016

For investigations in a wider parameter field, we designed a new modular experiment cell system. Different optical measurement methods are used to visualize and/or quantify the flow field inside the gap; not only due to the electric high tension field in the gap. Beside a Shadowgraphtechnique to visualize simple flow patterns we are preparing the use of a Back-oriented Schlieren-technique. By means of coating the outer cylinder with a transparent conductive (TCO) layer we are also planning to perform PIV-measurements. By using PIV we will visualize and quantify the 2D (later on 3D) flow field inside the gap.

In the following some results of our PFC-experiments in Oct. 2015 are presented. The shadowgraph-images in figure 6 show the base flow at 1g, 1.8g and at the end of the microgravity phase. Heating power was set at 80% corresponding to a ΔT of about 7K and no voltage applied. In the 1g phase one can see an inner structure, corresponding to a higher temperature due to the heated oil moving towards the top of the cell. This structure is enhanced during the 1.8g phase. In the microgravity phase there are no structures visible. The shadowgraph in the microgravity phase (right picture) shows that the buoyancy driven flow was stopped due to microgravity conditions. This behavior is verified by temperature measurements inside the gap as shown in figure 8.

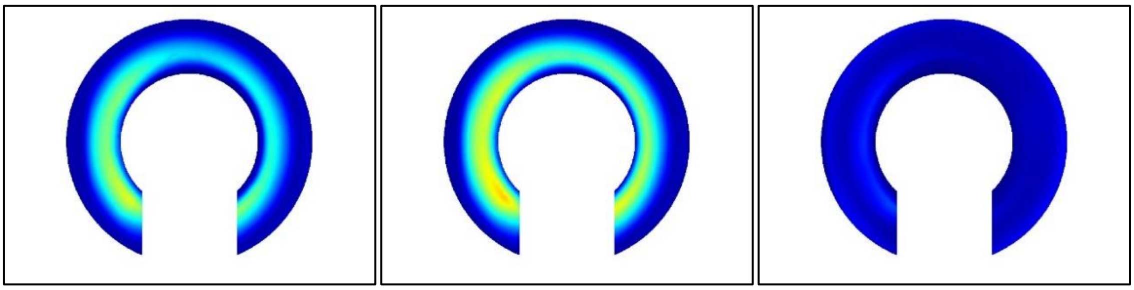


Figure 6: Shadowgraph pictures taken in succeeding three phases of one parabola – 1g (left), 1.8g (middle) and µg (right). Vertical annulus with a gap width of 5.1mm and a height of 100mm.

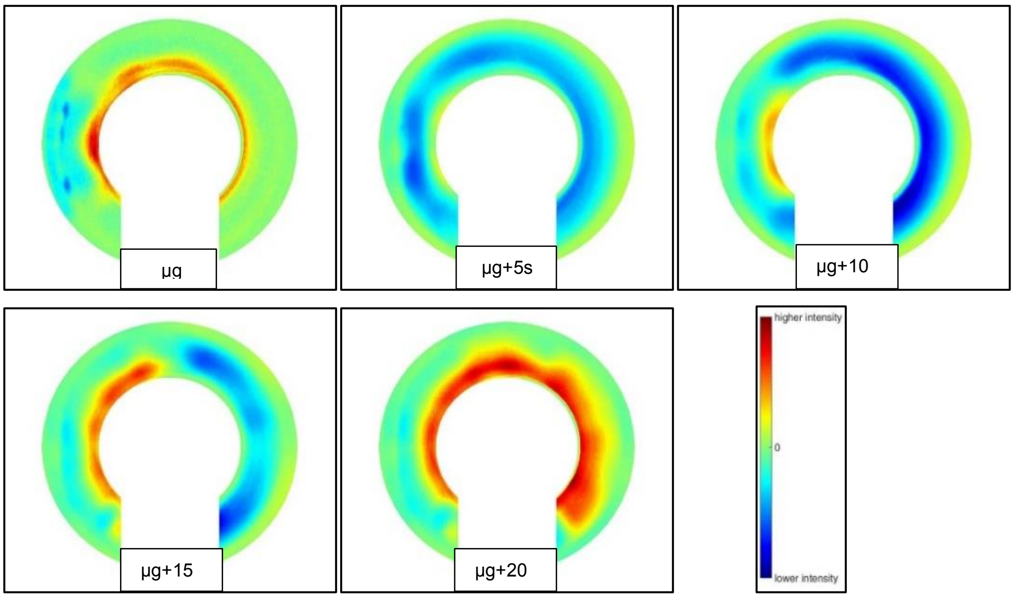


Figure 7: Shadowgraph pictures (enhanced false colored) taken in the microgravity phase of one parabola with a time distance of 5s. The first picture (top left) is taken at the start, the last (bottom right) at the end of the µg-phase. Vertical annulus with a gap width of 5.1mm and a height of 100mm; V_{peak} = 9kV, heating power is at 80% (ΔT of about 7K). The intensity scale bar is given in the last picture bottom right. Red areas have higher light intensity in the actual image than in the reference image, whereas blue areas have a lower light intensity.

In figure 7 Shadowgraph pictures taken in the microgravity phase of one parabola with a time distance of 5s can be seen. For comparison of intensities see the scale bar (picture bottom right). The enhanced false coloured images show the succeeding development of the flow during the microgravity phase. The first image is taken at the start of the µg-phase, the following are taken 5s, 10s, 15s and 20s later in the µg-phase. It takes roughly 15s for the flow to recover from the 1.8g phase with enhanced buoyancy and to enter another flow state influenced by the electrical gravity, mainly. This result is verified by the temperature measurement inside the cell given in figure 8 showing that the temperature distribution over the height of the cell is nearly equalized at the end of the µg-phase.

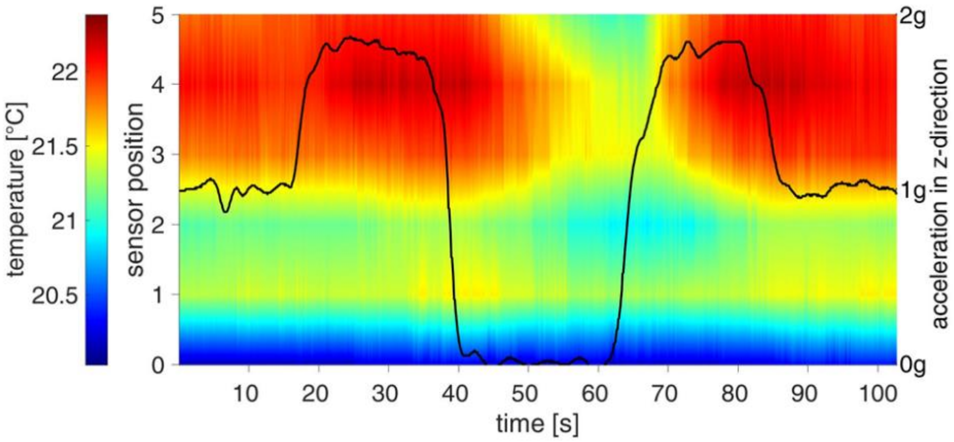


Figure 8: Temperature field measured at 6 vertical positions at the outside of the annulus. Plotted acceleration shows the 5 succeeding phases – 1g, 1.8g, µg, 1.8g, 1g – of one parabola.

Conclusion

The presented work addresses the stability of a dielectric liquid under a combined action of the Earth gravity and an electric gravity. Experiments performed in a parabolic flight campaign 2015 confirm the existence of non-axisymmetric modes predicted by theory. Further investigations are needed for a better description of this complex problem. Results of ongoing numerical simulations and stability analyses done by two cooperative partners (LOMC-CNRS, University Le Havre, France, and ICSC-EMCL, University of Heidelberg) will be validated by our experimental results.

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